natural resources research XVIII

case studies on desertification

Prepared by
Unesco/UNEP/UNDP

unesco

Natural resources research XVIII

Other titles in the series
Natural resources research

I. A review of the natural resources of the African continent
II. Bibliography of African hydrology
III. Geological Africa with explanatory note
IV. Review of research on laterites
V. Functioning of terrestrial ecosystems at the primary production level. Proceedings of the Copenhagen Symposium
VI. Aerial surveys and integrated studies. Proceedings of the Toulouse Conference
VII. Agroclimatological methods. Proceedings of the Reading Symposium
VIII. Proceedings of the Symposium on the Granites of West Africa: Ivory Coast, Nigeria, Cameroon, March 1965
IX. Soil biology. Reviews of research
X. Use and conservation of the biosphere
XI. Soils and tropical weathering. Proceedings of the Bandung Symposium, 16 to 23 November 1969
XII. Natural resources of humid tropical Asia
XIII. Computer handling of geographical data
XIV. Tropical forest ecosystems. A state-of-knowledge report
XV. Review of research on salt-affected soils
XVI. Tropical grazing land ecosystems. A state-of-knowledge report
XVII. Vegetation map of South America: explanatory notes

Case studies on desertification

Prepared by Unesco/UNEP/UNDP

Edited by
J. A. Mabbutt and C. Floret

unesco

Published in 1980 by the United Nations
Educational, Scientific and Cultural Organization,
7 Place de Fontenoy, 75700 Paris
Printed by Page Bros (Norwich) Ltd

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of Unesco, UNEP or UNDP concerning the legal status of any country or territory, or of its authorities, or concerning the delimitations of the frontiers of any country or territory.

ISBN 92-3-101820-5

© Unesco 1980
Printed in the United Kingdom

Preface

Hot, dry regions cover more than one-third of the world's surface and include a variety of ecological conditions. Arid and semi-arid lands, comprising much of Africa, Asia and Latin America, range from thinly vegetated desert areas which sustain nomadic populations and their grazing animals to marginal areas supporting settled populations, crops and livestock. All these areas are characterized by low productivity, often unreliable rainfall and a particularly adapted animal and plant life. Much of the usable land in these dry regions is being converted to unproductive waste by a combination of ecological and socio-economic factors. It is estimated that today the livelihood of some 50 to 80 million people is thus being threatened in the drier areas of the world.

For nearly three decades, the international community has been actively concerned with the inherent problems of arid and semi-arid zones. From 1951 to 1962, Unesco carried out a wide programme of studies to promote and stimulate research in various scientific disciplines bearing upon the problems of arid regions. This programme produced some thirty volumes on *Arid Zone Research*, covering such fields as hydrology, ecology, physiology, soil salinity or energy resources. It also led to the development of major arid zone research and training centres and the establishment of some 200 research units in forty countries. Unesco has also been involved in the preparation of several thematic maps presenting up-to-date scientific knowledge on the natural resources of arid areas. These include the *World Soil Map*, the bioclimatic maps of the Mediterranean zone, the vegetation maps of the Mediterranean region, of Africa and of South America, and continental geological maps.

The recent droughts which struck huge areas of Africa and Asia dramatically highlighted not only the need for urgent action in these zones but also the complexity of the obstacles to their implementation. Unesco mobilizes world-wide resources to address these problems and has been associated throughout with this international effort, in particular through its Man and the Biosphere Programme (MAB) and the International Hydrological Programme (IHP). Two of the fourteen major research themes under the MAB Programme are directly concerned. Theme 3 deals with the impact of human activities and land-use practices on grazing lands, especially those in arid and semi-arid areas, while theme 4 concerns the impact of human activities on the dynamics of arid and semi-arid ecosystems, with particular attention to the effects of irrigation. Unesco has also published a series of MAB Technical Notes on problems of the arid zone.

Unesco participated actively in the preparation of the United Nations Conference on Desertification which was convened in Nairobi in August–September 1977 following the United Nations General Assembly Resolution 3337 (XXIX). As part of its contribution to this conference, Unesco published a map of the world distribution of arid regions at the scale of 1/25 000 000[1] and co-operated with FAO and WMO in the preparation of a *World Map of Desertification*. In co-operation with UNDP, Unesco was responsible for the preparation of six national case studies on desertification and its control in Chile, India, Iraq, Niger, Pakistan and Tunisia. The case studies were presented to the conference and were welcomed as valuable insights into the causes of desertification under different socio-ecological conditions. Some of the conclusions formed the basis of the recommendations of the Plan of Action to Combat Desertification adopted by the conference.

Associated case studies were submitted to the conference by the Governments of Australia, China, Iran, Israel, U.S.S.R. and the United States to give further insights into different experiences of the desertification process. In view of the wealth of information contained in the case studies and the relevance of their conclusions to decision-makers, planners, scientists and students, their publication in the form of a book, together with a chapter synthesizing the lessons learned, was deemed important by Unesco and UNEP, who undertook to supply the necessary financial resources.

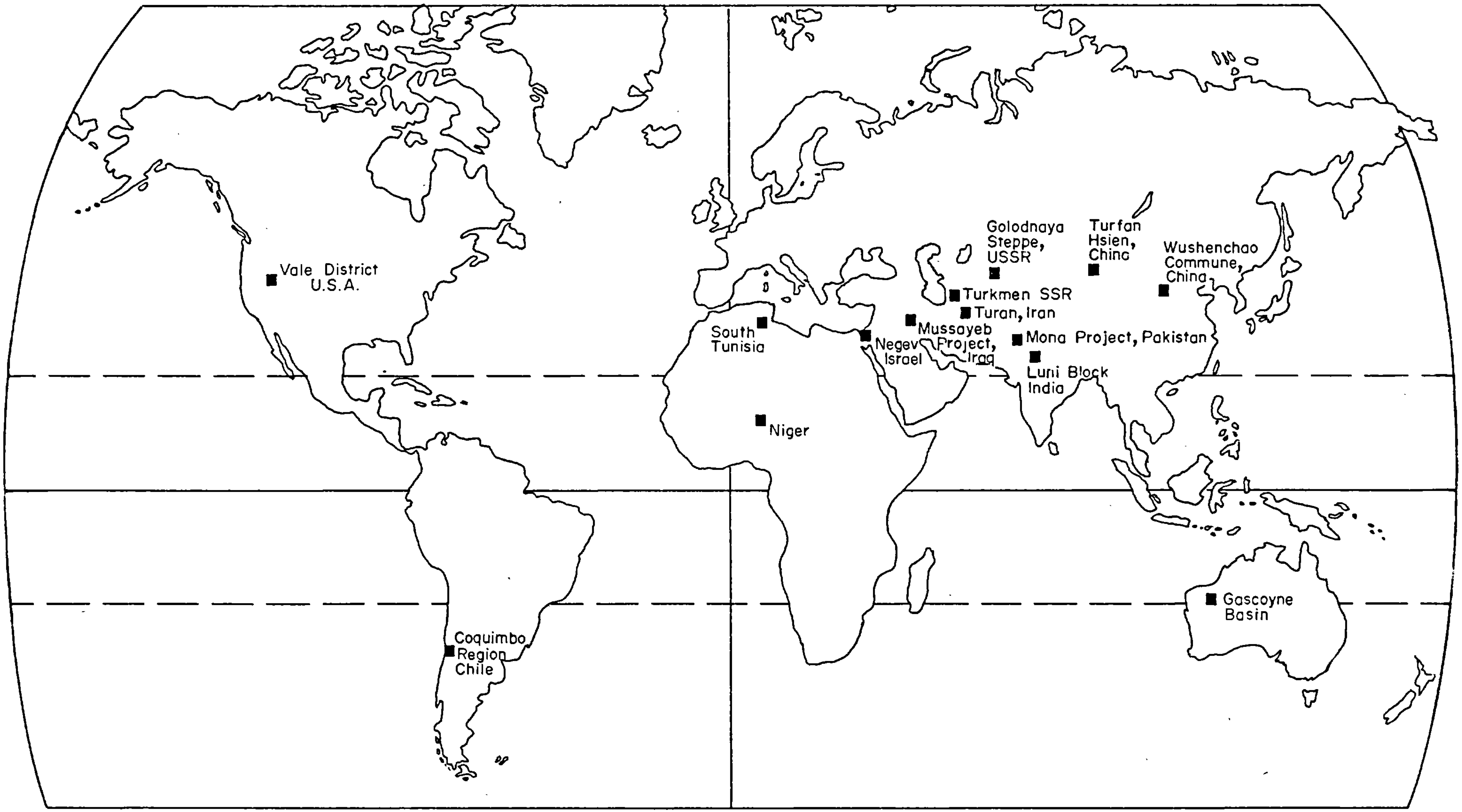
The present volume reproduces edited versions of the six case studies commissioned by Unesco and supported by UNDP, summarizes the associated case studies in a chapter, and then presents some general conclusions arising from the experience of desertification and measures to combat it.

The names, legal status and frontiers of all countries or territories mentioned in the text are given as indications only. The designations employed and the presentation of the material do not imply the expressions of any opinion on the part of Unesco concerning the legal status of any country or territory, its authorities, or the given frontiers of any country or territory.

Unesco, UNEP and UNDP wish to express their gratitude to the contributors of the case studies and to all those who provided suggestions and advice in the preparation of this work. Particular thanks are due to Professor J. A. Mabbutt, School of Geography, University of New South Wales, Kensington (Australia) and to Dr C. Floret, Research Scientist at the CNRS, Centre d'Etudes Phytosociologiques et Ecologiques Louis Emberger, Montpellier (France), who not only contributed towards several of the national case studies, but also undertook the task of editing this present volume.

1. See MAB Technical Notes 7.

Contents



Location of the case studies on desertification

Foreword

The drought which affected the Sahel and adjacent parts of Africa in the late 1960s and early 1970s, with its tragic impact on the peoples of the regions, drew world attention to the chronic problems of human survival and development on desert margins, in the face of an apparent extension or intensification of desert conditions in many parts of the arid zones of the world.

Was the Sahelian drought evidence of large changes in the global climate? Was the Sahara expanding south? What implications did this have for the countries involved, for their neighbours and for the international community? The crucial question however was what could be done to cushion the impact of those disastrous changes. In order to answer such questions, the General Assembly of the United Nations called a world Conference on Desertification, which was convened from 29 August to 9 September 1977 in Nairobi.

In the preparation of the conference, the conference secretariat felt it was desirable to present a number of case studies that would illustrate the various processes of desertification and their causes and, more particularly, give an account of measures to combat desertification.

The programme included six case studies to be carried out under the direction of Unesco, with the assistance of the Food and Agriculture Organization (FAO) and in co-operation with the World Meteorological Organization (WMO), and to be financed by UNDP. To allow representative comparisons these studies comprised two regions of cool-season rainfall, two of hot-season rainfall, and two areas exemplifying the problems of waterlogging and salinization of soils under irrigation. The case studies are as follows:

Cool-season rainfall areas
Tunisia: Region of Oglat Merteba.
Chile: Coquimbo region.

Hot-season rainfall areas
Niger: Eghazer and Azawak Region.
India: Luni Development Block.

Waterlogging and salinization of irrigated arid and semi-arid lands
Iraq: Greater Mussayeb Project.
Pakistan: Mona Reclamation Experimental Project.

In planning these studies, it was anticipated that they would illustrate regional variations in the factors of climate, ecological change, population and society and technology which were the subjects of the four component reviews of desertification prepared in the programme. The human aspects of desertification, notably the behavioural, health and demographic aspects, were required to be especially stressed, in the historical context of the last 200–250 years. It was anticipated that the maps represented with each case study would include a synoptic map of regional desertification, which would follow an approach similar to that employed by FAO for the *World Map of Desertification* at 1:25000000.[1]

In addition, the programme included a number of associated case studies offered by countries with experience of combating desertification. These comprised:

Australia: Gascoyne Basin.
China: Sinkiang Turfan.
Wushen Banner, Inner Mongolia.
Review of experiences in a variety of dryland environments in China.
Iran: Turan Programme.
Israel: The Negev.
U.S.S.R: Golodnaya Steppe.
Turkmenian S.S.R.
United States: Vale Rangeland Rehabilitation Programme.

Each case study forms a complete background document, in sufficient detail to give a comprehensive account of the regional processes of desertification and their causes, the ecological aspects, and a review of the measures already taken or still required to be taken to reverse the processes. On the basis of this regional experience it formulates lessons learned, arising from the success of measures taken or from continuing problems.

1. FAO, Unesco and WMO, *World Map of Desertification at a Scale of 1:25000000*, Nairobi, Kenya, United Nations Conference on Desertification, 1977 (A/CONF. 14/2, 11 p. mimeo.).

1 Desertification in the Oglat Merteba region, Tunisia
Case study presented by the Government of Tunisia

Acknowledgements

Unesco would like to express its thanks to the Institut National de la Recherche Agronomique de Tunisie, which was responsible for the preparation of this case study, and to the principal authors C. Floret (CEPE-CNRS), M. Le Floc'h (CEPE-CNRS), R. Pontanier (ORSTOM) and F. Romane (CEPE-CNRS).

The subchapter on 'Management' and the 'Conclusions and Recommendations' were written by M. S. Hadjej, Director of the Institut des Régions Arides, Tunisia. The maps and diagrams were drawn by M. Dupuy with the help of the draughtsmen of the CEPE-CNRS. Contributions to the original manuscript were given by: T. Ionesco, FAO expert; T. Jalel and N. Gaddas of the Direction des Forêts, Tunisia; and A. Ben Salah of the Direction des Ressources en Eau et Sol, Tunisia. G. Long, Director of the Écothèque Méditerranéenne, revised the original manuscript.

Unesco also wishes to thank the following organizations for their assistance: Institut des Régions Arides de Tunisie (IRAT); Direction des Ressources en Eau et Sol (DRES, Tunisia); Direction des Forêts, Tunisia; Centre National d'Études Agricoles (CNEA, Tunisia); Centre d'Études Phytosociologiques et Écologiques Louis Emberger of the Centre National de la Recherche Scientifique (CEPE-CNRS, France); Office de la Recherche Scientifique et Technique d'Outre-Mer (ORSTOM, France).

FAO, UNDP and WMO also collaborated in this study. Most of the information for this chapter was obtained under FAO/Unesco Project TUN/69/001 'Research and Development Project for Rangelands in Southern Central Tunisia'.

Introduction

General data on the arid and desert regions of Tunisia

The total area of Tunisia is 155000 km². The country's arid zones extend southwards from the foothills of the Tunisian dorsal ridge, i.e. roughly south of a line drawn from Kasserine to Enfidaville (Fig. 1.). These zones cover an area of about 120000 km², which represents four-fifths of the entire country, and have an average annual precipitation level of less than 350 mm. The overall area can be divided into two zones: one described as 'arid', with an annual average of between 350 and 100 mm and covering 55000 km²; the other described as 'desert', with an annual average of less than 100 mm and accounting for the remaining 65000 km².

Many authors, including Le Houérou (1959, 1969*a*, 1969*b*, 1973*a*, 1973*b*), on whose work this paper draws heavily, agree that the desert zone to the north of the Sahara extends as far as the 100 mm line. This level represents a permanent insufficiency of water (i.e. the potential evapotranspiration level is on average higher than the actual precipitation level during every month of the year). The relevant climatic indices are approximately as follows:

Emberger's pluviothermic ratio $Q2 < 10$
Thornthwaite's aridity factor $I_a > 90$

$$\frac{P}{ETP^1 \text{ (Penman)}} < 0{\cdot}08$$

In Tunisia, the desert proper begins south of the 100 mm average annual isohyet: there are both stony regs with extremely sparse vegetation and the dunes of the Great Eastern Erg which cover an area of approximately 25000 km². The area taken up by chotts—vast, saline depressions devoid of vegetation—amounts to 5575 km². Little will be said in this paper on the problems specific to these zones, where the desert is not due solely to human influence—which is slight—and where the existing ecosystems are likely to evolve only very slowly.

Taken as a whole, there is marked variation in precipitation, and the degree of variation is inversely related to the amount of rainfall. Thus, in the area which lies between the 100 and 200 mm isohyets, the maximum annual rainfall recorded is approximately ten to twelve times greater than the minimum recorded, whereas in the area lying between the 200 and 350 mm isohyets it is only four to eight times greater. In general, this rain falls mainly in the winter months but can also occur in winter and spring.

1. ETP = potential evapotranspiration.

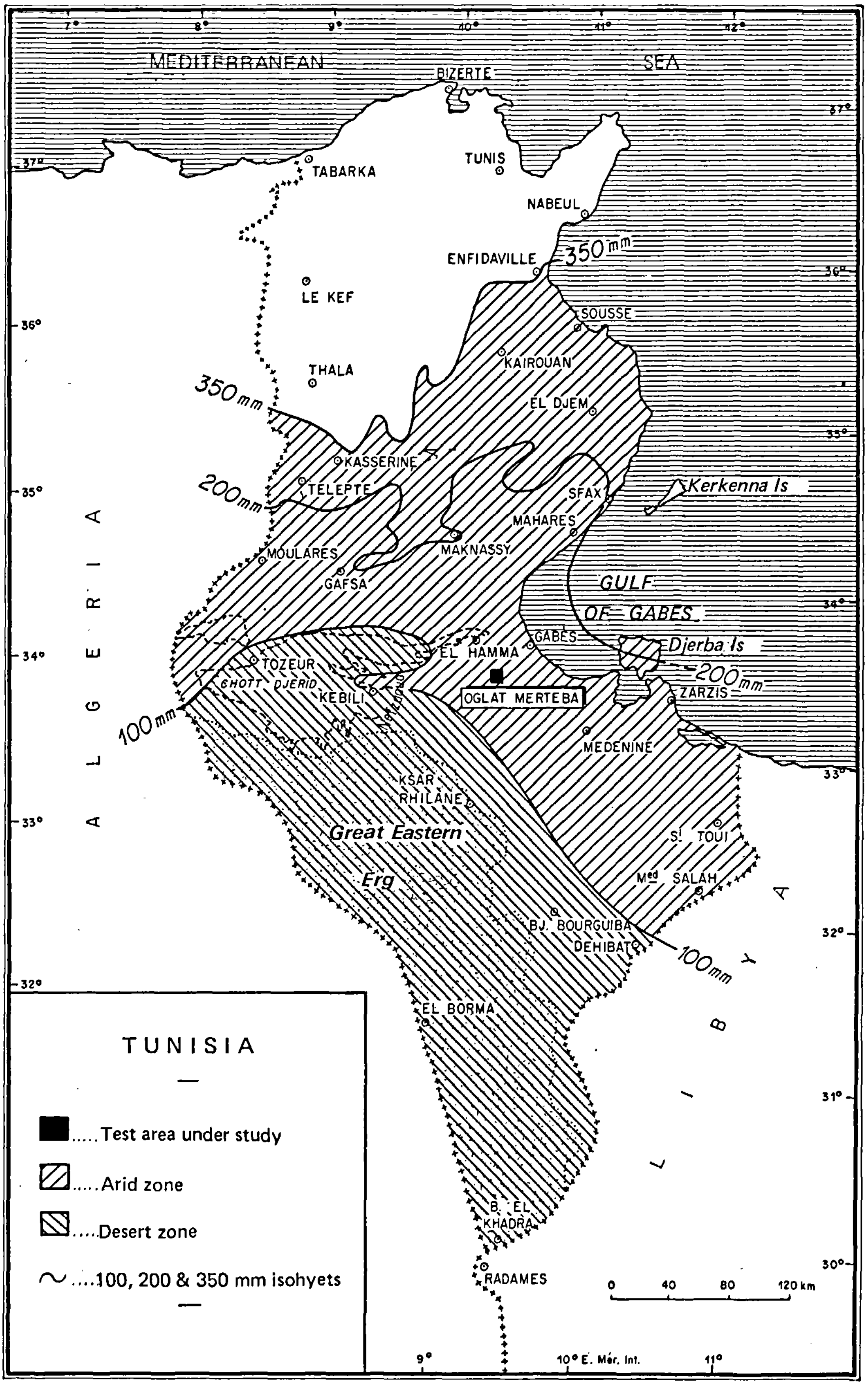


FIG. 1. Map of arid zones in Tunisia

Hence there is a very marked dry summer season, which is characteristic of the Mediterranean climate.

Mean annual temperatures vary between 15°C in the neighbourhood of the dorsal range and 21°C in the Sahara. Along the whole length of a fairly broad coastal strip frosts are rare, whereas in the interior the winters can be cold, with ten to twenty days of frost per year. The average minimum temperature for the coldest month is 6° to 7°C on the coast but this drops to 1°C further inland.

Estimated annual potential evapotranspiration varies between 1300 mm in the 350 mm rainfall areas and 1500 mm in the areas with 100 mm. Average daily evapotranspiration rates are 1–1·5 mm in January and 7–8 mm in July and August.

The geological formations are of sedimentary origin and are Mesozoic, Cainozoic and Quaternary in age. In outcrop there is a preponderance of limestone, marly limestone and marl, but sandstone and gypseous rocks are also found. The alluvial and colluvial Quaternary deposits are extremely varied: sandy deposits cover vast areas, whereas elsewhere the valleys, which more often than not drain to interior basins, contain a large quantity of fine and frequently saline material. The piedmont slopes are often covered by a calcareous or gypseous crust.

An extremely wide variety of soils has developed on these parent materials: skeletal soils on high ground and overlaying the crusts, 'steppic' soils on the sands, and young alluvial soils, which tend to be saline, in depressions and valley bottoms.

The natural vegetation is steppe-like except in the mountains where, especially around the 350-mm annual-rainfall line, there are still the remains of primitive forests which have been cut down by man, consisting basically of *Pinus halepensis* and *Juniperus phoenicea*. Among these shrub formations, vestiges of wooded savanna with *Acacia raddiana* can still be seen in certain dry parts of the area.

Apart from these few remains of forest species, the physiognomy of the steppe varies with the rainfall and nature of the substratum. The major categories are as follows:

— *Stipa tenacissima* (halfa) steppe in stony or duricrusted areas and in most of the mountainous area of the south. Although highly exploited for fibre used in paper-making, this steppe still extends over large areas of the inland plateau and connects up with the immense Algerian stretches of halfa;

— *Artemesia herba-alba* steppe which although considerably cleared still occupies large areas of relatively fine-textured deposits;

— Sand steppes, with *Artemesia campestris* in the highest-rainfall zones and *Rhantherium suaveolens* or *Aristida pungens* steppe in the driest areas. These steppes have also been largely cleared either for orchards or for cereal crops;

— very open steppe in the desert areas, with *Anthyllis henoniana* on stony plains (reg);

— saline steppe, bearing large numbers of halophytic plants, in the depressions; the less saline parts of this steppe tend to be cleared for cereals.

The human population of the arid and desert zones is estimated at over 2800000, of whom 2200000 are rural. Population density in the desert zone is low. For the whole of the arid zone it is estimated at 31·8 inhabitants/km^2 and it is certainly lower in the steppe areas (where rainfall is between 100 and 200 mm). The population is increasing rapidly, with a growth rate of 2·32 per cent between 1966 and 1975. This growing human pressure on the environment is one of the major causes of the progressive desertification of the areas bordering on the Sahara, even though efforts are now being made to reduce the birth rate. The rural population falls into three main groups: farmers, oasis dwellers and nomadic pastoralists. The divisions between these groups are far less clear-cut than in the past, since the pastoralists are showing a marked tendency to settle.

The growth of the population and this tendency towards sedentarization are leading to changes in land use. Clearing of the steppe allows dry farming to develop: tree crops (olives, almonds, apricots, etc.) with cereal crops (particularly barley and durum wheat) in areas where the average annual rainfall exceeds 200 mm, and mainly cereal crops where the rainfall is lower. The government has also devoted considerable efforts to establishing new irrigated areas in addition to the traditional oasis.

Stock-raising has been practised by the pastoralists on an extensive system for thousands of years. The present livestock population is estimated at *c.* 800000 fat-tailed Barbary ewes (500000 in the central Tunisian region and 300000 in the south), 450000 goats (200000 in the central region and 250000 in the south), 15000 head of cattle, 10000 horses, 17000 mules, 110000 donkeys and 120000 camels. The sheep, goats and camels, which are better able to make use of arid rangeland vegetation, depend on these arid and desert rangelands for 80 per cent of their sustenance in an average year. It has been estimated that in an average year the total fodder production of the arid zone amounts to approximately 2·3 million tonnes of dry fodder, of which 90 per cent is made up of roughage and the remainder consists of diverse products (barley, bran, concentrates, etc.).

It should be noted that these flocks and herds characteristically contain a high proportion of unproductive beasts and have a very variable fertility rate. The productivity of the flocks is directly linked to the condition of the rangeland and hence to climatic variations (essentially precipitation). The irregularity of precipitation from one year to another results in highly variable development of the vegetation. A succession of rainy years produces a spectacular increase in the number of animals, while on the other hand a single dry year can cause many deaths after a certain time lag.

Desertification

Desertification has been defined as 'a combination of processes which result in more or less irreversible reduction of the vegetation cover, leading to the extension of new desert landscapes to areas which were formerly not desert' (Le Houérou, 1969*b*). These landscapes are characterized by the presence of regs, hammadas and dunal formations. Different currents of thought blame desertification on long-term climatic changes (in the geological sense), cyclic fluctuations in climate and periodic droughts and the destructive consequences of human activities.

Rapp (1974) summed up the techniques used by different authors to detect long-term climatic changes north and south of the Sahara, including evidence from meteorology and hydrology, archaeology and history, geomorphology, history of the vegetation and of the fauna, dendrochronology and palynology. All lead to more or less similar conclusions. During the past 20000 years the climate of the Saharan regions has probably changed several times, passing through wetter periods—called pluvial periods—and drier or interpluvial periods. No change of this kind has been recorded during the past 2000 years, but there seem to have been frequent minor fluctuations. No sign of any trend towards a drier or wetter climate since the beginning of the century can be detected.

This last point has been well illustrated as far as Tunisia is concerned by Le Houérou (1959), Flohn and Ketata (1971) and by a study carried out in the Oglat Merteba test zone.

Fluctuations in climate and periodic droughts, highlighted in these studies, have always taken place and cannot alone explain the advance of desertification. To them must be added destructive activity by man. This opinion was expressed by Sherbrooke and Paylore (1973):

> Marginal areas may not recover from short term weather patterns induced by uncertain rainfall followed by cyclic droughts if they are subjected to continued attempts at intensive use in a dry year or succession of dry years.

The increasingly destructive influence exerted by man on the environment as a result of population growth and the indiscriminate use of enhanced technical measures are certainly major causes of the advance of desertification.

> It is man who creates the desert; the climate only provides the right conditions (Le Houérou, 1959).

Harmful human practices in this arid climate include the marginal cultivation of cereals, overgrazing, the destruction of woody plant species by burning them as fuel and salinization of the soil as a result of faulty irrigation techniques. These causes and the actual processes of desertification will be analysed in the context of the test zone studied. We have attempted, by studying the phenomena in the zone itself, to separate mere reversible 'degradation' from more or less permanent 'desertification', defined as an irreversible reduction in the productivity level of an ecosystem.

As an introduction, it is interesting to try to establish a historical account of the human activities that have resulted in the landscapes to be seen today in southern Tunisia.

Historical account of human activity in the arid and desert regions of Tunisia

This account is based mainly on the work of Despois (1961) and Le Houérou (1969*b*).

From the Neolithic Age onwards the Berbers cultivated wheat and barley and bred the domestic animals we know today.

The Phoenicians, who established greater numbers of trading posts along the African coast after the founding of Carthage (814 B.C.), no doubt taught the local inhabitants arboriculture, with the result that almost all the dry-farming practised today was already known to Carthaginian Africa. The types of swing-plough in use in those days are still employed today, and regions such as the Tunisian Sahel, the plains of Kairouan and the trading posts in the Gulf of Gabès have from ancient times enjoyed a considerable reputation as fertile areas for cereal crops. According to Despois, however, the people were still essentially pastoral.

Agriculture underwent its greatest expansion during the Roman era (between the second century B.C. and the fifth century A.D.), when it was protected against the wild nomads proper by the *limes*—a fortified line more or less demarcating the limit of Rome's influence. It spread almost to the borders of the Sahara. The spread of olive plantations took place from the second century onwards. The greater part of the area of light soils situated between the Tunisian dorsal chain and the Gafsa ranges, as well as the coastal areas of the Gulf of Gabès, was planted with olives, as can be seen from the ruins of oil-press buildings. Also dating from the same era are the remains of a large number of agricultural hydraulic-engineering works built for irrigation purposes or to divert flood or run-off waters (for example, within the 20000 ha of the Oglat Merteba test zone of this case study there is one overflow-spreader weir, seven sites of reservoirs and cisterns and one well). It should also be remembered that earthen hydraulic works are unlikely to leave any visible trace.

Little is known about stock-raising in Roman times, but we do know that agriculture drove the pastoral nomads proper back beyond the *limes*, although the remains of a large number of drinking troughs show that stock-raising was practised at the time. It appears that there have always been camels in the Sahara and along its northern borders, but their domestication does not appear to have developed until the third century. The breeding of horses developed from the second century onwards.

There is no doubt that forests were cleared on a large scale at that time, since they represented the basic source of fuel for domestic hearths and for the huge bath houses in the towns.

Some historians believe that towards the end of the Roman era Tunisia's population density may have been considerably higher than it is today.

The Arab conquests of the seventh and eighth centuries introduced marked changes in the economy and in methods of land use. The Arabs imported hard semolina wheat, which gradually took the place of soft wheat, and they also introduced a whole range of irrigated crops, including rice, apricots, citrus fruits, henna and saffron. To some extent they were able to encourage a return to pastoral life and an extension of stock-raising, but they did not neglect agriculture and irrigation.

However, invasions by eastern nomads from the middle of the eleventh century had dire results for the cultivated areas and favoured an extension of the pastoral and nomadic way of life. Their influence lasted for hundreds of years and resulted in the disappearance of a large number of villages and the abandonment of many irrigation works. There was an enormous decline in arboriculture and in terrace farming, doubtless accompanied by a sharp decline in population. Clearing of vegetation ceased, and the cultivated areas were again taken over by the natural steppe vegetation found today, such as halfa (*Stipa tenacissima*) and wormwood (*Artemisia herba-alba*).

No great change in land use took place in the centuries which followed the Middle Ages. The relative calm which reigned from the sixteenth century enabled the nomadic and sedentary populations to coexist in harmony. New irrigated vegetable crops were introduced, together with the prickly pear (*Opuntia ficus indica*), a precious summer reserve food both for cattle and man.

French colonization exerted relatively little influence on land use in the region bordering on the Sahara or in the Tunisian steppes, since the colonists settled mainly in the fertile lands in the north of the country.

In the Sfax area, which already had 350000 olive trees in 1881, there was a large-scale expansion of arboriculture with its accompanying dangers, i.e. the soils being light and having to be scrupulously weeded in that climate, they were highly susceptible to erosion.

The rapid growth of the population, however, led to an uncontrolled exploitation of resources. It cannot be denied that the flora and the fauna have become impoverished during the past 120 years; lions, panthers, ostriches and antelopes have disappeared, while moufflons, hyenas and gazelles have become rare.

A study of maps made of the forests at the beginning of the century shows that both the Aleppo pine in the mountains and the halfa steppe in central Tunisia have receded since then. Halfa, which now scarcely flowers at all in the steppe and barely exceeds 30–40 cm, was formerly capable of producing patches which stood higher than a man's head (Monchicourt, 1906).

Mechanized ploughing, which was introduced in the twenties and which has in recent years become particularly widespread in the south, is leading to rapid retreat of the steppe areas.

D. Schwaar (1965), interpreting the 1949 and 1963 series of aerial photographs of a 1680 ha zone near Sbeitla in central Tunisia, came up with the following results:

- disappearance of jujube scrub: 442 ha (i.e. 30 per cent);
- fruit-tree plantations: 66 ha as against 7·5 ha;
- cactus hedges: 54 km as against 10·5 km;
- cactus plantations: 1 ha as against 61 ha;
- stone-built houses: 143 as against 18;
- paths or tracks: 27 km as against 5 km;
- soil-restoration measures: 29 ha as against nil;
- gully erosion: 122 ha as against 81 (i.e. an annual loss of 3 ha).

C. Floret *et al.* (1978) used the same method of comparison of aerial photographs to study the evolution in land use in a steppe zone of 80000 ha between Gabès and Gafsa with an average rainfall of 170 mm. The results they obtained are shown in Table 1.

TABLE 1. Changes in relative areas of rangeland and crops in a steppe area of 80000 ha between Gabès and Gafsa

Date of photographs	Rangeland (%)	Crops (%)
1948	87	13
1963	72	28
1975	58	42

These two examples suffice to illustrate the vast transformation of the countryside that is taking place.

To sum up therefore, the earliest signs of desertification had certainly appeared in Roman times as a result of the enormous areas cleared and cultivated by sedentary populations. The Arabian era enabled the plant cover to recover, thanks to decreased pressure on the environment and to civilizations that were primarily pastoral and nomadic. Since the beginning of the century, and particularly during the last one or two decades, there has been increasingly rapid degradation of the natural vegetation and of the soil as a result of population growth, mechanization, the spread of agriculture and the sedentarization of the population.

The study area

There was a variety of reasons for selecting this study area.

The vegetation and soil become less and less capable of recovering from a disturbance the closer one gets to the desert zone, with less than 100 mm average annual precipitation. However, in that part of the arid zone which receives more than 200 mm precipitation, a reduction in human pressure should enable the natural vegetation to regenerate in almost every type of ecosystem where the critical threshold of soil denudation has not been reached.

The intermediate zone lying between the 100 and 200 mm average annual isohyets is the one that gives the authorities the most concern, since it is there that desertification phenomena are most marked. These phenomena are reversible in some of the region's many ecosystems, and specific management measures can be planned. It is for this reason that particular attention is devoted to this pre-Saharan region of Tunisia covering *c.* 3 million ha.

This account is based on a study of a 20000-ha area known as 'Oglat Merteba', which contains representative examples of the ecosystems of this pre-Saharan region. It has an average annual rainfall of about 150 mm, with wide fluctuations, as shown by the study of rainfall variability. It is only about 30 km from the desert proper.

The Tunisian Government has started management measures in this region over a 100000-ha area which takes in the case-study area. These measures, of which the purpose is to combat current desertification, are being preceded by thorough interdisciplinary studies by a number of national and international bodies. This interdisciplinary approach was considered to be necessary in view of the complexity of the problem to be solved, namely, to guarantee the population a decent living from the natural

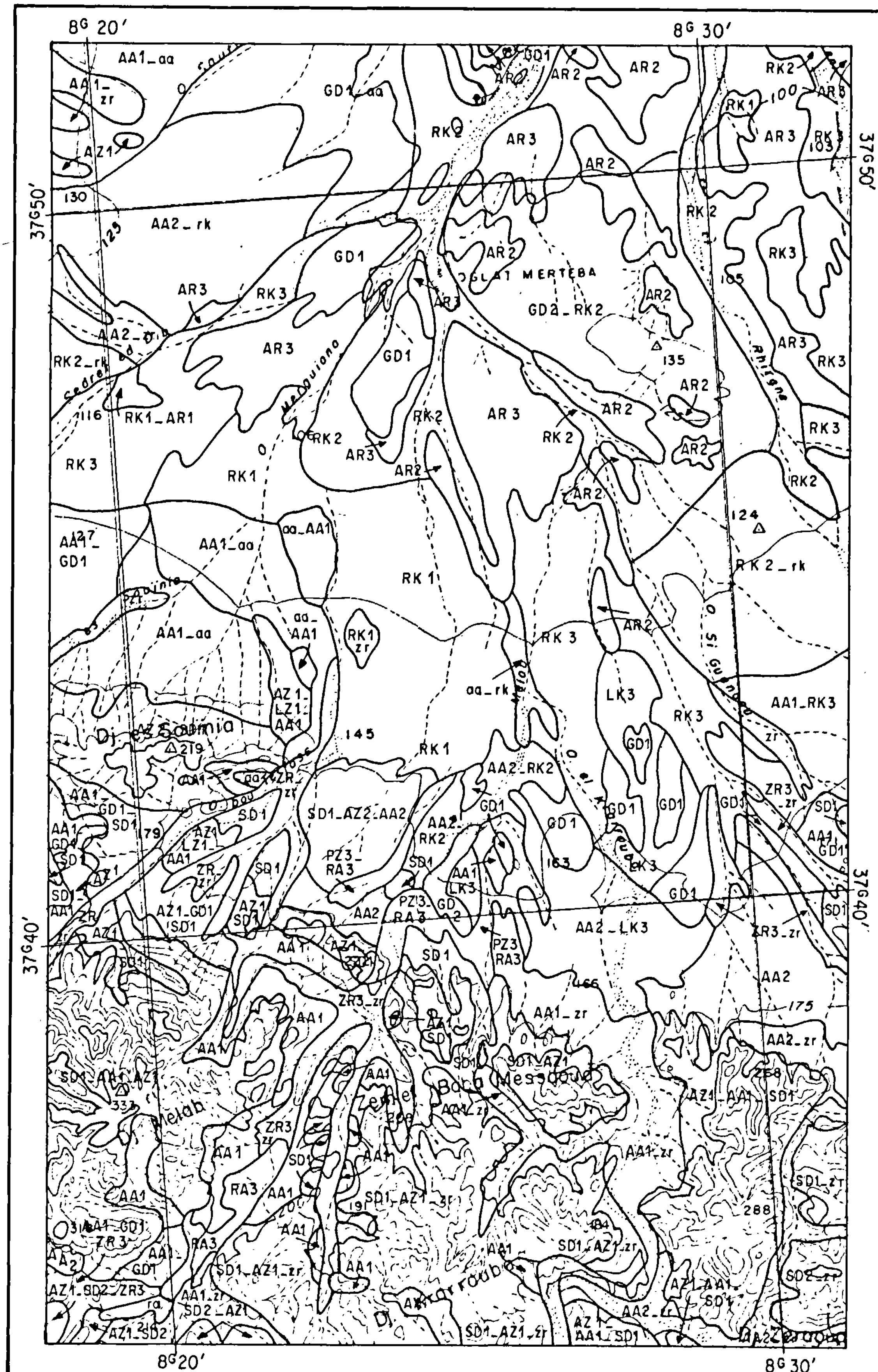


FIG. 2. Ecosystems of the Oglat Merteba Study Area

LEGEND FOR ECOSYSTEMS CHART OF OGLAT MERTEBA

(20 000 ha)

ECOSYSTEMS SYMBOLS		SD 2	SD 1	GD 2	GD 1	LZ 2	AZ 2	AZ 1	AA 2	AA 1	aa	LK 3	RK 3	RK 2	RK 1	rk	AR 3	AR 2	ZR 3	z r	PZ 3	RA 3	ra
BIOCLIMATE		AVERAGE ANNUAL PRECIPITATION P ≃ 150 mm AVERAGE ANNUAL TEMPERATURE T ≃ +19°C										MEDITERRANEAN BIOCLIMATIC DIVISION : Very arid Q2 (Emberger) = 15 m.........≃+ 5° C										NEAR SAHARAN P≃100mm Q2≃ 10 T≃+ 19°C m≃+5°C	
_ ALTITUDE _ LITHOLOGY _ GEOMORPHOLOGY		Altitude 200-300 m Calcareous mountain with dissected relief		Altitude 100-200 m Glacis with incrusted calcareous layer and residual hills from the former early quaternary surface with limestone crust.		Altitude 100 - 200 m Erosion glacis with gypseous crust or incrustation			Altitude 100 - 200 m Erosion glacis overlying material containing calcareous nodules. Upper terraces of mountains in badlands relief			Altitude 100 – 150 m Plains with accumulated sandy deposits at the bottoms of the glacis					Altitude 100 – 150 m More or less stabilized dunes		*Wadi* flood-out areas with stabilized dunes *(nebkas)*			*Wadi* flood-out areas coarse material subject to shifting by wind action. (marked-endoreism)	
SELF-SOWN VEGETATION	PHYSIOGNOMIC TYPE (Formations)	LOW WOODY HERBACEOUS SPECIES		LOW LIGNEOUS SPECIES		Low woody herbaceous species	LOW LIGNEOUS SPECIES				HERBS (stubble or fallow)	LOW WOODY HERBS	LOW LIGNEOUS SPECIES			HERBS (stubble or fallow)	HERBS		TALL AND LOW LIGNEOUS SPECIES	HERBS (stubble or fallow)	LOW WOODY HERBS	LOW LIGNEOUS SPECIES	HERBS (stubble or fallow)
	DOMINANT SPECIES	Stipa tenacissima Artemisia herba alba Gymnocarpos decander Arthrophytum scoparium		Gymnocarpos decander Atractylis serratuloïdes Helianthemum lipii var sessiliflorum Rhantherium suaveolens		Lygeum spartum Zygophyllum album Linaria aegyptiaca Gymnocarpos decander	Atractylis serratuloïdes Helianthemum kahiricum Gymnocarpos decander Anarrhinum brevifolium		Arthrophytum scoparium Artemisia herba alba Erodium glaucophyllum Asteriscus pygmaeus		Diplotaxis harra Launea nydicaulis Calendula aegyptiaca Enarthrocarpus clavatus	Lygeum spartum Rhantherium suaveolens Echiochilon fruticosum Arthrophytum schmittianum	Rhantherium suaveolens Salsola vermiculata var brevifolia Helianthemum lipii var. sessiliflorum Echiochilon fruticosum Plantago albicans			Pituranthos tortuosus Artemisia campestris Cutandia dichotoma Cynodon dactylon	Aristida pungens Argyrolobium uniflorum Nolletia chrysocomoïdes Rhantherium suaveolens		Ziziphus lotus Retama raetam Rhantherium suaveolens Polygonum equisetiforme	Artemisia campestris Cynodon dactylon Pituranthos tortuosus Polygonum equisetiforme	Lygeum spartum Ziziphus lotus Plantago albicans Pituranthos tortuosus	Arthrophytum schmittianum Retama raetam Plantago psyllium Cutandia dichotoma	Carduus getulus Helitropium bacciferum Artemisia campestris Cynodon dactylon Pituranthos tortuosus
	State of plant cover (% cover consisting of perennial vegetation)	slightly degraded 30%	highly degraded 15%	slightly degraded 25%	highly degraded 10%	slightly degraded 20%	slightly degraded 15%	highly degraded 5%	slightly degraded 25%	highly degraded 5%	— 5%	non degraded 30%	non degraded 35%	slightly degraded 20%	highly degraded 10%	— 5%	non degraded 45%	slightly degraded 25%	non degraded 50%	— 10%	non degraded 40%	non degraded 30%	— 5%
	Above-ground biomass Perennial plants (kg dry mat/ha)	1 300	700	800	200	600	600	300	400	200	30	1 300	1 300	700	400	40	1 800	900	4 000	50	2 000	1 800	30
SOILS	PEDOGENETIC TYPE	Raw erosion soil Lithogenic soil		Lithogenic soils overlying stripped calcareous crust		Crusted or incrusted gypseous deposit soils. Patches of aeolian sandy cover			Isohumic brown subtropical truncated soils or regosols overlying loams with calcareous nodules Sometimes with limestone incrustation			Sandy or juvenile sierozems in steppic deposits sometimes overlying a brown subtropical soil or gypseous incrustation			Sandy sierozems sometimes truncated down to the calcareous nodule horizon (regosols)		Raw, more or less stabilized, aeolian deposit soils		Deep juvenile alluvial soils of sandy-loam or silty-sand texture		Juvenile alluvial soils overlying a gypseous incrustation	Raw alluvial deposit soils. Coarse texture. Abundant stones	
	RUNOFF – EROSION	Severe runoff Severe water erosion		Moderate to severe runoff Severe water erosion		Moderate to severe runoff Moderate to slight water and wind erosion			Slight to moderate runoff Slight to moderate water erosion			Runoff nil to slight. Moderate wind erosion			Runoff slight to moderate. Severe wind erosion and slight water erosion.		Nil runoff. Slight wind erosion		Subject to temporary flooding. Area of infiltration and accumulation.			Infiltration areas. Moderate wind erosion	
	Average water reserve in soil available to vegetation (in mm)	120	45	84	60	75	52	42	120	80	80	80	115	105	95	100	200	80	190	190	126	120	120
FAUNA (Mammals, birds, reptiles, arachnids)		– Hieraetus fasciatus *Bonelli's eagle* – Corvus corax *raven* – Ctenodactylus gundi *«gundi»* – Paraechinus aethiopicus *hedgehog*		– Canis aureus *jackal* – Vulpes vulpes *fox* – Fennecus zerda *fennec* – Felis sylvestris *wildcat*		– Lepus capensis *Iberian hare* – Dipodillus sp. *jerboa* – Meriones shawi *jird* – Psammomys obesus *psammomys*		– Butes rufinus *long-legged buzzard* – Falco tinninculus *kestrel* – Athene noctua *little owl*		– Chlamydotis undulata *houbara bustard* – Burhinus œdicemus *stone curlew* – Pterocles alchata *pin-tailed sand grouse* – Cursorius cursor *cream-coloured courser* – Alectoris barbara *barbary partridge*		– Columba livia *rock dove* – Galerida cristata *crested lark* – Alaemon alaudipes *hoopoe lark* – Oenanthe sp. *wheatear* – Passer domesticus *house sparrow*		– Cerastes cerastes *horned viper* – Vipera libetina *«lébétine» viper* – Uromastix acanthinurus *mastigure* – Varanus griseus griseus *varanian lizard*		– Scinsus scinsus *skink* – Chalceides ocellatus *gongoyle* – Stenodactylus sp. *gecko*		– Androctonus amoreuxi *yellow scorpion* – Galeodibus olivieri *galeode* – Hyalomma lusitanicum *tick*	– Naja haye *corbra* – Lanius excubitor *great grey shrike*			Gazella dorcus *dorcas gazelle*	
HUMAN POPULATION (Approximately 1 300 inhabitants)	DWELLINGS	ISOLATED DWELLINGS – BUILDINGS IN STONE					LARGE COLLECTION OF DWELLINGS (buildings in stone)		SCATTERED DWELLINGS AMONG THE HIGH VALLEYS (cave dwellers)			NOMAD DWELLINGS – (Tents and shelters)											
	Water points		Runoff cisterns						Runoff cisterns										Surface wells			Surface wells	
	OCCUPATIONS – domesticated animals – crops etc...	Wood gathering for domestic use. Gathering of halfa fibres for plaiting summer use fo rangelands for goats.	– Wood-gathering for domestic use – Spring and summer use of rangelands for sheep and goats – Lime Kilns			Gathering of *esparto* fibres and wood for plaiting. Intensive use of rangelands all yeau round for goats and sheep	– Wood-gathering – Grazing area for herds – Intensive year-round use of rangelands for sheep, goats and draught animal		– Gathering of Arthrophytum scoparium *(«nefa»)* – Winter and spring use of rangelands for sheep and goats		Development of valleys *(jessours)* and glacis *(«tabias»)*. Arboriculture (olives, figs, almonds cactus ..) Cereal-crops. Food crops. Grazing on stubble	– Wood-gathering for domestic use – Year-round use of rangelands for sheep and goats ; spring use for young camels and summer use for full-grown camels				Intermittent cereal crops Grazing on stubble or fallow land	– Fibre-gathering for making mats and shelters – Year-round use of rangelands by camels ; autumn,winter and spring use by sheep and goats		Wood-gathering Year-round use of rangelands for sheep,goats and draught animals	Cereal crops. Arboriculture behind the *«jessours»* Grazing on stubble	Gathering of wood and *esparto* fibres. Year-round use of rangelands	Wood-gathering for charcoal *(«R' tem»)*. Year-round use of rangelands by sheep and goats	Very intermittent cereal crops Grazing on stubble and fallow land

ECOSYSTEMS	SYMBOLS	SD 2	SD 1	GD 2	GD 1	LZ 2	AZ 2	AZ 1	AA 2	AA 1	aa	LK 3	RK 3	RK 2	RK 1	rk	AR 3	AR 2	ZR 3	z r	PZ 3	RA 3	ra
	AREA (in ha and %)	480 (2,4%)	2 420 (12,1%)	820 (4,1%)	1 000 (5%)	40 (0,2%)	320 (1,6%)	1 000 (5%)	1 240 (6,2%)	2 660 (13,3%)	500 (2,5%)	420 (2,1%)	1 280 (6,4%)	1 740 (8,7%)	1 560 (7,8%)	560 (2,8%)	1 640 (8,2%)	560 (2,8%)	400 (2%)	880 (4,4%)	120 (0,6%)	180 (0,9%)	20 (0,1%)
ANNUAL PRODUCTION OF ABOVE-GROUND BIOMASS OF SELF-SOWN VEGETATION IN A MODERATE-RAINFALL YEAR (kg dry mat./ha/yr)	ANNUAL	70	60	120	55	80	35	30	100	70	90	80	100	30	20	45	120	80	300	180	80	60	60
	PERENNIAL	800	500	600	250	130	250	150	350	60	20	650	700	400	300	80	1 000	400	1 500	250	900	300	60
	EDIBLE PORTION of the total production	205	180	265	130	230	150	100	200	100	65	365	495	265	200	130	300	200	825	265	495	230	100
CROP PRODUCTION IN A MODERATE RAINFALL YEAR	CEREAL/GRAIN CROPS (kg/ha/yr)	–	–	–	–	–	–	–	–	–	200	–	–	–	–	200	–	–	–	400	–	–	–
	OLIVES (kg/ha/yr)	–	–	–	–	–	–	–	–	–	80 000	–	–	–	–	–	–	–	–	80 000	–	–	–
DOMESTIC LIVESTOCK	BIOMASS (kg live weight/ha)	11,1	7,9	9,2	5,5	7,9	5,1	4,2	6,9	4,2	2,7	12,5	17,1	11,1	8,3	4,6	10,2	8,3	28,6	9,2	17,1	7,8	3,2
	PRODUCTION (kg live weight/ha/yr)	2,7	1,9	2,7	1,4	2,4	1,5	1,0	2,1	1,0	0,7	3,7	5,1	2,7	1,8	1,4	3,1	2,1	8,6	2,8	5,1	2,3	1,0

resources without eating into the 'capital' represented by the soil and vegetation.

The level of intensity at which these resources are exploited should be such that the natural equilibrium is preserved and the productivity of the ecosystems maintained or increased. What is in fact happening in this region at present is that, because of the growth in population, the local farmers are tending to ask more of the environment than it is able to give, thus bringing about progressive desertification through the formation of dunes and denuded areas.

After examining rainfall variation, we shall attempt to describe the situation existing in the Oglat Merteba region in its present state, taking as base units the ecosystems that have been identified and mapped. Thanks to readings which have been recorded for the past five years it is possible to make approximate quantitative statements about the major parameters of these ecosystems: biomass, productivity, soil water-regime, etc.

We shall then attempt, using observations of the land-use history and with the assistance of comparative analysis of old and recent aerial photographs, to demonstrate the dynamics of these ecosystems, their interrelationships and the variations in their productivity as a function of time. On the basis of these data we shall then attempt to forecast the future evolution of the desertification process in the Oglat Merteba study area over the next twenty-five years, postulating various levels of intensity of human pressure on the environment. Finally, we shall set out the management measures traditionally taken by the local population in order to fight against difficult climatic conditions and desertification, and we shall explain the principles underlying the management measures advocated by the government.

Also included are two technical appendices setting out the management methods applied to the specific cases of a pastoral improvement area and dune fixation on a regional scale.

Present condition of ecosystems in the study area

The basic features of the ecosystems are shown in the legend of Figure 2.

Climate

Although a pluviometer has recently been installed, there is no full-scale meteorological station either at El Hamma, the nearest town, or within the area under study; we shall therefore assess the values of the principal climatic parameters from those recorded at the Matmata, Kébili and Gabès meteorological stations. We shall concentrate essentially on precipitation and precipitation patterns as being the main climatic variables that contribute to the desertification of these pre-Saharan regions.

Rainfall

Table 2 provides a picture of the regional climate of the Oglat Merteba zone. The continental climatic characteristics become more marked the further one goes south-west away from the sea. The average precipitation level is probably between 150 and 100 mm, while Emberger's pluviothermic ratio is between 20 and 10.

The aridity of these regions is accentuated by the prevailing wind patterns:

— from November to April the prevailing winds come from the west, north-west and south-west; they are very violent, dry and cold, and are frequently accompanied by sandstorms which seriously damage the cereal crops and retard the growth of annuals on the rangelands;

— from May to October the prevailing winds in the coastal zones come off the sea, but these exert only a very limited influence in the Oglat Merteba area, where the edge of the Saharan warm front is generally located. This is also the period of the sirocco, an extremely hot, dry wind

TABLE 2. Climatic data

Station	Rainfall				Temperatures				Q_2	Bioclimatic division, subdivision and variety	Incidental phenomenon (number of days)	
	$\bar{m}P$ (mm)	N	p (mm)	P (mm)	M (°C)	m (°C)	T (°C)	t (°C)			Frost	Sirocco
Gabès	183	75	39	460	32·7	5·9	27·4	10·9	22·2	Very arid with mild winters	1	28
Matmata	231	43	38	692	35·2	5·4	29·0	9·0	27·2	Near arid with temperate winters		
Kébili	85	49	11	217	42·2	3·1	32·0	9·2	7·6	Near Saharan with temperate winters	25	35
El Hamma	164	9	55	401	—	—	—	—	—			

where: $\bar{m}P$ = mean annual precipitation.
N = number of years of readings.
p = minimum annual precipitation.
P = maximum annual precipitation.

M° C = mean maximum temperature for the hottest month.
m° C = mean minimum temperature for the coldest month.
T° C = mean average temperature for the hottest month.
t° C = mean average temperature for the coldest month.
$Q_2 = \frac{2000 \cdot P}{M^2 - m^2}$ (Emberger's pluviothermic ratio).

(consisting of masses of Saharan air), which characteristically causes an abrupt rise in temperature (10°–15°C in one or two hours) and a drop in relative air humidity (r.h. is frequently < 10 per cent).

Lacking a long-established meterological station at El Hamma as a basis for the analysis of rainfall variation, we shall use the Gabès National Meteorological Station, providing a series of 75 complete years (1885 to 1975, with breaks) for monthly precipitation and a series of 43 years for daily precipitation. Situated only 35 km from the Oglat Merteba area, the Gabès station gives the most representative picture of the region's rainfall patterns such as variation, distribution of total annual and seasonal amounts, etc.; land managers should nevertheless remember that the climate of the Oglat Merteba area is more continental and that precipitation will therefore be *c.* 20–30 per cent less.

The most notable feature is the extreme irregularity of rainfall in the Gabès area. While the annual rainfall averages 183·2 mm, the minimum recorded was 39·3 mm in 1946–47 and the maximum 460·3 mm in 1959–60[1] constituting a minimum/maximum interannual ratio of about 1:12; on a seasonal basis moreover, the ratio is sometimes 1:20 or even 1:30, and on a monthly basis as high as 1:50.

There is no clear-cut distribution of rainfall within the year, and it is difficult to identify rainy seasons as such. There is in general, however, a dry season extending from the beginning of May to the end of August (and in certain years continuing right up into December). All the remaining months each receive a roughly equal share of the annual rainfall with an average of 20 mm, except for October which is considerably wetter with 41·5 mm.

The number of rainy days averages out between 30 and 40/yr, but here again great irregularity is found. It is not unusual for 60 or 70 per cent of the year's rainfall—and more than 100 per cent of the annual average—to occur in a single 24-hour-period. Violent downpours are common, capable of reaching 150 mm/h in the space of five minutes, especially in autumn, and causing catastrophic floods.

The annual and seasonal totals for the 75 years covered by the Gabès records have been adjusted for the purpose of graphic representation. The Gauss logarithmic system was considered to be the best in accounting for the region's characteristic extremes in rainfall distribution.

Having taken these various adjustments into account, the figures for Gabès are as set out in Table 3. It should be noted that a total annual precipitation of 500 mm or more at Gabès (or of 50 mm or less) constitutes an event that occurs once in half a century.

The rural manager not only takes account of total rainfall but is also very interested in rainfall distribution throughout the year. In an average year, for instance, the seasonal distribution is extremely irregular. On the basis of annual and seasonal fluctuations in the 75 complete years recorded at the Gabès Meteorological Station, we have defined types of years and seasons, taking a recurrence in 3 years out of 5 as characterizing an average (m) year (Y), autumn (A), winter (H) or spring (P). For dry (s) or wet (h) years and seasons, we have taken a recurrence rate of 1 year out of 5.

1. Since then, a level of 518 mm has been recorded for the period 1.IX.1975 to 31.V.1976.

TABLE 3. Inter-annual distribution of seasonal and annual rainfall at Gabès

Annual rainfall
100 mm or less: 1 yr out of 5
250 mm or more: 1 yr out of 5
Between 100 and 250 mm: 3 yrs out of 5

Autumn rainfall (September, October, November)
30 mm or less: 1 yr out of 5
120 mm or more: 1 yr out of 5
Between 30 and 120 mm: 3 yrs out of 5

Winter rainfall (December, January, February)
20 mm or less: 1 yr out of 5
80 mm or more: 1 yr out of 5
Between 20 and 80 mm: 3 yrs out of 5

Spring rainfall (March, April, May)
15 mm or less: 1 yr out of 5
65 mm or more: 1 yr out of 5
Between 15 and 65 mm: 3 yrs out of 5

Hence the types of years and seasons as far as rainfall distribution is concerned are as follows:

Ys ≤ 100 mm	100 mm < Ym < 250 mm	Yh ≥ 250 mm
As ≤ 30 mm	30 mm < Am < 120 mm	Ah ≥ 120 mm
Hs ≤ 20 mm	20 mm < Hm < 80 mm	Hh ≥ 80 mm
Ps ≤ 15 mm	15 mm < Pm < 65 mm	Ph ≥ 65 mm

On the basis of these typical years and seasons it is possible to define typical years with typical seasonal distribution.

It is practically impossible to establish any distribution principle from these combinations. The years with the most common distribution patterns are shown in Table 4.

Therefore Gabès has a chance of getting a year with both an average total rainfall and an average seasonal rainfall distribution every 5·5 (1 ÷ 0·179) years.

The timely arrival of the rainy season is very important in the pre-Saharan region, enabling ploughing to be started and triggering off plant growth on the steppes after the long summer drought. A late start to the rainy season (later than 1 November) results in poor regrowth of the self-sown vegetation because of the cold. In the same way, an early end to the rainy season (before 1 April), at a time when the plants are at the height of their growing period, is very harmful to the pastures and cereal crops.

We take as the start of the rainy season the first

TABLE 4. Rainfall distribution patterns

Type of year	Frequency	Type of year	Frequency
Ym Am Hm Pm	0·179	Ys Am Hs Ps	0·038
Ym Am Hm Pm	0·064	Ys Am Hm Ph	0·038
Ym As Hh Pm	0·064	Ym Ah Hs Pm	0·038
Ym Am Hs Pm	0·051	Ym Ah Hm Pm	0·038
Ym Am Hm Ps	0·051	Yh Ah Hm Pm	0·038
Ys As Hm Pm	0·038	Yh Ah Hm Ph	0·038

TABLE 5. Potential and actual evapotranspiration

Gabès	S	O	N	D	J	F	M	A	M	J	J	A	Annual total
Evaporation ('Piche') (mm)	192	158	132	133	133	132	167	141	186	189	229	229	2021
ETP(Turc) (mm)	142	102	74	56	57	74	105	127	151	169	185	175	1417
ETP (Penman) (mm)	128·2	87·5	48·4	40·3	43·0	56·2	89·2	118·5	144·2	161·1	176·5	162·0	1255·1
Rainfall (mm)	19·1	41·5	24·4	18·0	20·7	17·5	18·3	17·5	5·0	1·6	0·4	0·6	184·6
Kikuyu *ETP* (mm)	129	101	76	57	63	56	97	128	164	170	203	187	1431
Deficit	122·9	60·5	49·6	36·0	36·3	56·5	86·7	109·5	146·0	167·4	184·6	174·4	1230·4

daily rainfall[1] of 10 mm or more occurring after 1 September, and as the end of the rainy season the last daily rainfall of 10 mm or more occurring before 31 May (in fact, in the 43 years for which records have been kept, there has never been a daily rainfall of 10 mm or more at Gabès after 31 May). From the data on 'daily rainfall contribution to monthly and annual total rainfall at the Gabès station', covering 43 complete years, we find that:

— the observed frequency of occurrence of the first daily rainfall of 10 mm or more is:

Before 1 December	*Before 1 November*	*Before 1 October*
0·790	0·628	0·326

— the observed frequency of occurrence of the last daily rainfall of 10 mm or more is:

After 1 May	*After 1 April*	*After 1 March*
0·214	0·333	0·571

The rainy season is considered to have started early if the first daily rainfall of 10 mm or more occurs before 1 October, which happens in roughly one year out of three. Similarly, it is regarded as having ended late if the last daily rainfall of 10 mm or more occurs after 1 April, which also happens in about one year out of three. It should be noted that in approximately one year out of five the start of the rainy season can occur after 1 December, and in one year out of 2·3 the rainy season can end before 1 March.

By compiling sets of overlapping averages spanning five- and ten-year periods we find cycles of favourable or unfavourable years succeeding one another without any set periodic pattern; moreover, since 1885, there does not appear to have been any evolution in the rainfall. Averages based on different five-year periods can differ in the ratio of 1 : 2.

If, however, we define:

a dry year as one having less than 100 mm rainfall,
a moderately dry year as one with between 100 and 154·5 mm,
a wet year as one having over 250 mm, and
a moderately wet year as one with between 250 and 154·5 mm,

in the complete 75 years of readings at Gabès we can distinguish:

four 2-year sequences of dry years;
three 2-year sequences of moderately dry years;
two 3-year sequences of moderately dry years;
one 4-year sequence of moderately dry years;
one 5-year sequence of moderately dry years (including two 2-year sequences of dry years);
three 2-year sequences of wet years;
three 2-year sequences of moderately wet years;
two 3-year sequences of moderately wet years (one of which includes a sequence of two wet years);
one 5-year sequence of moderately wet years (including one sequence of two wet years);
one 7-year sequence of moderately wet years (including one sequence of two wet years).

Not all the region's rainfall is equally effective in recharging the soil water reserves. Depending on the degree of vegetation and soil degradation, the presence of crusts and incrustations, slopes, etc., a high proportion of the rain water may either run off or go towards recharging the ground-water reserves (e.g. *wadi* beds and piedmont or lowland basin areas).

If, therefore, we express the water balance in the form of the following equation:

$$P = R + \Delta S + D + E$$

where P = total rainfall; R = run-off; ΔS = increase in soil-water reserves; E = evapotranspiration (when rainfall $\simeq 0$); D = drainage, yield and recovery, we can say that effective rainfall (PE) is rainfall that effectively goes towards recharging the soil water reserves:

$$Pe = \Delta S = P - (R + D + E).$$

Rainfall effectiveness can be ascertained either by measuring the water content of the soil immediately before and after rainfall, in cases where it is possible to check that part of the profile which is not subject to any variation in humidity (90 per cent of cases), or by measuring R (in run-off plots where there is no deep infiltration) and checking ΔS.

With the exception of infiltration and flood-out areas (ZR_3, zr, RA_3 and ra on Figure 2), we find that the water-balance equation for a fall of rain can be expressed as follows:

$$Pe \simeq P - R.$$

Table 5 shows, for the Gabès station:

— 'Piche' evaporation measured under cover;
— potential evapotranspiration calculated in accordance with Turc's formula: $ETP = (50 + Ig)\ 0{\cdot}4(t/[t + 15])$ where: t = mean monthly temperature; Ig = total radiation;
— potential evapotranspiration calculated in accordance with Penman's formula;
— potential evapotranspiration measured in a Thornthwaite tank planted with *Pennisetum clandestinum* (Kikuyu grass), situated at the edge of the Gabès oasis;
— theoretical water deficit calculated by taking the difference between *ETP* (Turc) and rainfall.

1. Daily rainfall is defined as total rain falling between 08.00 hours on one day and 08.00 hours on the following day.

The theoretical annual deficit for Gabès is of the order of 1200 mm, but this deficit is an underestimate because it is based on total rainfall rather than rainfall which effectively replenishes the soil-water reserves. We consider that for the Oglat Merteba area, which has a lower level of effective rainfall than Gabès and a higher *ETP* due to a more continental climate, the deficit is probably around 1300 mm.

In fact, this very theoretical calculation would appear to indicate that in southern Tunisia the dry season lasts for the whole year, which is not the case, since there are several months during which both the natural and the cultivated vegetation develop normally. We therefore have been measuring the actual evapotranspiration of the soil and of the vegetation in steppe areas similar to that of Oglat Merteba for the last five years. We find that on average the soil-water reserves allow:

- at least a slight degree of growth of annuals from October to April, with interruptions during long rainless periods;
- almost normal water uptake by perennials, which have deeper roots, from November to May without interruption.

As an example, for *Rhantherium suaveolens* steppeland in good condition (RK_3), we now know that for a water-reserve level available to vegetation ($Rd = \Sigma_o^z dz$ ($H_v - H_v$ pF 4·2, where Rd = soil-water reserve; o,z = depth in soil; H_v = humidity by volume; H_v pF 4·2 = humidity at wilting point) of the order of 50 to 60 mm, the mean daily *ETR* (real evapotranspiration) is:

1·2 to 1·5 mm in autumn;
0·8 to 1·0 mm in winter;
1·8 to 2·5 mm in spring.

Climate as a desertification factor

Study of the sequence of precipitations that have occurred since the end of the last century does not reveal any reduction in rainfall levels. With an Emberger pluviothermic ratio of between 10 and 20, the Oglat Merteba area thus comes between the very arid and near Saharan bioclimatic divisions of the Mediterranean climate.

According to the climatic classification used in the Unesco 1:25000000 map of deserts and semi-deserts, the climate of the Oglat Merteba zone is:

- arid, $0{\cdot}03 < (P/ETP) < 0{\cdot}20$ (at Gabès $P/ETP = 0{\cdot}146$);
- with very warm summers ($T > 30°C$);
- with mild to cool winters (*t* in the neighbourhood of 10° C);
- with 4 to 6 months drought during the hot season (April to September).

The main features of the climatic aridity are the low rainfall and very hot summer months.

This overall aridity, which is capable of contributing to desertification, is aggravated by the following climatic features:

- the rainfall occurs during the cold season, and very often at the end of the autumn and at the beginning of the winter, so that it is of little use to the vegetation, which grows mainly in the spring;
- the precipitation frequently takes the form of violent rainstorms; this favours run-off and erosion in areas that are already very degraded, thus aggravating the general water deficit of the region;
- the variability of precipitation is another factor which increases degradation as a result of successions of dry years or very uneven annual distribution. For example, a series of wet years, which have enabled certain areas to be developed with cereal crops, followed by a series of dry years, will have disastrous consequences for the environment that has thus been deprived of its natural vegetation;
- the variable timing of the start of the rainy season must also be taken into account. A late start to the rainy season can accelerate the desertification process through overgrazing, unless the animals leave the area;
- finally, another factor that has an adverse effect on the water balance is the predominance of violent and desiccating winds from the south-west, west and north-west during the growing season. These winds also have a marked effect on the local relief of the sandy steppes by causing all types of sand accumulation (sand sheets, *nebkas*, larger dunes, dunefields, etc).

Landforms and soils (Fig. 3)

The steppes of Oglat Merteba lie on a vast array of plateaux and plains stretching from the Tebaga hills to the west, Hallouga to the north-east and the northern foothills of the Matmatas chain to the south. These heights, consisting generally of Upper and Lower Senonian limestone, rise to 200–300 m. To the north the plain opens out through the El Hamma gate (between the Azziza and Hallouga hills) into the Fedjadj Chott basin at an altitude ranging approximately from 100 to 150 m.

The whole is a vast system of interlocking erosional piedmonts and of depositional glacis formed from the Mio-Pliocene gypseous sandy clays derived mainly from the Tebaga and Matmata hills. These plains converge towards the lowest-lying part of the region with an altitude of 100 m.

The most ancient erosion surface is the Villafranchian (early Quaternary), which has been stripped to a great degree, but there are still throughout the region outliers consisting of hills or plateaux whose crests are protected by a fractured calcareous crust; these take the form of regs.

The Matmata silts were deposited at the same time, over a period that probably lasted until the mid or even late Quaternary, in sites favourable to the trapping of sediments; these can be seen today in the Chemlali, Beni Aïssa and other valleys as huge spreads which sometimes extend a great distance into the plain.

Characteristics of the mid and recent Quaternary eras are:

- stripping of the 'Villefranchian' surface;
- formation of young calcareous crusts in some of the Matmata silts;
- erosion of these silts in the form of badlands and the deposition of derived colluvium in the plain;
- denudation of the Mio-Pliocene substratum together with the formation of vast sloping plains

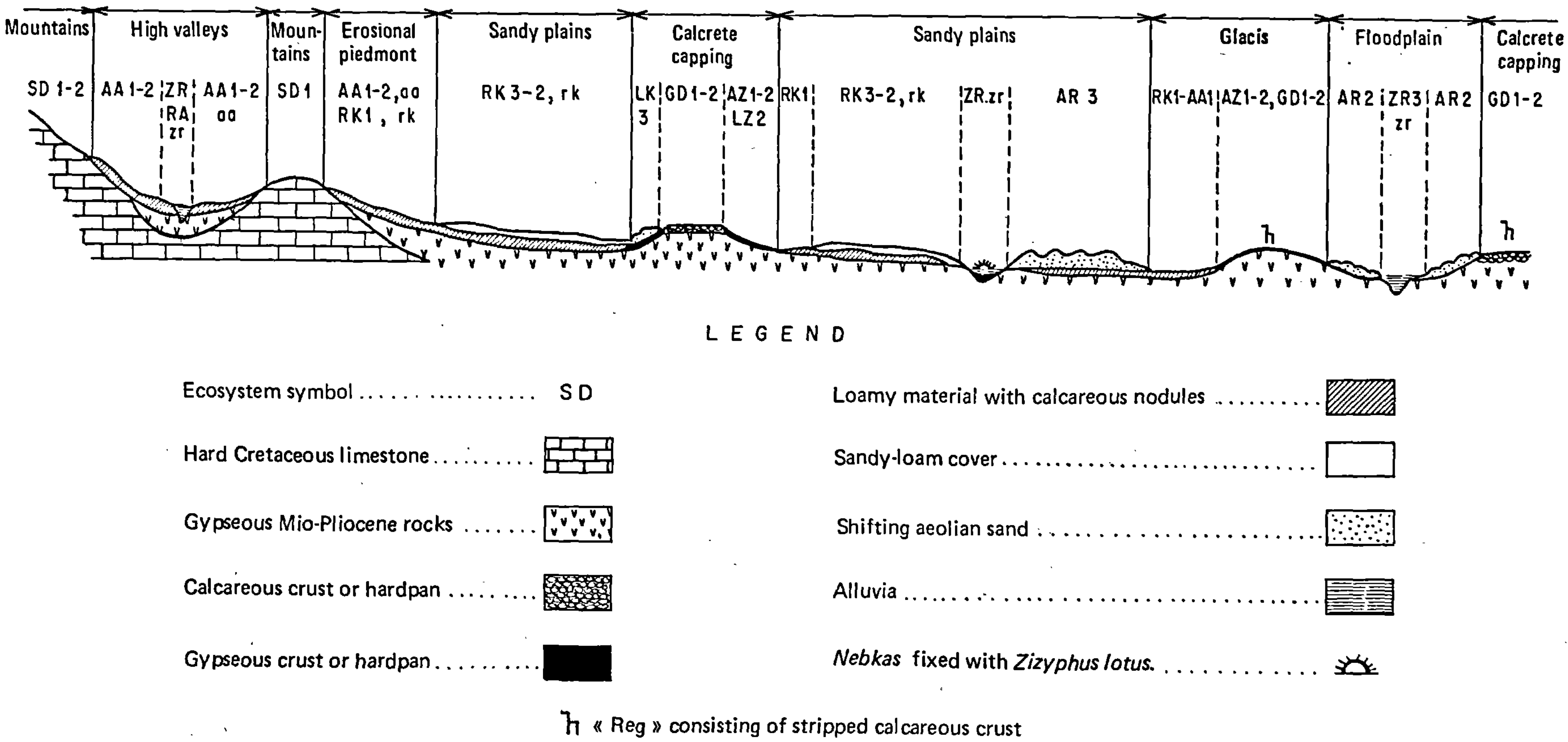


FIG. 3. diagram of the Oglat Merteba test zone showing disposition of ecosystems in relation to relief and geomorphology

with gypseous crusts below the Villafranchian surface;
- deposition, above the silts and colluvial silt deposits or on the Mio-Pliocene substratum, of present soil-forming materials.

The present morphological features are characterized by:
- marked water erosion (sheet erosion on the glacis and gully erosion in the badlands), denuding either the calcareous crusts or the geological calcareous substratum at the foot of the hills, or the gypseous Mio-Pliocene, forming gypseous crusts;
- marked wind action on the surface materials, with erosion in some areas and accumulation in others.

The following types of soils are found in the area (Fig. 2):
- the summits of the Matmata chain are covered mainly with lithosols which still contain minute pockets of calcimorphic soil of proto-rendzina type within fissures; the scarps are covered with stony screes and spreads of silty colluvium containing calcareous nodules sometimes more or less eroded (regosols) into badlands, or crusted and consisting of truncated, ancient isohumic soils; the high valley terraces are frequently composed of immature alluvium which is constantly being shifted by floodwaters; the *wadi* beds are very stony and directly overlie bedrock;
- the Tebaga and Hallouga hills have lithosols overlying hard, more or less fissured limestones;
- the residual hills from the ancient Villafranchian surface have lithosols overlying a calcareous crust, sometimes with a sandy covering or else with a reg consisting of stripped calcareous crust and combined with gypseous soils (gypseous crust and pan);
- the mid and late Quaternary glacis have either lithosols overlying a calcareous or gypseous crust or pan, or else immature regosols overlying loamy surfaces (truncated, old isohumic soils);
- the base of the glacis and the bottoms of recent valleys have young isohumic soils of the sierozem type or immature colluvial and alluvial soils. The regional parent materials are essentially sand to sandy loam on the surface covering the various crusts and the extremity of the silty colluvium spreads; the substratum is Mio-Pliocene throughout and lies at a depth of 1–3 m;
- the plains and high terraces of the *wadis* have raw, aeolian sandy soils that are more or less stabilized by *Aristida pungens*, *Zizyphus lotus* and *Retama raetam* and may lie over any type of substratum.

Generally speaking, the soils of the region are extremely infertile. The best soils have an organic matter content which rarely exceeds 0·5–0·6 per cent and an exchange capacity, for the less sandy soils, which is never more than 10 meq/100 g (truncated brown soils). The nitrogen, potassium and phosphate contents are in general very low. In the recent sandy formations the organic-matter content is generally of the order of 0·1–0·3 per cent and the exchange capacity in the neighbourhood of 4–5 meq/100 g, the base exchange complex being saturated mainly by calcium.

The soil-water characteristics vary greatly from one soil to another. The soil-water reserves available to vegetation,[1] which are shown in the ecosystems chart legend, vary between 40 mm for the shallowest soils and 200 mm for the deepest.

Hydrology and hydrogeology

The Oglat Merteba study area is situated entirely in the El Hamma Wadi drainage basin. Upstream, in the Matmatas ranges and in the footslopes area, the drainage network consists of well-defined channels, consisting principally of the Beni Aïssa, Sidi Guenaou, Melab, Souinia and Rhirane *wadis*, which are of an extremely torrential character, as are the *wadis* of the Tebaga djebel and of its glacis. Downstream, with the exception of the largest *wadis*, the network becomes disorganized, with a tendency towards endoreism which favours infiltration. This normally takes place in depressions in which the water seeps away, although on rare occasions, when there are high floods, these can overflow and lead to a resumption of streamflow.

All these *wadis*, including those that are semi-endoreic, converge towards the Oglat Merteba basin, which is itself completely endoreic. It is there that the El Hamma Wadi begins. By virtue of its position in the drainage network, the hamlet of Oglat Merteba is the only spot in the area where the local inhabitants can draw water all the year round from wells sunk to tap the underflow. The other water points of the region consist essentially of family cisterns, located on glacis with crusts or loamy soils, but subject to the vagaries of the rainfall, and a few large cisterns (150–200 m^3) constructed by the local authorities.

The importance of the traditional small *jessours* (little dams) on the Tebaga piedmont slopes and especially in the Matmatas should be noted.

Little is known about the hydrogeology, but the region is thought to constitute a major intake area for deep ground water, particularly at the foot of the Matmatas massif and along the *wadis*. In any case, there is no artesian water and, for exploitation with any degree of profitability, boreholes have to be positioned below the 125 m contour in order to keep pumping costs down. Out of four existing boreholes in the limestone aquifer of the Lower Senonian horizon in or near the test zone, at an elevation of *c.* 50–100 m, one (Rhirane) has turned out to be totally unproductive and, except for the one at Oglat, the other three have yielded fairly disappointing results:
- *Oglat borehole:*
  Average depth of water table: 40·7 m.
  Discharge: 28 litres/s.
  Dry residue: 3·620 g/litre.
- *North Beni Aïssa borehole:*
  Average depth of water table: 50·0 m.
  Discharge: 3.5 litres/s.
  Dry residue: 1·960 g/litre.

1. Soil-water reserve available to vegetation: quantity of water contained in the soil layer accessible to the plant roots, for capillary potentials ranging from 500 g/cm^2 to 16000 g/cm^2.

— *Gouraï Wadi borehole:*
Average depth of water table: 43·68 m.
Discharge: 7 to 8 litres/s.
Dry residue: 2·840 g/litre.
The waters contain sulphates and chlorides.

Natural vegetation

The most characteristic feature of the natural vegetation of the study area is the presence of low ligneous species rarely attaining a height of more than 0·5 m. In describing the vegetation, we shall relate the various physiognomic types to the region's major geomorphological elements. For the purposes of this description we shall define:

- as steppe, all low, sparse plant formations devoid of trees (low woody or chamaephyte steppe and graminaceous steppe);
- as scrub, formations with a predominance of dense thorny bushes;
- as grassland, herbaceous formations possessing a marked seasonal rhythm.

As well as the physiognomic types of plant formations, the legend of the ecosystems map (Fig. 2) provides additional details of the perennial vegetation cover (expressed as the percentage of the ground covered by such vegetation), its degree of degradation (indicating whether or not overgrazing occurs), the dominant physiognomic species, the above-ground biomass of the perennials and annuals (in kg of dry plant matter/ha), and annual production of the above-ground portion of the natural vegetation (in kg of dry plant matter/ha for a moderate rainfall year).

Various measurements taken *in situ* show that, on steppe that is in good condition, the below-ground biomass of the perennial species is equal to their above-ground biomass.

Vegetation of the limestone uplands

In the Matmatas massif, rangelands situated at an elevation of more than 300 m are still (despite increasing pressure in the form of grazing and fibre-picking for plaiting) composed of halfa steppe (*Stipa tenacissima*). The halfa forms a layer which is sometimes quite dense, especially on the northern scarps (general cover reaching as much as 30 per cent in the best instances—unit SD_2). There are traces of former xerophilous forest consisting of species such as: *Rhus tripartitum*, *Periploca laevigata*, *Teucrium alopecurus* and *Rosmarinus officinalis* var. *troglodytarum* still to be found in the many crevices of the more inaccessible rocks.

As the halfa regresses (on south-facing slopes and where the pressure exerted by man is too great), it is giving way to *Gymnocarpos decander*, a low woody-type which forms a homogeneous though not very dense steppe on calcareous lithosols, whether sand-covered or not. The presence of a sand covering on these lithosols is evidence that pastoral use is not excessive and allows the woody species to develop substantial above-ground biomass as well as favouring the development of a large number of annuals (GD_2).

Vegetation of gypseous areas

The presence of dwellings in the gypseous lithosol areas means that these areas are usually covered in sparse woody-type low steppe with reduced plant biomass as a result of permanent overgrazing by herds belonging to the sedentary farmers. In addition to a number of species characteristically found on gypseous soils, this vegetation also comprises many species associated with lithosols: *Atractylis serratuloïdes*, *Helianthemum lippe* var. *intricatum* (AZ). In some less-degraded areas small superficial deposits of sand are still held in place by the vegetation and are colonized by esparto (*Ligeum spartum*), thus giving greater plant cover than that produced by the annual species (LZ_2).

Vegetation on glacis with loamy soils

The vegetation of the deep loam deposits of the piedmonts has also long been badly treated, and it is now almost impossible to find any of the original steppe (AA_2), which consisted of low, woody formations dominated by *Artemisia herba-alba*, with a cover of more than 25 per cent. The more palatable species have almost disappeared, so that wormwood (*Artemisia herba-alba*) has been progressively replaced by *Arthrophytum scoparium* (AA_1), a species unattractive to livestock.

There is considerable run-off on all these lithosols and piedmonts with degraded vegetation (SD_1, GD_1, AZ_2, AZ_1, AA_2 and AA_1). The farmers have exploited this feature in order to cultivate these loamy soils (aa) with a fair guarantee of success, in the form of small plots situated behind 'tabia' or earth banks which help to retain the soil and water. Although cultivation helps the water to penetrate into the soil, the texture of these loams rapidly causes surface sealing, which hinders the germination of almost all annual species in the fallow areas.

Vegetation of the sandy plains

In low-lying areas these loams are overlain with sand, and the sierozems thus formed have allowed the development of homogeneous formations of low woody species with a predominance of *Rhantherium suaveolens* or, where the sand overlies a deep gypseous crust or pan, of esparto (*Lygeum spartum*). These steppes can achieve a degree of ground cover that is high for the region, in favourable cases approaching 30 to 35 per cent (LK_3 and RK_3). In these cases the above-ground biomass of the perennials is also high, reaching 1300 kg of dry matter/ha, and the annual vegetation is also abundant. These areas are often degraded by overgrazing, which is particularly marked around wells.

In the course of transhumance a few small plots are ploughed and sown with cereals, but the likelihood of success is usually small.

In places where the sand accumulates too quickly and too deeply, *Rhantherium suaveolens* gives way to a tall graminaceous species, *Aristida pungens*, which is little sought after by sheep and goats and so develops dense formations (45–60 per cent coverage in AR_3), stabilizing the dunes and favouring a very substantial development of annuals.

Vegetation of the flood-outs

The flood-out areas, with deep soils and a more abundant water supply, provide favourable conditions for the development of tree vegetation (sometimes exceeding 2 m). This loose scrub develops in long, narrow ribbon-like patterns on ground lying lower than the surrounding steppe. It is notable mainly for the presence of particular species growing on the sand-drift hillocks. Some jujube shrubs (*Zizyphus lotus*) for instance, manage to survive the action of the drift sand and to grow up with it, and if protected against the teeth of the cattle can grow into trees and reach a height of 3 or 4 m (ZR_3). Between these sand hillocks can be found a low woody formation which is similar to that already described and consisting mainly of *Rhantherium suaveolens*. In this vegetation type the biomass of both perennials and annuals is particularly high and has been estimated at 4000 kg of dry matter/ha for the perennials and 300 kg of dry matter/ha for the annuals. The land has often been under cultivation for a long time, and jujube sandhills (*nebkhas*) which impeded cultivation have sometimes been levelled. When cultivation is abandoned a cover of couch-grass (*Cynodon dactylon*) rapidly develops (zr).

Some of the *wadi*-bed terraces, in places where these deep alluvial soils overlie a gypseous crust, display a preponderance of esparto (*Lygeum spartum*) (PZ_3) and have a high above-ground perennial biomass (estimated at 2000 kg of dry matter/ha).

In the south of the Oglat Merteba area, considerable depths of sand give drier habitats and the low woody vegetation is of the Saharan type. For the study area, this unit has been designated RA and is characteristically marked by abundant tufts of *Retama raetam* and *Arthrophytum schmittianium* var. *schmittianium*, with a high biomass but a poor production of annuals because of the dryness. Agriculture in this environment (ra) allows some stubble grazing of the annuals which develop among the cereals, and on the vegetation produced by the few woody species not totally eradicated by agricultural activity.

Native fauna

Lack of means has prevented us from drawing up a systematic inventory of the fauna of the test zone; we are therefore unable to provide biomass and production data for the wild fauna.

All we have done, therefore, is to set out in the body of the paper and in the legend to the ecosystems map (Fig. 2) lists containing essentially the main vertebrates, making no attempt here to deal with the entomological and microfaunal elements, which are nevertheless important.

We have not included migratory or occasional visiting species in the ecosystems map legend, which contains a main list of the species considered to be present in all the environments of the area together with subsidiary lists, in the appropriate columns, of species peculiar to certain environments (e.g. mountains and flood-out areas). Although we have been unable to list the names of all the species found, we should like to stress, as far as birds are concerned, the large number both of species and of individual birds of the lark family (*Alaudidae*).

Mountain species

Apart from the *gundi* (*Ctenodactylon gundi*), the species listed are, in the main, species which are dying out, members of which have sought refuge in this mountainous environment.

Species of flood-out areas

The hillocks of drift sand (*nebkas*), stabilized by large jujube bushes (*Zizyphus lotus*), found in the *wadi* flood-outs provide a great many species with relatively cool shelter (shady places, burrows, perches, etc.) throughout the year. It is mainly in these areas that the principal predators – carnivorous animals, birds of prey and reptiles – are to be found. The dorcas gazelle (*Gazella dorcas*) is also occasionally seen, in places where *Retama raetam* bushes are prevalent.

Species belonging to sandy plains and piedmonts

The sandy plains are in general relatively poor in species because of the scarcity of shelter, water points and crops. For this reason, those found there are mostly roving species such as the houbara bustard (*Chlamydotis undulata*), the pin-tailed sand grouse (*Pterocles alchata*) and the hare (*Lepus capensis*). Numerous rodents, consisting of jirds (*Meriones shawi*) and psammomys (*Psammomys obesus*), make considerable inroads into the primary produce.

In the piedmont and valley areas, the presence of crops (cereals, trees and food crops), water points (run-off cisterns and wells) and uneven ground (providing cover) favours the development of sedentary fauna such as the Barbary partridge (*Alectoris barbara*), the rock dove (*Columba livia*), the fox (*Vulpes vulpes*) and the jackal (*Canis aureus*). The yellow scorpion (*Androtocnus amoreuxi*)) and the horned viper (*Cerastes cerastes*) have also frequently been observed on stony regs possessing some degree of sand covering.

Migratory and incidental species

From November through to the end of March, thrushes (*Turdus philomenos*) and starlings (*Sturnus vulgaris*) spend the winter in the olive groves of the foothills; during the spring and summer their place is taken by turtle-doves (*Streptopelia turtur*) which come to nest there, while the bee-eater (*Merops apiaster*) spends the warm season and nests in the jujube bushes (*Zizyphus lotus*). White storks (*Ciconia ciconia*) occasionally stop to rest in the zone during their migrations; similarly, certain ducks (*Anatidae*) alight on the temporary lakes that sometimes form after heavy rain. In years when grain is abundant, quail (*Coturnix coturnix*) may settle for a time among the crops.

Human population

Density and composition

The study area belongs to the El Hamma district in the governorship of Gabès and is situated 20 km from El Hamma oasis, the district headquarters.

The total population of the El Hamma district (which covers 3466 km^2) amounted to 32250 inhabitants in 1966 and about 41000 in 1975, their ethnic group being the Benizid tribe, which is in turn divided into a large number of subgroups. Of the population of the district, 58·8 per cent is rural and scattered despite the oases, which represent a fundamental cause of concentration of rural populations. The average population density for the entire district is 11·8 inhabitants/km^2. The average density of the rural population if only 6·6 inhabitants/km^2, so that the population of the study area works out at a total of 1320 inhabitants. This density is on the low side in relation to that of Tunisia's pre-Saharan arid regions as a whole, but it must be borne in mind that not all those who use the zone live within it.

In 1966 the age distribution for the population of the El Hamma district was as follows: under 15 (46 per cent), 15–50 (38 per cent), 50 and over (16 per cent). In rural areas the school-age population (6–14) represents 26 per cent of the total population.

As far as sex ratios are concerned, there is a marked shortage of men aged between 15 and 50, the numbers being 18 per cent lower than for women and reflecting the phenomenon of migration by men of working age. There is, on the other hand, a 28 per cent excess of old men – a phenomenon that cannot easily be explained.

Within the study area it may be assumed that 100 per cent of the settled males of working age are engaged in agricultural activities, since there are no towns or villages. For the El Hamma district, which possesses a town, 71·5 per cent of the men of working age have an agricultural occupation (as compared with 50 per cent for the whole of the Gabès governorship). Eighty per cent of the population of the district may be considered to depend directly on agriculture for their subsistence.

Migration and employment

Of the total population of the district (including emigrants) some 9 per cent emigrate abroad. This figure is relatively low for southern Tunisia (for the Gabès governorship, average emigration during the period 1964–72 was 28 per cent).

It is suggested that this low level of emigration is due partly to certain factors which have recently made emigration more difficult and partly to the proximity of the new industrial complex at Gabès, which may have helped to stabilize the population by providing employment. At the same time, other surveys have shown that 30 per cent of the men of working age are outside the district, working either elsewhere in Tunisia or abroad.

The phenomenon of migration in southern Tunisia is one that affects essentially the breadwinner himself, since in most cases the family stays behind.

In the El Hamma district, 75 per cent of the extended families with one or more emigrants also keep one or more working men in Tunisia and are thus able to rely on a joint income from local sources and from abroad. More than twice as many sons of heads of families are found among emigrants as heads of families themselves.

Bearing in mind that 30 per cent of the working-age group under consideration are temporary seasonal workers with nothing to offer other than their capacity for physical work, one can say that at present there is almost 50 per cent more labour than there is local employment. It should be noted, however, that at certain times of the year (e.g. at harvest time) there is a shortage of manpower due to limitations in mobility and to the rates of pay offered for such work.

The breakdown by work categories for men in the rural areas is at present estimated to be as follows:

	%
Self-employed	40
Labourers	41
Domestic workers	7
Both self-employed and labouring	12
	100

This shows that there is still a low proportion of regular wage-earners.

In the area studied one can hardly speak of an organized labour market. Indeed, less than a quarter of the workers who provide a proportion of their services in exchange for remuneration (either in cash or in kind) describe themselves as entirely wage-earning. The dominant feature, in fact, is a family type of agricultural holding, although seasonal or temporary work performed for other employers is extremely widespread. In this kind of rural society, which is tightly knit with ties of kinship and obligation to one's neighbours, work takes the form primarily of services rendered on a reciprocal basis.

Gross income from agricultural activities

Within the study area, the population obtains its income essentially from agriculture (stock-raising, cereal farming, arboriculture and the gathering of various forms of vegetation) and from small-scale family crafts. Despite a lack of precise figures, an estimate of the gross agricultural income has been attempted.

Estimated domestic animal production by type of ecosystem (Fig. 2) totals 46000 kg live weight for the 20000 ha, worth—including the fleeces—*c.* 37000 Tunisian dinars (TD).[1]

Estimated cereal production (about 2000 ha) gives 5640 q[2] of grain, worth *c.* 25000 TD/yr.

The extent of orchards and market gardens (for olives, fruit trees and food crops) is reckoned to be about 150 ha, with a gross yield worth about 200 TD/ha/yr or 30000 TD/yr for the entire area.

The amount of firewood gathered is estimated at 750 t/yr for the zone, equivalent in energy to 12600 TD of oil.

1. TD = U.S.$2·35.
2. 1 q = 100 kg.

Family production in such forms as aviculture, milk and craft objects is even more difficult to evaluate but has been estimated as representing 100 TD/yr per family, i.e. about 16500 TD in total.

This works out to an average gross yield from the test zone of 121000 TD, i.e. about 6 TD/ha ($14·30) or 97 TD/inhabitant/yr ($230·00).

This figure is clearly only a very rough approximation. The income derived from work outside the zone (especially from emigrants) should also be added.

Settlements

Each of the subgroups which make up the Benizid tribe possesses a number of collective lands varying in area from a few dozen to several thousand ha. These lands are used for various purposes: grazing, cereal-growing in low-lying areas, arboriculture in the foothills, etc., and the form of agropastoral use determines the type of dwelling. The main kind of settlement here is on a pluri-residential basis for seasonal occupation; the agricultural and rural type of extended family possesses from three to five dwelling places, of which two or three are vacant at any one time.

Three-quarters of the rural population live in scattered dwellings situated mainly in the foothill areas, where it is possible to build underground cisterns for storing run-off water. In periods of prolonged drought an entire family will abandon the house and its dry cistern in order to go and live temporarily at the main population centre of the district.

Thus every farming family has at least one stone-built room at the population centre of the district, which is lived in almost permanently by one member of the family (either an aged member or one engaged in trade or in some other non-agricultural activity). At the same time a roof is provided for the young members of the family who are attending school.

The use of the tent as a form of dwelling in Tunisia is very localized, occurring mainly in the south of the country and involving less than 3 per cent of the total population. On the other hand, 50 per cent of the rural population surveyed in the El Hamma district possess a tent.

At certain times of the year, such as the beginning of spring when the young animals are being born and suckled, the entire family may live in the tent, and sometimes, a little later in the season, part of the family may go off with the tent to the cereal-growing areas for the harvest.

The types of dwelling found, in order of decreasing frequency, are the *gourbi* (constructed without cement out of various materials such as palm fronds), the stone-built house and the tent, together with a very ancient form of cave-dwelling which can still be found in the mountains.

The government has encouraged a relative degree of sedentarization during the past few decades by building schools and dispensaries in the countryside, sometimes with a borehole to provide constant water and enable an irrigated area to be developed. These centres form the nuclei for settlements which are tented at first, the tents then giving way to *gourbis* and later to stone-built houses. The government also sometimes constructs an entire village out of stone and lets the houses to individuals at very favourable rates. Within the study area, this type of improvement scheme is only now being introduced.

Diet

The diet of the population is based on cereals, mainly in the form of semolina made from barley and durum wheat and used to prepare pancakes, couscous and gruel. At certain times of the year animals, especially goats, are milked. The main source of meat is poultry, mutton being eaten only occasionally, although to a growing extent. At the end of winter and throughout the spring in a wet year, fresh vegetables may be grown near the dwelling for family consumption (garden peas, chickpeas, beans, peppers, etc.). The main fruits are grapes, figs, watermelons and melons, almonds and dates. Almonds and dates are preserved for eating throughout the year. Olives are either preserved or pressed to extract the oil.

With the large market centre now existing at the nearby population centre of the district there is a tendency for the diet of the people to become more varied and to include such things as pasta, tinned foods, tea and sugar, but it nevertheless still appears to contain too high a proportion of starchy foods.

Land use

Main activities and land-ownership

Disregarding external income (some 30 per cent of the working males work outside the area), the economy of the Oglat Merteba area is based on extensive stock-breeding (89 per cent of the zone consisting of natural rangeland), periodic cereal crops (10 per cent of the land at any time is either under cultivation or lying fallow) and on irrigated arboriculture (1 per cent). On top of this there is the hidden income derived from the gathering of wood and fibres, and we should also remember the existence of small-scale, family-based craft activities (wool and fibre-weaving).

The main activities and produce are listed in the ecosystem chart legend (Fig. 2).

The system of land tenure is closely linked with the pattern of land use by the local population. In the area where there is extensive use of land for grazing, the land is collectively owned (at least at the group or extended family-group level). The cereal-farming areas have for some years now been progressively acquired for private ownership, whereas for a long time previously the only privately owned areas were the plantations. Property titles were granted for the first time in 1903. At the present time (since 1974) the authorities supervise the collectively owned land, which is administered by a management council composed of members elected from the community concerned.

Rangeland and stock-raising

The grazing lands are often erroneously thought to be fully communal and freely available to anyone who drives his animals on to them. They are in reality privately owned for the most part (except for the mountain rangelands) by individual groups of the population, subgroups and sometimes even extended family groups. Only the use of them is collective. Not all the owners, moreover, enjoy the same rights, since the herds vary immensely in size and some of the interested parties do not even possess a herd.

From the end of the spring until the autumn the herds are collectively managed and the grazing land is also used communally. These periods in fact are the times when most of the agricultural work is done (harvesting, fruit-picking, ploughing, etc.). The stock-breeders are unable to look after the animals whilst engaged in this agricultural work, and entrust them to herdsmen for six or seven months of the year. It is during this period that the herds are concentrated around the watering points and overgrazing occurs. It is also the mating season: combining the herds helps the small stock-raiser who cannot afford a ram of his own.

Within the group the notion of individual grazing land does not exist, except for grazing on stubble and in cultivated areas as a whole, where the herds are increasingly grazed on a private basis. The cereal farmers let out their stubble for grazing (*achaba*) if they are not using it for their own herds.

From the end of autumn through to the end of spring two distinct types of herding can be found:

— Collective herding on distant ranges, mainly by the owners of large herds. Since the animals no longer require to be watered at this time of the year, it is possible for them to graze in these distant areas. During this time some of the pastoralists follow their herds for the lambing, calfing, etc. and the milking. Ranges that are a long way from watering points are generally in fairly good condition.

— Individual herding on rangeland situated in the neighbourhood of the dwellings, by breeders who have withdrawn all or some of their animals from the collective herd. It is during the winter period that the young are born; individual herds are therefore kept near the dwellings and are given extra feed if necessary in the form of dates, olive-tree trimmings, barley, hay, etc. This arrangement also makes it easier for the milking, which takes place mainly in the spring. Sedentarization therefore tends to promote private ownership of part of the rangeland and marked overgrazing around dwelling places, the animals remaining within a radius of not much more than 2–3 km.

When localized drought occurs the groups can graze their herds on rangeland they possess in areas where rain has fallen, since each group generally owns several areas of rangeland scattered throughout the district.

If a generalized drought occurs throughout the region, the herds are moved to distant pastures, either southwards as far as the Libyan border or to the north. Small lorries are usually used for transporting the herds, with the pastoralist always going on ahead to look for grazing land to let (*achaba*). Their stay in the north does not last more than two months, the animals returning south at the beginning of autumn when the rains start becoming frequent in the north, since they have no shelter. In any case the farmers plough up their fallow land as soon as the rains start.

Apart then from land in the immediate vicinity of watering points and clusters of dwellings, the rangeland gets some temporary rest and rotation of grazing as a result of periods of drought and removal of the herds to some distance from the watering points during the summer. It is probably for this reason that is is still possible to find productive natural rangeland in the region, in places where agriculture has not destroyed the pastures.

The animals bred consist mainly of sheep and goats. In the study area the grazing animals are estimated to number 5000 head, although it is not easy to count them because few herds graze in the same place throughout the year. The size of the herds can vary between 30 and 1100 head, with an average of the order of 320 head. It is the smallest herds which remain in the neighbourhood of the dwellings, being made up either of animals that are too young to be subjected to range conditions or of animals for sale. Thirty-seven per cent of the breeders live at the population centre of the district, and among these there is a progressive trend towards giving up stock-raising, sometimes because they have found another source of income. There is also the fact that stock-raising requires the breeder's presence, even if only at certain times in order to attend to the lambing, shearing, etc.

Most of the herds are collectively owned, only 30 per cent belonging to single owners. There are very few breeders owning more than 20 head.

There are at least twice as many sheep as goats and they are usually combined in mixed herds. Despite the smaller number of goats, there are more goat owners than sheep owners, indicating that goats are more commonly found in the households than sheep, probably mainly for their milk production. The goat, incidentally, is also better adapted to grazing on degraded or mountain rangelands, whereas the sheep requires rangeland that is in relatively good condition. It appears that for these two reasons the proportion of goats is increasing.

Mating takes place during the summer months (on average one ram to twenty-three ewes), and lambing is staggered over a long period. The male lambs are not weaned until just before they are sold, whereas the females are prematurely weaned in order to allow the mother to recover her strength and to enable a certain amount of milking to be carried out.

Shearing usually takes place in April and May, normally after the beginning of the mating season.

The females are rarely sold, and serve to increase the size of the herd. Selective breeding is not practised and the reproduction rate is mediocre. The ewes are most often rejected for breeding purposes after they reach the age of 8.

Watering is needed only in summer, the water contained in the vegetation generally being sufficient for the animals at other times of the year.

In summer the herds do not on average move more than 5 or 6 km away from the watering points, and are watered every other day. At these times the herds are massed close together and considerable overgrazing occurs within the limits of this 5–6 km radius (e.g. in the Oglets region in the study area).

Water is scarce and some of the inhabitants sell the water from their underground run-off cisterns or bring in water for sale, in mobile tanks, from the population centres of the district. At times when there is a shortage of water it sells at 1 to 2 TD/m^3 (U.S.$2 to 4) and thus becomes an enormously expensive item for the stock-breeder, who is often forced to sell some of his animals in order to be able to keep the rest of the herd alive.

The animals are usually sold at the market. The average selling price of lambs is of the order of 17 TD, but varies considerably depending on the weight of the animal, the time of the year, the dryness of the rangeland, etc. The milk is always kept for family consumption. The selling price of a fleece ranges from 1·5 to 2·5 TD (U.S.$3 to 6). Some of the wool is used by the family to make carpets and blankets (tents and sacks being made of goat hair) and the rest is sold. The manure is not sold by the breeder but collected up free of charge by traders who then sell it in the oases.

The animals are rarely given supplementary feed except in times of severe shortage, when they may be fed barley, bran, dates, olive trimmings and olive-oil cakes, straw, etc. Fodder production for the provision of supplementary feed is not practised by the breeders themselves, but during periods of drought they sometimes buy lucerne hay grown in irrigated areas.

The still-birth rate is as high as 20 per cent and in times of fodder scarcity exceeds 50 per cent for all the herds taken as a whole.

In addition to the sheep and goats, mention must be made of the draught animals used for agricultural tasks (donkeys, mules and camels) and of the horses used for display. It is difficult to assess the number of these. In the zone in question herds of camels sometimes spend brief periods of the year on certain types of rangeland.

Mention should also be made of the breeding of poultry, rabbits, etc., which is of importance for domestic needs and represents a major source of protein in the people's diet.

The ecosystems chart legend (Fig. 2) shows the annual natural vegetation production for each type of ecosystem. This primary production ranges from 100–110 kg of dry matter/ha/yr, for the most highly degraded ranges, up to 1 800 kg for ecosystems which benefit from direct run-off. The mountain ecosystems are capable of producing 900 kg/yr.

Of course, not all this primary production is edible by livestock (especially in the esparto-grass areas). The legend also gives the quantity of edible production:

- the low-lying areas that are subject to flooding give the highest production (800 kg of dry matter/ha/yr);
- non-degraded sandy steppe produces something approaching 500 kg, but rather less than half (200 kg) when it is in bad condition;
- steppe overlying calcareous or gypseous crust produces an average ranging from 100 kg when it is degraded to 250 kg when in good condition;
- post-harvest and fallow land produce varying amounts of edible matter depending on the ecosystem (from 50 to 250 kg).

The present stocking rate related to this production is expressed in the ecosystems chart legend as biomass, representing kilograms of live weight/ha/yr for the average number of livestock which a stock-breeder keeps on a given ecosystem over the whole year, even though the grazing periods do not in general extend over the entire year. In order to obtain an idea of the stocking rate at any given time, therefore, it is necessary to look at the periods when intermittent grazing takes place on the various ecosystems.

It was concluded that the degraded ranges were in general overstocked, and that those in good condition had a balanced stocking rate.

The livestock biomass varies from 28·6 kg of live weight down to 4·2 kg for the most degraded rangeland areas, which is equivalent to a stocking rate of one sheep to about one hectare on the best ranges, dropping to one sheep to seven hectares on the worst. The current average stocking rate for the entire zone works out at one sheep to about four hectares, whereas the balanced stocking rate is about one sheep to five hectares.

There is no easy way of evaluating the density of wild animals living off the environment. Outstanding among these are the rodents (jird and psammomys) which, in sandy environments, can at certain times of the year represent 3–9 kg of live weight/ha. Their numbers fluctuate enormously, and there is no doubt that they consume a significant amount of the vegetable matter produced. At the present time the other wild animals are of lesser importance.

Agriculture

This territory has been undergoing partial clearing for agricultural purposes for an extremely long time—probably since before the Roman era, as attested by Roman oil presses.

Agriculture has almost always been concentrated in areas where there is a possibility of obtaining run-off. Cereal crops and fruit trees are therefore found mainly in natural, frequently flooded depressions with deep colluvial sediments, these deposits being of a kind to produce relatively regular yields, even in an arid climate.

On the land adjacent to natural areas of this kind the inhabitants have created small-scale surface improvements in order to retard the rate of run-off, retain the water and promote infiltration. It is possible in this way to enlarge the area suitable for cultivation. A device frequently constructed in this region is the *tabia*, a kind of earth contour bank which makes it possible to cultivate the ground upslope to an extent that would otherwise require two or three times as much rainfall. Part of the slope serves as run-off area and is left uncultivated, the water being channelled along small shallow gullies to the area just behind the tabia. This kind of construction is found principally on loamy-sand glacis. The soil surface becomes sealed through the action of raindrops and also naturally assists run-off.

Another form of water-management construction, both very ancient and very widespread, is the *jessour*, a small dam across a valley in mountain or piedmont areas. An outlet is provided to drain off the surplus water when the *jessour* is full. A succession of *jessours* placed across a valley floor in this way slows down the rate of run-off and causes the flood water to infiltrate over several days.

Arboriculture is practised in particular behind the *jessours*, and olives have certainly been grown in this way in the mountainous areas since very ancient times. Behind the *tabias* and *jessours* today we find olives grown together with almonds, figs and often date-palms (producing poor-quality dates). The earth bank of the dam itself is sometimes planted with fruit trees, while in the same place, under the trees, are grown the food crops whose produce is normally destined for family consumption. Behind the *jessours*, cereal crops may be grown each year, the dam making it possible for a relatively regular yield to be obtained even if there is a shortage of rain (400–600 kg of barley/ha, for instance). An olive tree can produce on average 800 kg of olives/ha, the oil generally being extracted and used locally.

There are about 150 ha of land developed for intensive agriculture in this fashion, representing 0·7 per cent of the study area.

Apart from these areas of relatively intense cultivation, which are more a sort of gardening because of their small scale, there are also vast areas used for large-scale cereal-cropping. The heaviest soils (loamy glacis of the *segui* type) are traditionally earmarked for this kind of farming, but mechanized ploughing has made it possible to extend cereal-cropping to the sandy areas as well.

These cereal-growing areas are often remote from the inhabited areas, which means that part of the family has to move there for sowing and for harvesting. The mode of cultivation used is extremely simple: after the seed has been scattered over the unworked ground, using some 30 kg of seed/ha, the plough then turns the soil, automatically putting the seed in at the same time. Until very recently the ploughing was done using animals (camels and mules) for traction, with the elementary swing-plough, as still seen in the *jessours*. The swing-plough would usually be taken around bushes and shrubs, parts of which were left growing, and this helped to prevent the soil from becoming eroded too rapidly. One can now see a large number of tractors during the sowing season, drawing disc-harrows, and many families hire a tractor for a few hours (at 2·5 TD or U.S.$6/h), the surface ploughing of one hectare taking approximately one hour.

Barley is by far the most commonly sown cereal, followed by durum wheat (for making into semolina, the staple diet) and in a very good rainfall year by soft wheat. Yields are extremely uncertain, and non-existent if no rain falls after sowing. The average barley yield from this extensive type of cereal farming is about 200 kg/ha.

Threshing is carried out on the spot, and the grain is stocked in silos for consumption by the family and also to provide a reserve in case of lean years caused by drought.

When there has been a good year, the problem of harvesting arises, since labour is in relatively short supply because of emigration and it is hardly worth while using mechanized harvesting methods for such low yields. Hence part of the harvest is sometimes left standing for the livestock.

Extensive cereal farming accounts for approximately 2000 ha or 10 per cent of the study area.

The woody plants which the population gather for heating and cooking constitute an important natural resource. A stock of wood can be seen beside each house and tent in the countryside. The plants are either torn out of the ground or cut – together with part of the root system. Those most commonly torn up are *Rhantherium suaveolens* and *Anarrhinum brevifolium*, but all woody plants are likely to suffer the same fate. It has been calculated that some 750 tonnes of wood are removed in this way each year, bit by bit, throughout the zone's 20000 ha.

Some species are used to make charcoal, which may then be sold outside the area. *Calligonum* was formerly used for this purpose, but was not very abundant in the area and has now almost disappeared in the southern parts, in the neighbourhood of the erg, as a result of charcoal-making activities. Charcoal is now made mainly from *r'tem* (*Retama raetam*).

Woody species are still sometimes used as fuel for lime kilns, bread ovens and hammams. Halfa (*Stipa tenacissima*) and common esparto grass (*Ligeum spartum*), both of which grow in the mountains, are collected for use in small-scale family craft activities, the fibres being plaited to make baskets, matting, ropes and *scourtins* (used in oil presses). The plant called *sboth* (*Aristida pungens*), which grows on stabilized dunes, is used for making shelters.

Another plant picked is *r'meth* (*Arthrophytum scoparium*), which is mixed with the tobacco grown in the oasis in order to make *nefa* snuff.

Degradation and regeneration processes of ecosystems

Causes of degradation

When arid-zone vegetation is not too degraded, ground cover of at least 20–40 per cent is provided at all seasons by the perennial plant species. The cover increases considerably during rainy periods as a result of the growth of annual species, and is enough not only to protect the soil from wind erosion but even to cause the soil particles stirred up by the winds, which are often violent in these parts, to be deposited around the stalks of the perennials. This plant cover also provides an obstacle to run-off and slows down water erosion, while the roots reinforce the physical resistance of the soil substratum and encourage water infiltration.

If for any reason the plant cover is destroyed, the surface layer of the soil is then subjected to wind and water erosion. The sand particles removed by the wind tend to accumulate in particular spots in the form of sand sheets or dunes. This removal continues until a compact layer of soil is reached, the final result being a surface composed of stones and exposed harder soil horizons, so that water penetration into the soil is greatly reduced. The remaining perennial plants can barely survive, and germination in general becomes difficult for both annuals and perennials. The 'glazed' surfaces allow the water to run off easily, swelling the *wadis* and leading to water erosion, with the formation of rills and gullies.

Such are the prevailing physical processes whereby ecosystems become degraded in Tunisia. To these we might also add the less prevalent phenomena of salinization and alkalinization that have occurred in a few places where irrigation has been carried out, either using water that was too saline or with inadequate drainage.

This physical degradation of the environment is accompanied by changes of considerable significance for the other components of the ecosystem, i.e. human beings and animals. The sandstorms and the impoverishment of the soil make life unpleasant and difficult, and can disrupt the way of life of the population. The emigration of one or more active members of a family is a reflection of this social disorganization, which can ultimately lead to the whole family abandoning the land and going to increase the population of some urban centre.

In parallel with the processes of degradation however, there are certainly other processes that tend either to stabilize the phenomenon or even to reverse the trend. In the first place, there are the efforts made by the population and the government: the creation of wind-breaks, reafforestation and structures for controlling run-off (earth banks, small dams, etc.). There is also the resilience of the natural vegetation, which in good rainfall years is capable of regenerating and thus of reconstituting adequate ground cover. This dynamic resilience and 'speed of healing' on the part of the vegetation varies tremendously from one ecosystem to another.

In the study area, the degradation processes are at present acting more swiftly and on a larger scale than the processes of regeneration and improvement of the plant cover and of the soil. It has been demonstrated that no major climatic change has occurred north of the Sahara since the end of the nineteenth century. The causes of this increasing degradation must therefore be sought in the growing pressure exerted by man on the natural environment, with its visible manifestation in the shape of a more aggressive technology. These phenomena are accentuated by the marked general aridity of the climate and by a rainfall pattern that characteristically varies enormously from one year to another. The main causes are as follows:

- The principal cause is without doubt the spread of cultivation on to new ground on the steppes. It is generally accepted that during the period 1890–1975, over 2700000 ha of steppeland in the dry regions of Tunisia have been brought under cultivation. This state of affairs results from the understandable desire of the growing population to increase their immediate income. Fruit trees and cereals, especially in areas where the rainfall is in excess of 200 mm, certainly make it possible—in the early years, before the fertile layer of soil is carried away by erosion—to realize a cash income which is higher than that to be made from pastoralism. In recent years, moreover, the widespread introduction of mechanization throughout the country has enabled hectare upon hectare of steppeland to be cleared rapidly and with relative ease by means of the disc-harrow. For this reason, and following a series of good rainfall years, this clearing of ground has progressed at an accelerating rate in the zone between the 100 and 200 mm annual isohyets.
- Overgrazing is another cause of degradation. Because of the increase in human population there has been no reduction in the average total number of livestock, even though the areas left for grazing have grown progressively smaller with the expansion of agricultural activity. As well as diminishing the edible species and encouraging the development of inedible species, overgrazing leads to a reduction in the cover of long-lived species, and thereby opens the door to degradation processes. Another harmful factor is excessive trampling. In some places the opening up of new watering points for the herds, or the creation of irrigated areas, without regulating the use of the range, has resulted in overgrazing and deterioration of the environment over a radius of 10 km or so.
- Eradication of woody species. Although less noticeable than the two foregoing causes, this is nevertheless very extensive. *C.* 1·5 kg of wood/person/d is required for domestic purposes, and this supply comes almost entirely from the vegetation of the steppe. Many of the shrubs producing the most wood have disappeared entirely, and wood-gathering is now directed towards smaller and smaller individual plants and involves an ever-growing number of species. What is more, the plants are often torn up rather than cut, and this discourages subsequent regrowth.

Soil degradation and regeneration

The soils rapidly become degraded and eroded through these principal causes of degradation. The materials removed by the different forms of erosion, however, may be carried to other parts of the region where they form soils that are less mature and also frequently less fertile, possessing physical properties and water relationships inferior to those of the soils from which they originated. Hence, although regeneration does sometimes occur, as a whole it does no more than slow down the general deterioration of the soil resources.

Soil degradation

Soil degradation represents the phase that leads to erosion. It is linked, generally speaking, with degradation of the natural vegetation, since the progressive disappearance of plant cover leads to:

- impoverishment in organic matter, resulting firstly in a breakdown of the structure and physico-chemical properties of the soil, and secondly in lowering of its fertility;
- removal of the wind-blown sand sheet, which is very mobile but performs an extremely important function during heavy rainstorms by mitigating the impact of the raindrops and reducing initial run-off. In the absence of the sand sheet,

soils very rapidly become 'glazed' on the surface (a few showers over a period of 2–3 months are enough to cause this) as a 'rain-beat seal' a few millimetres thick very quickly forms, even on highly sandy soils such as sierozems.

When this phenomenon becomes widespread, it entails the following consequences:

— reduction of rainfall effectiveness from the point of view of recharging the soil-water reserve;
— increased run-off, which carries plant seeds away from the area;
— poor soil-water economy during the course of the year, with increased evaporation and absence of mulch;
— increased water erosion.

Another aspect of soil degradation is the partial sterilization caused by massive aeolian deposits in the form of unstabilized dunes. This phenomenon has increased greatly in recent years with the introduction of mechanized cereal farming. The steppes near the cereal-growing areas become fossilized, the soil being covered by a few decimetres—and sometimes up to one or two metres—of wind-blown sand. The natural vegetation is frequently unable to recolonize these sands and this results in the formation of mobile sand dunes, which, in pre-Saharan areas, leads rapidly to the creation of a dunefield.

In these arid areas, where the already degraded soils are extremely sensitive, erosion is at the present time becoming more marked.

Water erosion

In the Oglat Merteba region water erosion occurs mainly in the hills and foothills, on the glacis and along the river banks, with very little effect in the sandy plains:

— in the hills it usually leads to denudation of the limestone (ecosystem type SD_1);
— on erosion glacis with soil crusts, it removes the calcareous and gypseous crusts, thereby exposing an extremely skeletal type of soil (GD_1 and AZ_1);
— on depositional glacis (loam containing calcareous nodules—ecosystem types AA_2 and AA_1), it results in sheet or gully erosion. This type of erosion can lead ultimately to total truncation of the soil, frequently as far down as the calcareous hardpan, leaving a skeletal type of soil (GD_1), or even down to the gypseous bedrock, so that a gypseous crust tends to form (AZ_1);
— on the banks of the river channels which drain these piedmont and glacis areas, regressive gully erosion is now taking place on the upper terraces, which consist mainly of material containing calcareous nodules; this leads ultimately to badland formation;
— every time there is a heavy fall of rain, the flood water scours the beds of the channels and constantly redistributes the sediments in their flood-out areas. Only those areas situated furthest downstream are unaffected by this phenomenon, or benefit from it in the form of relatively fine alluvial deposits (ZR_3, RA_3 and PZ_3 ecosystems).

Factors tending to promote water erosion are:

— degradation of plant cover;
— increased run-off resulting from degradation of the soil's physical characteristics;
— unsuitable methods of cultivation;
— violence of rainfall (intensity and duration).

We possess very few direct measurements of water erosion for the area, with the exception of two adapted run-off cisterns (Trapsa I and Trapsa II). The first, with a drainage basin of 2·38 ha, provides a measurement of run-off and erosion (gully and rill) taking place on the Melab Djebel (SD_1, GD_1 and AA_1). The second, with a drainage basin of 1·04 ha, provides representative readings for an environment situated on a calcareous crust (GD_1) and possessing a fair degree of cover (GD_2).

For the period 1 September 1969 to 31 August 1970, with a rainfall of 137·4 mm and an average run-off of *c.* 20 per cent, it was calculated that the effect of water erosion over the whole of the basin associated with the first cistern amounted to 16·5 t of sediment/ha/yr. This high figure was for an average year with only one isolated instance of heavy rainfall on 25/26 September 1969 (63·2 mm in 48 h). On depositional glacis where sheet erosion is greater than gully erosion, the amount of earth eroded by water is probably of the order of 2–4 t/ha/yr.

We were able to check these figures at the Dissa Djebel station where on a 50 m slope having a gypseous crust at the upper end and a truncated steppe soil downslope ($AZ_1 + RK_1$), we obtained a water sheet-erosion measurement for the 1973–74 season of 4·029 t/ha/yr. Similarly, in the second cistern, where the erosion in question was largely sheet erosion, a value of 2–4 t/ha for an average year was obtained.

In contrast, in an AA_1 environment treated as a protected area (the Telman cistern), situated to the north of El Hamma, with sheet erosion only, the amount of material eroded in an average year rarely exceeds 0·6 t/ha/yr.

With exceptional rainfall, these average annual erosion figures no longer have any meaning. On 12 December 1973 for example, within a predominantly marly drainage basin (0. Zita) of 320 ha situated 15 km north of El Hamma and having SD_1, AA_2 and GD_1 environment types, 258·3 mm fell in 19 h (with maximum intensities ranging from 100 to 150 mm/h), causing an average run-off for the whole of the basin of 89 per cent and average erosion of 108 t/ha (in one day).

It is very difficult therefore to quantify the effect of water erosion as an average for the region, but the few figures given above nevertheless serve to show the extent and extreme irregularity of the phenomenon.

Wind erosion

This is especially prevalent on the sandy steppes (RK_3, RK_2, RK_1, LK_3, AR_2 and AR_3).

It is associated with:

— soil characteristics, where the texture is sandy, sandy loam, fine sand or very fine sand, with little or no structure and extremely vulnerable to deflation;

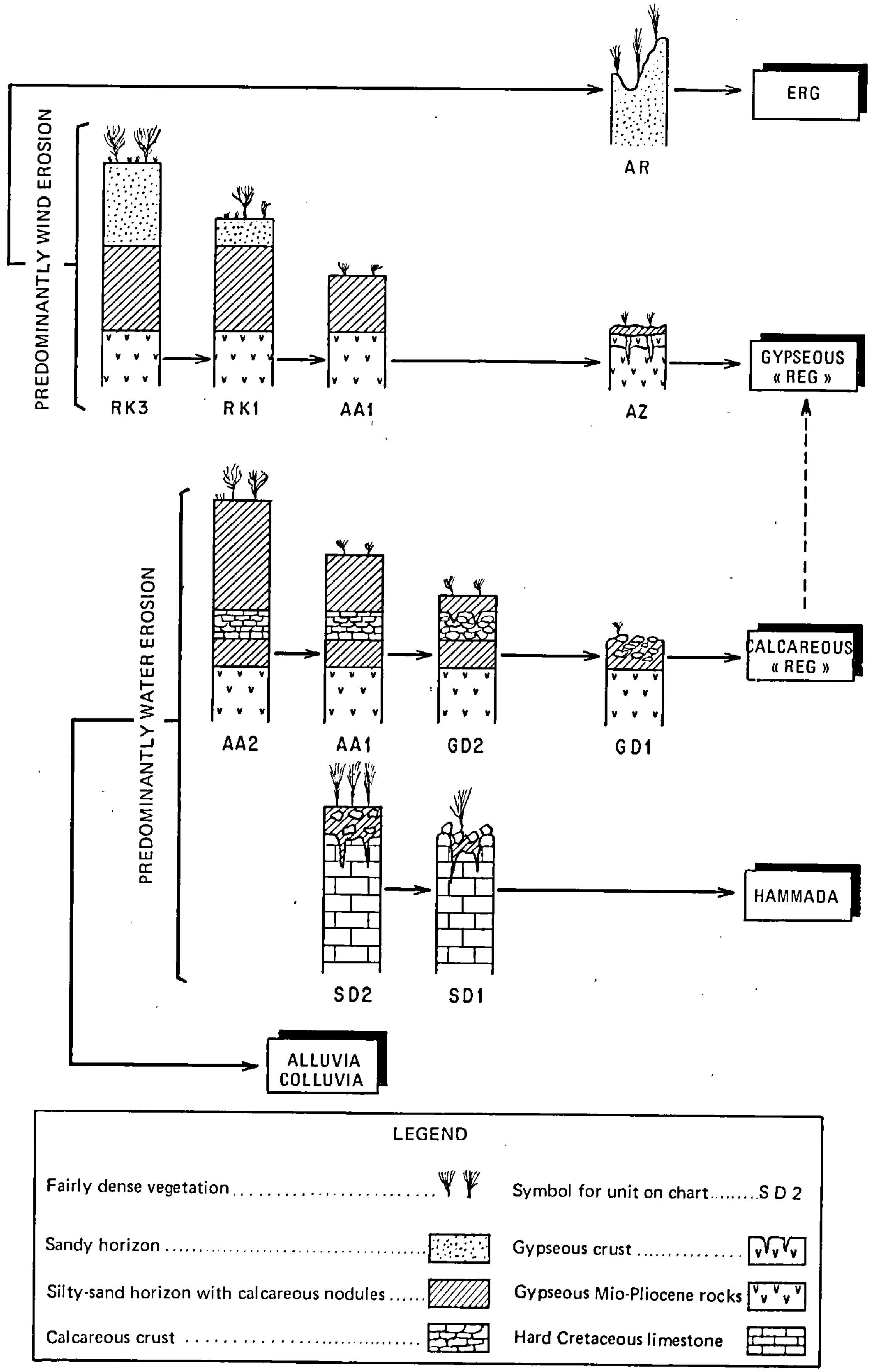


FIG. 4. Degradation of soils and vegetation of the principal ecosystems of Oglat Merteba

— plant cover that is more or less degraded and therefore does not hold the soil in place;
— the strong attraction exerted by sandy soils for periodic cultivation of cereal crops;
— overgrazing and eradication of the low woody plants;
— the extremely violent winds to which the area is subjected;
— prolonged drought.

On *Rhantherium* steppe, wind erosion generally leads to disappearance of the sand sheet that is so beneficial (RK_2), and to truncation of the soil down to the calcareous nodule horizon, which is more resistant to wind erosion (RK_1 and AA_1). At this point, water erosion takes over (Fig. 4). On esparto steppe (LK_3) the final stage is denudation of the gypseous crust (AZ_1).

On *Aristida pungens* steppe (AR_3 and AR_2), degradation of the vegetation rapidly causes the stabilized dunes to be mobilized, and these then encroach on and bury neighbouring environments.

Here again, we do not have accurate measurements for the zone. Le Houérou (1969*b*) gives for *Rhantherium suaveolens* steppe in the Ben Gardane, Tatahouine and Sidi-Toui regions average annual wind-erosion values ranging from 1 to 1·5 cm over a period of 10 years. This represents something like 150–225 t/ha/yr of erosion, which is an enormous amount! However the deflated sand is frequently redeposited elsewhere—sometimes not very far from the deflation area—in identical environments.

Since 1971 a small-scale monitoring has been carried out at 52 km on the Gafsa to Gabès road, on a *Rhantherium* steppe in good condition, with simulation of total overgrazing, without plant eradication. Measurements for the period 5 months 1972 to May 1973 revealed soil truncation equivalent to erosion of 88·5 t of soil/ha. Since this period includes the windiest months (March to April), the values for an entire year might be in the region of 100/t/ha/yr.

In conclusion, allowing for the fact that wind patterns do not vary greatly and that rainfall amounts are very much more variable, it would appear that in certain very localized areas wind erosion is of greater significance than water erosion.

Soil regeneration

This is associated with regeneration of the vegetation and the recolonization of eroded soil that has been redeposited within the zone. Such regeneration in the present state of affairs is practically non-existent in environments affected by water erosion (AA_1, SD_1, GD_1 and AZ_1), erosion processes being far in excess of soil-formation processes, which are practically unknown in this arid type of climate (except for the formation of gypseous soils). The nearest approach to a form of pedogenesis is an increase in depth of the immature alluvial soils in depressions and valley floors.

On the other hand, in sandy environments certain forms of regeneration can retard, although not entirely overcome, the wind-erosion processes. This applies mainly to *Rhantherium suaveolens* environments in good condition (RK_3 and RK_2) and *Aristida pungens* environments (AR_2 and AR_3), which thanks to the ability of the two species to rise quickly above the level of sand accumulations, stabilize the wind-borne drift sand and enable the soil to recover to some extent (giving immature steppe soils).

Vegetation degradation and regeneration

The process of degradation of the vegetation under the influence of desertification factors has been described in considerable detail by Le Houérou (1969*b*); here, we shall reiterate the main points. The notion of the 'sensitivity' of the vegetation is very important.

Ploughing removes long-lived, deep-rooted species and consequently reduces plant cover and perennial plant biomass. However, ploughing works the soil and breaks up the rain-beat seal, thus creating favourable conditions for the germination of annuals and promoting their growth by improving water infiltration. Unfortunately many of these annual plants are of no value for grazing, live for only a short time in spring and are not capable of holding the soil in place.

The degree of degradation varies according to the sensitivity of the vegetation in question. The method of land clearing used is also relevant, since the traditional swing-plough spares a large proportion of the long-lived plants, which can regenerate themselves if cultivation is later abandoned. The tractor-drawn disc-harrow on the other hand destroys the perennial vegetation almost completely. Furthermore, the number of self-sown plant species is considerably reduced in cultivated areas.

This latter phenomenon is illustrated by measurements in a sandy *Rhantherium suaveolens* steppe (RK_3) which was initially not very degraded, although used as pastureland, and was subsequently cleared of vegetation (Table 6).

Overgrazing reduces the plant cover and the biomass of the long-lived plants, which is not too serious as long as the species remain reasonably dense and retain good regeneration potential. If overgrazing continues, however, in the end the best pasture species disappear. Continuous grazing without any period of rest amounts to disregarding the physiology of the plants, which need a certain minimum photosynthetically active surface area in order to build up their reserves for the production of new shoots. The plant otherwise withers, its root system is impoverished and it finally dies.

This is also true for annual species that are grazed before they have had time to produce seed.

TABLE 6. Effect of cultivation and of clearing method employed

Sandy *Rhantherium suaveolens* steppe	Plant cover (%)	Cereal crop cover (%)	*Rhantherium* cover (%)	Number of self-sown species
Pastureland	25	0	17	39
Cleared by traditional swing-plough (for cereals)	11	0.7	7	25
Cleared by disc-harrow (for cereals)	5	0·5	2	13

TABLE 7. Relative proportions of pastoral and inedible species

Rhantherium suaveolens steppe	Biomass (kg dry matter/ha)	Species	
		Pastoral (%)	Inedible (%)
In good condition (RK_3)	1312	83	17
Degraded (RK_1)	415	59	41

In subsequent years, when the rains come, the stock of seeds will be low and poor use will therefore be made of the water in the soil.

In these ways the good pastoral plants are progressively disappearing and giving way to inedible ones that are either thorny, strong-smelling or contain to much salt for livestock.

Table 7 shows the relative proportions of pastoral and inedible species on *Rhantherium suaveolens* sandy steppe.

The eradication of woody species is also a degrading influence.

This may take the form either of generalized degradation throughout the region, the inhabitants pulling up-plants in various places here and there, or of more concentrated degradation in the immediate neighbourhood of permanent dwellings. It is difficult in either case to determine the proportion of degradation attributable to overgrazing as opposed to uprooting, since the net result of both activities is the disappearance of smaller and smaller species of woody shrubs.

An attempt has been made to evaluate the quantity of wood available from the natural vegetation: within the area in question (20000 ha) the present above-ground biomass of the perennial plants (mainly the woody parts) represents 14000 tonnes of dry matter, and the roots probably make up a similar amount. Assuming that 50 per cent of the root is pulled up with the plant, this would give a total 21000 tonnes available for firewood—or slightly over one tonne/ha.

The daily consumption of wood per person is of the order of 1·5 kg, which means that the population of this area of 20000 ha uses in all approximately 750 tonnes/yr. In theory therefore, 750 ha (i.e. 3·7 per cent of the area) are denuded each year.

This wood-gathering activity on the steppe is of course spread out and some of the plants pulled up grow again. It is quite clear, however, that this activity would be less harmful if the plants were merely cut off at ground level without tearing out the parts below the surface. Measurements have shown that a sandy *Rhantherium suaveolens* steppe (RK_3) on which the vegetation was completely cut off at ground level but with the below-ground parts left in place had already reconstituted half of its initial above-ground biomass by the end of seven months.

TABLE 8. Reduction in above-ground plant biomass and primary production in degraded ecosystems, during an average-rainfall year (kg dry matter/ha)

Ecosystems	In good condition		Degraded	
	Biomass	Production	Biomass	Production
Sandy area (RK)	1300	800	400	500
Loamy area (AA)	400	450	200	130
Gypseous area (AZ)	600	285	300	180
Mountain area (SD and GD)	1300	870	200	305

When desertified areas are studied, it is sometimes difficult to know how much weight to attribute to each of the three factors we have just mentioned above. Generally speaking the degree of degradation of certain ecosystems can be expressed as a reduction in above-ground biomass and in annual plant production, as shown in Table 8.

In order to evaluate the regeneration capacity, or 'speed of healing' (Godron and Poissonnet, 1972) of the vegetation, a survey was made of all parts of the area in which protective or pastoral management measures had been applied.

Ecosystems in sandy areas

Arrangements made to protect roads against sand drifts have produced spectacular results after a few years. As an example, Table 9 shows the difference between the quantities of edible plants within and outside a protected area. The measurements were taken following copious spring rains. A considerable stock of seeds was present within the area, and the germination was not hampered by deflation.

TABLE 9. Effect of protective measures on above-ground biomass and primary production edible to livestock in a sandy area (kg dry matter/ha)

Sandy area ecosystems (RK)	Above-ground plant biomass	Edible perennial plant shoots	Edible annual plants	Total edible plant matter
C. 3 years' protection	966	173	207	380
Grazed	809	169	20	189

These sandy ecosystems in general display good regeneration potential as far as the vegetation is concerned.

Ecosystems in loamy areas

The adjacent plots compared in our example involved a highly degraded ecosystem on loamy soil (type AA), with *Arthrophytum scoparium* as the dominant plant species. All these areas are cultivated in rotation, with grazing during the fallow periods. One of them has been closed to agriculture for the past nine years (because it serves as the run-off catchment area for a cistern) but has not been totally protected, as it is still used for grazing. Table 10 shows that in this type of environment, although protection measures produce a very slight increase in plant cover, the grazing is not improved. The system of alternating cultivation with fallow grazing is more advantageous since it allows the annuals to germinate in the spring, whereas the rain-glazed surfaces or these loams in protected areas are unfavourable to germination.

TABLE 10. Effect of forbidding agriculture on the plant cover of a loamy area (cover expressed as a percentage of the ground area)

Loamy-area ecosystems (AA)	Total plant cover	*Arthrophytum scoparium* cover	Edible species cover	Number of self-sown species
Cultivation/fallow rotation	2·6	0·5	1·0	11
Grazing only	4·6	4·3	0·3	2

Generally speaking, where the natural vegetation is already highly degraded by intermittent agriculture, regeneration potential is very low in these loamy areas.

Ecosystems in gypseous areas

An area (Dissa Djebel) with a gypseous crust and highly degraded vegetation (type AZ_1) was protected for three years. There was no increase in plant cover, which remained at about 7·0 per cent for the perennial vegetation. No annuals became established in the area.

This is an extreme case. Ecosystems in gypseous areas frequently have an aeolian sand sheet of varying thickness over the gypseous crust. It may be assumed that further development of the protected perennial plants, some of which manage to grow into small bushes, would lead to trapping of sand carried by the wind. The more or less rapid formation of this sandy layer enables annuals to germinate when conditions are good.

The regeneration potential of the vegetation in such gypseous areas depends largely on the initial state of degradation.

Mountain ecosystems

The example chosen is of a small mountainous massif in the region (Brerhits Djebel), which has been totally protected for the past five years. The vegetation consists mainly of halfa (*Stipa tenacissima*). As Table 11 shows, the plant cover has almost doubled in five years; more important, the cover of species edible by livestock has been increased by a factor of 6 in relation to the adjacent overgrazed area. The number of self-sown and edible species has shown little change. These species, although not very abundant, are 'potentially' present in the grazed area.

Regeneration potential and regeneration rates for vegetation in the mountain ecosystems are in general excellent.

TABLE 11. Effect of protective measures in a mountain area on plant cover (total and edible) (in percentage of ground area)

Mountain ecosystems	Total plant cover	Halfa cover	Edible plant species cover	Number of edible plant species	Number of self-sown plant species
C. 5 years' protection (SD_2)	27·4	13·7	22·9	9	19
Unprotected area (SD_1)	13·6	1·0	3·6	8	15

Ecological progressions and relationships between ecosystems

From the foregoing analysis of processes of degradation and regeneration, it can be seen that at present the evolution of ecosystems is very closely linked with the use of the environment by man.

Starting with an ecosystem possessing vegetation in good condition (RK_3, for example), the influence of prolonged overgrazing can lead to a succession of ecosystems, each of which is more degraded than the last (RK_2, RK_1, rk . . .). Protection can produce regeneration which reverses the sequence. 'Ecological progressions' represent links between the different ecosystems in the area being studied, and the possibilities of transition from one ecosystem to another, either through degradation or regeneration.

The relationships between the ecosystems charted are summarized below and illustrated by Figures 4 and 5.

Mountains and glacis

Under the joint influence of halfa-picking and overgrazing, with the ensuing reduction in plant cover and incidence of soil erosion, the SD_2 ecosystem passes rapidly to SD_1, then to GD_2, and in the driest areas may ultimately form hammadas.

On loamy piedmont slopes, with hardpans reaching to some depth, the self-sown vegetation has probably been in a degraded state (AA_1) for a long time (except for a few areas which are still in good condition—AA_2). Because of this, the soil is subject to sheet and gully erosion by water, tending to expose the calcareous pans (GD_1) or the gypseous substratum (AZ_1). The total disappearance of the vegetation in these last two ecosystems gives rise to calcareous or gypseous regs.

The various materials eroded from these surfaces by water accumulate in the flood-out areas: forming ecosystems ZR_3, PZ_3 and RA_3.

Plains of sand accumulation

The combined effect of overgrazing and uprooting of woody species causes the plant cover to regress rapidly, leaving the superficial sandy horizon of the RK_3 and LK_3 ecosystems at the mercy of deflation. LK_3 thereby rapidly degenerates into AZ_1 and then into a gypseous reg. RK_3 rapidly turns into RK_2, followed by RK_1—through truncation of the upper horizons—with the result that the underlying loamy horizon is left uncovered. From this stage onwards, and under the influence of agricultural activity, the self-sown vegetation of the rk type of ecosystem is joined by new species that are characteristic of aa and AA_1 ecosystems.

Material removed by wind erosion may be either transported outside the area or redeposited on RK_3, RK_2, LK_3, GD_2, AZ_2 or LZ_2 ecosystems, where the plant cover is liable to trap it, or alternatively heaped up within the area in the form of dunes colonized by *Aristida pungens* (AR_2 and AR_3 ecosystems).

Persistent uprooting of stabilizing vegetation in these last two ecosystems results within a very short time in the formation of a dunefield (erg).

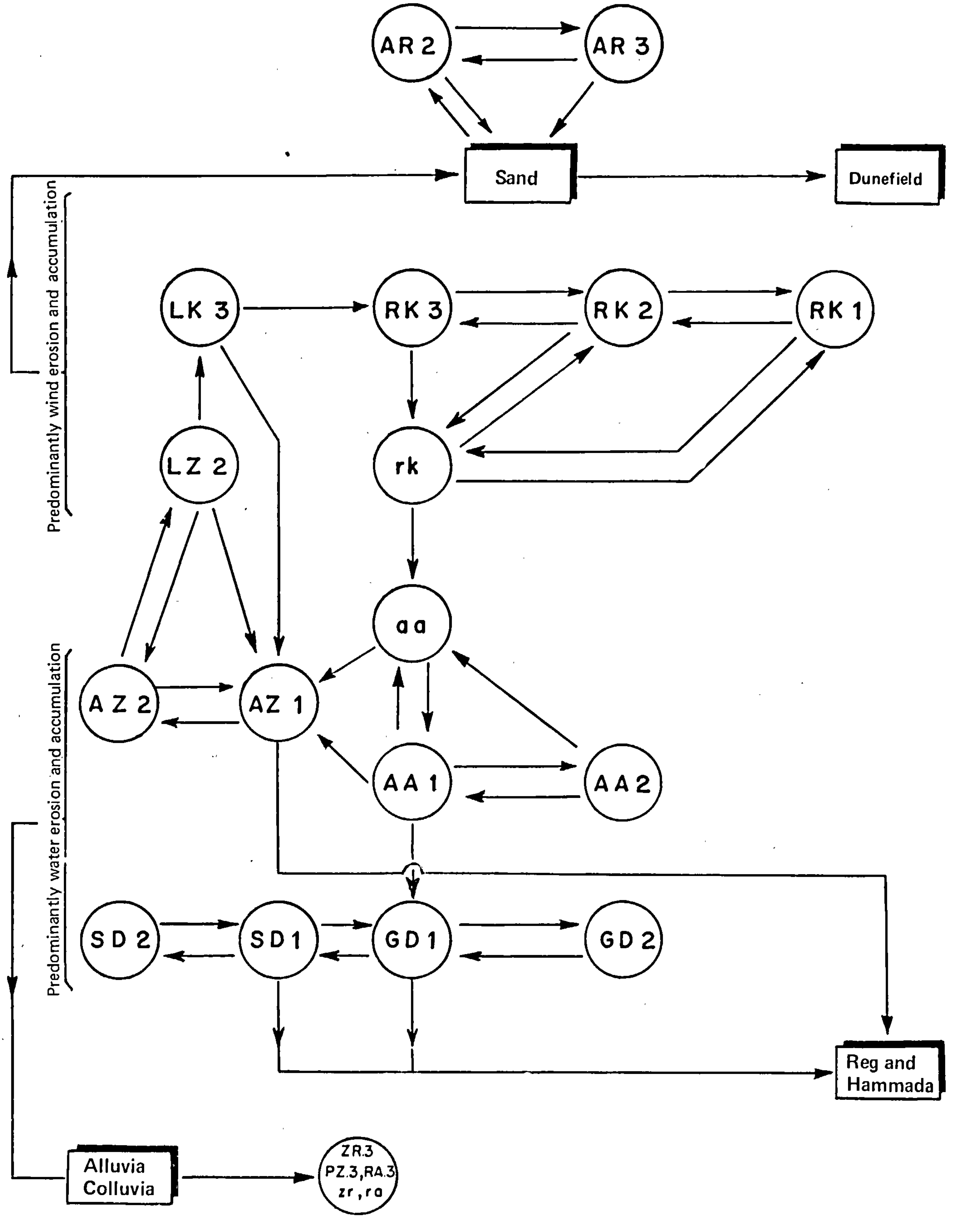


FIG. 5. Correlations between Oglat Merteba test zone ecosystems. (Arrows indicate possible transition from one ecosystem to another as a result of either degradation or regeneration of the environment)

Desertification

'Desertification' has been defined as 'a combination of processes which result in more or less irreversible reduction of the vegetation cover, leading to the extension of new desert landscapes to areas which were formerly not desert. These landscapes are characterized by the presence of regs, hammadas and dunal formations' (Le Houérou, 1969*b*).

The notion of irreversibility is important in connection with the processes in question. A clear distinction must be drawn between degradation and desertification. Parts of degraded areas may undergo regeneration of the vegetation and of the soil; they have not definitely lost their potential productivity. Desertified areas on the other hand have lost all or part of their potential productivity and are thus irreversibly desertified.[1] Hence the desertification of an ecosystem consists primarily in the loss of a significant part of its biological productivity.

We must also distinguish between different meanings of desertification according to the purpose for which man uses the land. An area from which the vegetation has been cleared, and in which it will be impossible for the perennial vegetation to re-establish itself unaided, such as an AA-type ecosystem for example, may be regarded as 'desertified' for grazing purposes; at this stage however, before any erosion has taken place, the soil will not yet have lost its production potential for agricultural purposes. The characteristics of desertification as far as the soil is concerned are primarily erosion and degradation of the physico-chemical properties of the soil. In view of the fact that, in the climate in question, water represents the main limiting factor for production, the most important criterion by which desertification may be judged is a reduction of the soil's ability to store water which can effectively further plant production.

When considering these concepts of degradation and desertification, the time factor must also be taken into consideration. There is no doubt, for example, that over a very long period and in the absence of human pressure (i.e. if the environment is protected from human activity), any of the environments in the zone concerned (with rainfall of between 100 and 200 mm) is capable of at least partial regeneration and an increase in potential productivity. On a time scale of several centuries a steppic soil could certainly become reconstituted and perennial vegetation could re-establish itself.

For the sake of laying down a time limit we have decided to consider as completely desertified—for the purpose of a given type of land use—any areas whose ecosystems are likely to remain at their present minimal productivity level despite twenty-five years (one human generation) of management or protection. We have also ruled out the hypothesis of employing management practices involving massive and costly techniques such as removal of crusts or large-scale irrigation, the use of which obviously makes it possible to increase the productivity of any type of environment, provided no major errors are made in implementing such techniques or in the ensuing maintenance work.

1. The term 'desert' is arbitrarily applied to zones situated below the 100 mm average annual isohyet, little affected by human activity and possessing a very low production potential and likelihood of future evolution; these zones comprise the ergs, regs, hammadas and chotts of Tunisia's great southern desert and do not come within the scope of this paper.

Criteria selected for defining and tracing the course of desertification

Although the processes of desertification may be relatively easy to describe, it is difficult to quantify the overall degree of desertification of an area at a given moment in time. For this purpose, therefore, a number of desertification indicators are employed in an attempt to follow how they evolve with the passage of time.

Criteria associated with reduction in productivity

We find that the main criterion for the desertification of an ecosystem is the reduction in its biological productivity. In an arid environment, the main limiting factor for plant production is the amount of water in the soil available to the vegetation. We have therefore made a point of tracing the progressive reduction in the capacity of the 'water reservoir' constituted by the soil, and of the soil's ability to absorb rain-water. It should be noted at this point that this method of assessing desertification is fully justified in a wet year (a year in which the production of an ecosystem corresponds roughly to its productivity) if there is an adequate fertility level, but it is obvious that in an average or low rainfall year the rain-water will never completely saturate the 'soil reservoir', and reduction in the volume of this reservoir (through erosion) will not be a determining factor as far as production levels are concerned.

The following criteria have therefore been selected:

- maximum water reserve in the soil available to vegetation = 'effective supply';
- primary run-off coefficient of the soil;
- relative reduction in natural plant production in a 'wet' year.

Effective supply. This term indicates the soil's ability to absorb water, involving factors such as soil depth, porosity, capillary potential, etc. It is defined as the maximum quantity of water available to vegetation that can be stored in that part of the soil which is accessible to the plant roots, between the wilting point (pF 4·2) and the field capacity (pF 2·7).

A mean profile was drawn up for each ecosystem and its effective supply calculated. Having measured the areas of the various ecosystems, we were able to calculate the average effective supply for the whole of the study area. At present it is about 98 mm of water.

This effective supply is diminishing under the influence of current erosion, although this loss may be slowed down in places by regeneration processes (drift of wind-blown soil for example).

Primary run-off coefficient. This expresses the state of the soil surface and hence the extent to which it permits penetration by water. It involves factors such as the presence of a rain-beat seal, slope, micro-relief, plant cover and intensity and duration of rainfall.

The primary run-off coefficient of an ecosystem is expressed in the formula:

$$Kr = \frac{\text{primary run-off}}{\text{rainfall}} \times 100$$

This criterion is obviously not used for *wadi* flood-out areas and beds.

These coefficients have been calculated on the basis of measurements or estimations, made in the zone or in adjacent regions, for each ecosystem and for two types of rainfall year:

Kr1: an 'average' rainfall year (150 mm) with at least one instance of 50–60 mm of rainfall within 24 h.

Kr2: a 'wet' year, of the 1973–74 type (300 mm), with one instance of 150–200 mm of rain within 24 h.

Mean Kr1 and Kr2 levels for the whole of the test zone have been calculated on the basis of the areas of the various ecosystems. Kr1 at present equals 8·3 per cent and Kr2 33·0 per cent.

Relative reduction in self-sown plant production in a 'wet' year. Degradation of the various physico-hydraulic properties of the soil leads to a reduction in productivity of the habitat. This effect on production is particularly marked in the 'wet' years when rainfall is no longer the major limiting factor. Degradation of agricultural soils is then manifested by water wastage, i.e. the soil's inability to store water. The criterion of desertification used over the whole of the study area is therefore the reduction in production in a wet year (300 mm or more) of that part of the self-sown vegetation which is edible to livestock.

Criteria associated with irreversibility of degradation

It has already been mentioned that in the long term, if the present intense human pressure is removed, the vegetation and soils of many of the ecosystems would be able to regenerate. Plant cover could re-form and trap the mobile sand and pedogenic processes could reconstitute the soil. Strictly speaking, there is no such thing as absolute desertification of an environment, since over a period of several centuries almost all systems are capable of achieving regeneration of their biological productivity. Having established the ecological progressions that are possible between ecosystems, we have therefore defined as 'currently desertified' areas occupied by degraded ecosystems in which a twenty-five year period of protection (the renewal time represented by one human generation) would be insufficient to produce regeneration.

Furthermore, a different approach must be adopted in studying areas that are desertified from the point of view of exclusively pastoral use as opposed to those that are desertified from the point of view of use based on cereal farming. Indeed, an ecosystem may well have lost all its pastoral potential but still retain some of its potential for cereal crops, since, even if the perennial vegetation is unable to re-establish itself, there may still be a sufficient depth of arable soil for the growth of certain crops.

On this basis therefore, we have classified as 'desertified for grazing purposes' areas containing degraded systems of the following types: SD_1, Gd_1, AZ_1, AA_1, RK_1 and AR_2 and which would not, after twenty-five years, have reverted respectively to at least SD_2, GD_2, AZ_2, AA_2, RK_2 or AR_3. The total area involved at the present time is of the order of 4600 ha of the 20000 ha in the study area.

We have, on the other hand, classified as 'desertified for the purpose of combined pastoral and cereal-farming use' areas containing ecosystems SD_1, GD_1, AZ_1 and AR_2 which, at the end of twenty-five years of protection, would not have reverted to at least SD_2, GD_2, AZ_2 and AR_3 respectively. This area at present covers 2200 ha.

The criteria that we have used as indicators of desertification are particularly valuable for evaluating the dynamics of physical processes. As already emphasized, the human aspects of the phenomenon of desertification are more difficult to study. Lacking the necessary data to quantify the degradation in way of life, in the following section we shall restrict ourselves to predicting the evolution of the various indicators of ecosystem desertification over a period of twenty-five years for various levels of human pressure on the environment.

Predictable evolution of the study area under the influence of four different levels of intensity of human pressure on the environment

Selection of systems and of levels of land-use intensity to be tested

In the Oglat Merteba zone, as indeed in all pre-Saharan areas, land use is mainly pastoral with a current tendency towards sedentarization and the development of cereal farming. Human and animal pressures tend to bear increasingly heavily on the environment as a result of increased stocking rates and the extension of cereal farming made possible by mechanization. Careful management, however, is capable of counteracting this trend.

In order to gain a better idea of the predictable evolution of degradation and desertification in the Oglat Merteba area as a basis for selecting management methods, we have decided to consider four different hypotheses concerning levels of intensity of human pressure, corresponding to land-use systems of varying intensity. The hypotheses selected are explained below.

Level 1: protection of the environment. This hypothesis implies total cessation in the short term of all forms of human and animal pressure. When this occurs, the various ecosystems gradually begin to evolve at varying rates according to their regenerative capacity. The abandoned agricultural land is gradually reconquered by the steppe to an extent determined by the prevailing ecological conditions. Steppe which is protected against grazing evolves in the direction of greater plant cover, enabling changes in environmental conditions to taken place (e.g. the fixation of mobile sand). This hypothesis is clearly not a realistic one from the economic point of view, and in any case protection does not necessarily guarantee a biological improvement of pastoral ecosystems. We have used this hypothesis, however, to provide comparison with other levels for the sake of better understanding. This hypothesis moreover may be of interest to the authorities responsible for nature conservation and protection.

Level 2: rational regional management. This hypothesis consists in achieving, if possible, rational use of rangelands from the point of view of the biology of the plant species. It implies adjusting the stocking rate to the actual consumable production of the pastoral species so as to halt degradation caused by overgrazing. Pastoral ecosystems that are already degraded should have stocking rates that will enable regeneration to take place. Agriculture would be restricted to suitable areas which benefit from direct run-off water as a result either of natural topographical conditions or of water management. The consequence of this hypothesis for the test zone would be a 50 per cent reduction in the cereal-farming area over a period of twenty-five years, which is not necessarily an economically viable solution.

This hypothesis of rational use of the 'plant and soil capital' could be brought about through rational management of the territory under consideration, by: creation of water points and irrigated fodder-crop reserves; providing employment and limiting rural depopulation; herd rotation; improved cereal-farming techniques; provision of subsidized forms of energy to the inhabitants. A system such as this does not necessarily ensure immediate yield from investments, but economists, in their calculations of profit and loss, rarely take into consideration such factors as 'biological recovery', the fight against desertification, the check in rural depopulation and the improvement of the people's way of life in their environment.

Level 3: continuation of present land-use system. The possibilities opened up by mechanization tend to accelerate the extension of agriculture and hence to promote clearing of more attractive cereal-farming areas. Current prices make cereal farming, despite its low yields, more immediately profitable per hectare for the present time than stock-raising, even though in the medium term it eats away into the 'land capital'. Furthermore, the constant decrease in the area of land used for grazing without any effort on the part of the stock-breeder to reduce the size of his herds results in permanent overgrazing in areas where the regeneration potential of the vegetation is low. The trend towards replacing wood by oil as a fuel for domestic purposes, moreover, is not well established.

Level 4: intensification of present practices. This hypothesis postulates a 50 per cent increase within twenty-five years in the total area given over to cereals. This relatively low increase has been postulated because of the difficulties already mentioned that are involved in the harvesting of large areas by hand, while it is difficult at present to visualize the introduction of mechanized harvesting where such low yields are concerned.

In view of the foreseeable increase in human pressure, this last hypothesis is the most likely unless the people start to become aware of its consequences and a special effort made on the part of the government for these impoverished regions. This hypothesis is also likely to be realized if investments are made to promote pastoral use (increasing the number of water points, for example) without the population accepting the principle of full pastoral management (limited stocking rates, rotational grazing, etc.).

The following analysis based on these four hypotheses has been made with the use of the 'succession matrices' technique (Godron and Lepart, 1973), which makes it possible to simulate by computation the progressive evolution of different ecosystems in the zone. Although theoretical, this analysis should give the manager a better idea of the maximum permissible level of land use intensity to avoid exceeding an acceptable rate of desertification.

The period of time used in the calculations covers the coming twenty-five years, analysed in successive five-year 'stages'.

Predictable degradation and regeneration

The most significant results concerning degradation and regeneration of ecosystems are shown in Figure 6.

Degraded rangelands with RK_1, AA_1, SD_1, GD_1, AZ_1 and AR_2 ecosystems (Fig. 6a) occupy at present almost half the area. The maximum degradation or regeneration possible, depending on levels of land-use intensity, is 50 per cent.

Degradation of the self-sown vegetation on deep soils (RK_2, RK_3, LK_3, AA_2 and AR_3) will be faster than on skeletal soils, which are less attractive for ploughing. Furthermore, regeneration of vegetation on deep, cultivated soils will be slow because ploughing has destroyed the plant 'capital'.

When one speaks of desertification, the first picture that comes to mind is that of the dune. Looking at Figure 6d one can see that the area of dunal sand (AR_2 and AR_3) (caused here mainly by wind-blown sand as a result of the introduction of agricultural activity) should increase only very slowly. The sand, in fact, tends to concentrate in certain spots and to increase progressively in height as it accumulates.

Evolution in total above-ground plant biomass (Fig. 6f) provides a measure of the degradation or regeneration of the vegetation. The present biomass has been evaluated at 14000 tonnes of dry matter, giving an average for the zone of 700 kg/ha. The levels of land-use intensity postulated would, in the space of twenty-five years, alter the amount of this biomass to values ranging from 500 kg/ha (Level 4) to 1100 kg/ha (Level 1).

Predictable progress of desertification

The ways in which the indicators of desertification are predicted to evolve in function of the four postulated levels of environmental exploitation are

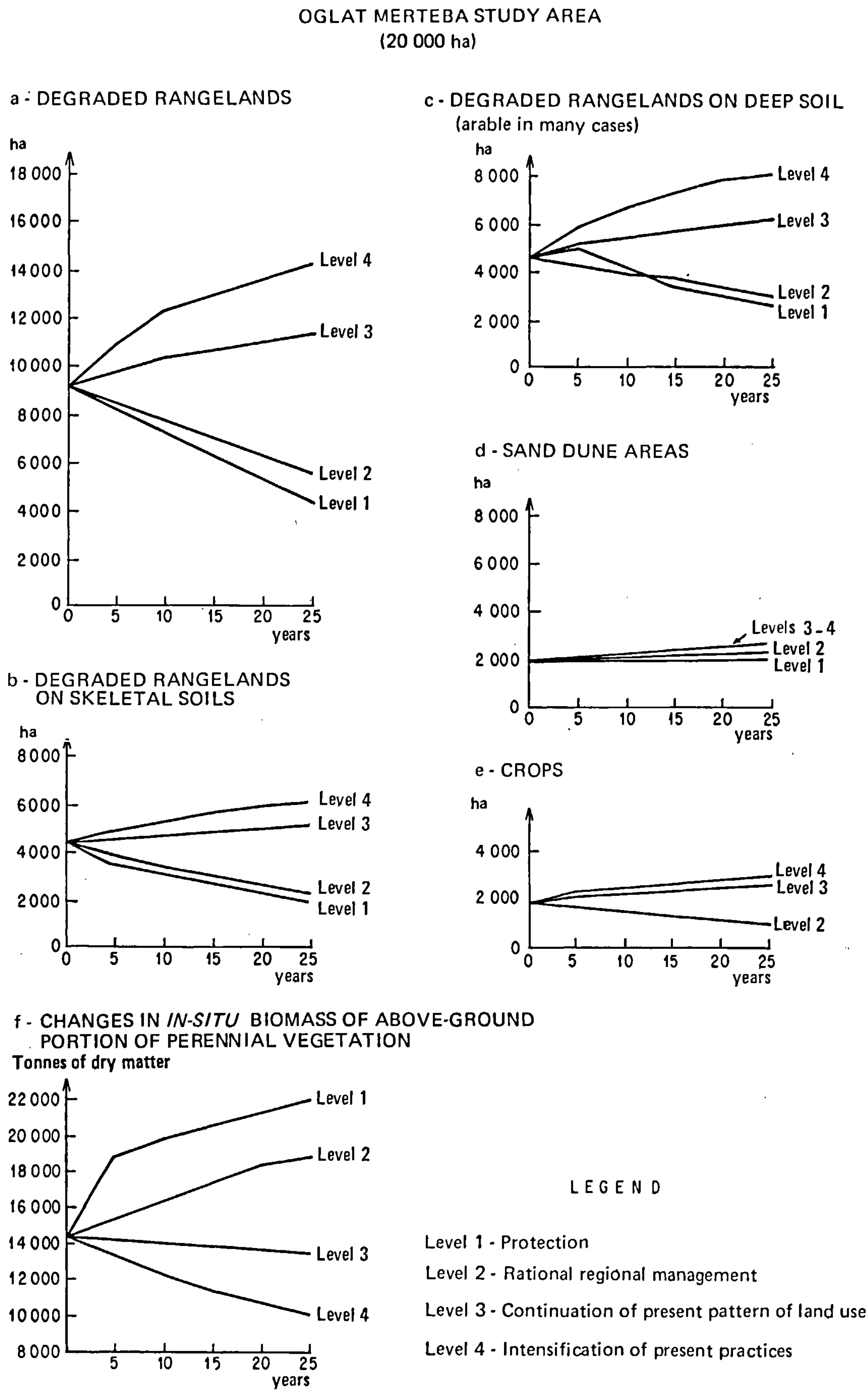


FIG. 6. Predictable degradation or regeneration rates resulting from four different levels of land-use intensity

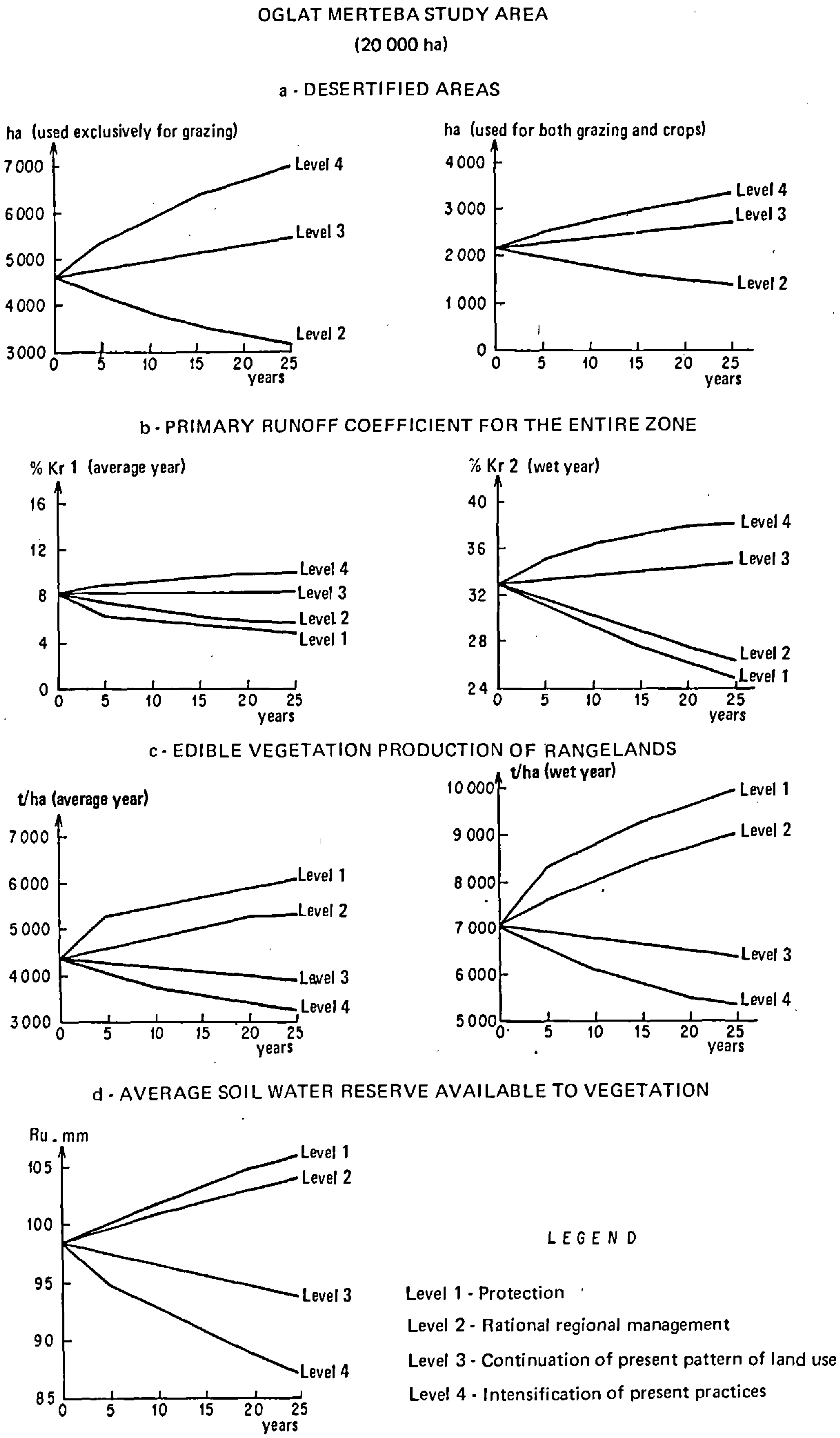


FIG. 7. Predictable changes in desertification indicators resulting from four different levels of land-use intensity

represented in Figure 7. Protection or regional management would lead to a reduction in desertification for all the indicators used, whereas the present system or an intensification of that system would help to accentuate the phenomenon.

Mean effective water supply (Fig. 7d)

Protective measures and management would lead to increases in the mean effective water supply of the order of 7·5 mm and 5·5 mm respectively. This represents average regeneration by trapping sand to a depth of respectively 8 cm and 6 cm in twenty-five years.

Continuation of the present system and intensification of present practices would lead, over twenty-five years, to a reduction of 5 and 11 mm respectively in the mean effective supply, corresponding to an average truncation of 5·5 and 12 cm respectively for sandy soils and 4 and 10 cm respectively for silty-sand soils. These are average values. Thus if erosion were localized to a single homogeneous area, one would have to consider areas of 1100 ha or 2400 ha respectively of sandy soil and 800 ha or 2000 ha of silty-sand soils in order to reach a total disappearance of the soil to a depth of 1 metre.

Mean primary run-off coefficients (Fig. 7b)

These coefficients are significant in a heavy-rainfall year (300 mm). In an average-rainfall year, only minor differences are observed between the various levels, although Levels 1 and 2 tend to limit the run-off coefficient for the entire region.

For 300 mm of rainfall in one year, the water lost through run-off throughout the entire zone at the end of the twenty-five-year period, with the exception of *wadi* beds and flood-out areas, would be:

$14{\cdot}0 \times 10^6$ m^3 for Level 1;
$14{\cdot}8 \times 10^6$ m^3 for Level 2;
$19{\cdot}0 \times 10^6$ m^3 for Level 3;
$21{\cdot}2 \times 10^6$ m^3 for Level 4.

It can be seen, then, that by continuing the present system or by accelerating present trends it is likely that the water loss at the end of twenty-five years would be $0{\cdot}5 \times 10^6$ or $2{\cdot}7 \times 10^6$ m^3, respectively, more than the present losses. This would be equivalent to the formation of 200 ha or 933 ha respectively of land in which infiltration is nil.

Rational management of the region could lead to a 22 per cent reduction in water wastage in comparison with the present state of affairs, i.e. approximately an additional 230 m^3 per ha.

Portion of the natural vegetation edible by livestock

In order to quantify the reduction in productivity associated with desertification, the evolution of the production of edible vegetation has been shown for an 'average' rainfall year (150 mm) and for a 'wet' year (300 mm). The results are expressed in tonnes of dry matter per hectare in Figure 7c.

The most significant variations in this production from the point of view of checking desertification are seen to occur in a 'wet' year. In Table 12 for example, it can be seen that if the present system is maintained for twenty-five years, both total production (roughly equivalent to edible production) and potential livestock-carrying capacity will drop by 11 per cent. This percentage rises to 26 per cent in the likely hypothesis of intensification of present practices, which will ultimately lead to desertification.

TABLE 12. Predicted values for pastoral production and potential livestock-carrying capacity at the end of twenty-five years (in the year 2000)

Level of land-use intensity	Variation in production of edible portion of vegetation (in kg dry matter/ha/yr)		Variation in potential carrying capacity (sheep)	
	'Average' year[1]	'Wet' year[2]	'Average' year[3]	'Wet' year[4]
Protected	+ 80	+ 150	+ 1508	+ 2820
Regional management	+ 50	+ 100	+ 942	+ 1885
Continuation of present system	− 25	− 40	− 471	− 754
Intensification of present practices	− 50	− 90	− 942	− 1697

1. At present 220 kg dry matter/ha/yr.
2. At present 350 kg dry matter/ha/yr.
3. Present potential carrying capacity: 4150 sheep.
4. Present carrying capacity: 6600 sheep.

Desertified areas

The evolution of desertified areas (defined as degraded ecosystems which would not have recovered part of their productivity after twenty-five years of protection) in terms of the four levels of land-use intensity has been considered for two different types of environmental use:

— exclusively pastoral use throughout the zone;
— pastoral use combined with agriculture for all the ecosystems that are desertified as far as grazing is concerned but still capable of cultivation.

The results are shown in Figure 7a.

It can be seen that for both types of environmental use, after twenty-five years there would be a 17 per cent increase in desertified area if present land-use practices were continued and a 49 per cent increase if these practices were intensified. These figures, as well as those given for the other factors of desertification and for the evolution of desertification, should be regarded as approximate levels intended solely to give a better idea of the intensity of these phenomena.

Synoptic map of desertification hazards (Fig. 8)

Vulnerability of ecosystems to desertification processes

Potential sensitivity[1] of vegetation and soils

The various types of vegetation and soil are not equally resistant to desertification, even under ident-

1. See footnote to Table 13.

ical conditions of use by man and livestock. It is therefore possible to classify these types of vegetation and soil according to their potential sensitivity to the influence of factors such as overgrazing or the introduction of agriculture (Table 13). This potential sensitivity depends on the following parameters:
— for vegetation: physiognomic type, botanical structure, biology of the species, present state of degradation of cover, speed of regeneration, etc.;
— for soil: depth, texture, geomorphic processes, slope, orientation, etc.

Human pressure on vegetation and soils

Man does not exert a uniform pressure on nature, either because he recognizes that different environments possess different degrees of productivity or because he is aware of the harmful consequences of certain practices. The same area, moreover, can be more or less attractive to man depending on the ease with which it can be used. This depends on:
— ease of bringing in machinery;
— proximity of water points and transit routes, which tends to encourage overgrazing;
— proximity of dwellings or of stabling for livestock.

Take, for example, the *Rhantherium suaveolens* steppe described in Table 13 (ecosystems RK_3, RK_2 and RK_1). These ecosystems, if subjected to overgrazing, possess a type of vegetation which readily re-forms its cover as long as the tufts are not actually torn up; for the purpose of grazing therefore, they are defined as being not very vulnerable to the degrading action of this factor. When agriculture is introduced, however, the total destruction of the vegetation leaves the steppe with very little chance of regaining its former state, even if ploughing is abandoned, which is why these ecosystems are considered to be sensitive to the introduction of agriculture. Grazing livestock reduce the plant cover and trample the ground, making the sandy soils very susceptible to aeolian erosion. The phenomenon is further accelerated by the introduction of agriculture. These soils have therefore been classified as sensitive to overgrazing and highly sensitive to the introduction of agriculture. What is more, these ecosystems are extremely attractive to man for both grazing and agriculture as they represent the best rangeland as well as the areas most favourable to the extension of cereal farming.

Categories of vulnerability

All the concepts discussed at the beginning of this section have been combined to produce a classification of ecosystems in accordance with their overall vulnerability to desertification.[1]

Hence, the susceptibility of an ecosystem to desertification results from a combination of the potential vulnerability of the vegetation and of the soils together with the attractiveness of the ecosystem. The scale of susceptibility contains five categories. At present, for instance, 38 per cent of the study area is regarded as being either highly susceptible (20 per cent) or of medium susceptibility (18 per cent) to desertification.

Principal desertification sectors

The areas on the chart have also been identified by a letter (C for cereal farming and S for overgrazing) showing the principal desertification factor. Areas with a population density estimated to exceed seven inhabitants/km^2 have been shaded on the chart and represent areas that are subject to relatively intense human pressure.

The principal desertification factor for the test zone is the introduction of agriculture, since 30 per cent of the area has been classified as either very highly vulnerable (19 per cent) or highly vulnerable (11 per cent) to this type of use.

Major changes in population density or in the way of life of the population are obviously likely to bring about considerable modifications in the attractiveness of ecosystems for the various possible types of use. Because of this, overall susceptibility may alter with the course of time.

Current degradation processes

Independently of 'potential' sensitivity to desertification, it is possible to add symbols indicating current dominant and subsidiary degradation processes, as was done on the FAO charts. The study area, by virtue of its relatively low population density in comparison with southern Tunisia as a whole, has not yet been totally affected by desertification, despite its fairly high degree of sensitivity. It is nevertheless true to say that degradation of the ecosystems is tending to become generalized. Symbols indicating degradation processes have therefore been included on the chart for each part of the study area. For the relevant part of the legend we have drawn freely on the categories used in the charts published by FAO, but the legend and further detail have been added so that it conforms better to the scale used (1:100000).

It should be emphasized that these current processes are not directly related to susceptibility. Ecosystem RK_3, for example, although considered highly sensitive to desertification factors, is at present subject to only slight deflation affecting its sand-sheet cover (process E in the legend). Some of the ecosystems (ZR_3 and PZ_3) are at present not subject to any degradation at all.

The processes dealt with are as follows (the process is shown by a capital letter on the map if it is a major one, and by a small letter if it is an associated process).

Regression of the natural plant cover (R, r). This process results from overgrazing and always appears first in the chronological sequence. It is considered to be present throughout the zone except on the barest steppes and in cultivated areas where the natural vegetation has been destroyed.

It can in fact be estimated that 100 years ago there was a lower population than at present, consisting principally of stock-breeders and nomads. Land clearing for agricultural purposes must have

1. The map (FAO) is based on a published study of the area (Floret and Le Floc'h, 1973).

TABLE 13. Sensitivity* to desertification factors of ecosystems degradation process currently taking place (Oglat Merteba Test Zone)

CURRENT DEGRADATION PROCESS	ECO-SYSTEMS SYMBOLS	BRIEF ECOLOGICAL DESCRIPTION	VULNERABILITY OF VEGETATION		VULNERABILITY OF SOILS		DEGREE OF ATTRACTION (to man)		SUSCEPTIBILITY CATEGORY (desertification hazards)
			to overgrazing & eradication	to cultivation	to overgrazing & eradication of vegetation	to cultivation	for grazing & gathering wood etc...	for cultivation	
E	RK 3	Non-degraded steppe on sandy soil	Slight	High	High	Very high	High	Very high	1 Very high susceptibility
R, e	RK 2	Slightly degraded steppe on sandy soil							
T, l	RK 1	Highly degraded steppe on truncated sandy soil							
T, l	rk	Agriculture on sandy soil	Slight	Slight	Very high	Very high	High	Very high	
N, r	AZ 1	Highly degraded steppe on gypseous soil	Very high	–	High	–	Very high	Nil	
E	LK 3	Non-degraded steppe on sandy soil with gypsum	Medium	High	High	Very High	High	Low	2 High
R, p/R, b	LZ 2	Slightly degraded steppe on gypseous soil							
N, r	GD 1	Highly degraded soil on calcareous crust	High	–	Medium	–	Very high	Nil	
R, n	AZ 2	Slightly degraded steppe on gypseous soil							
R, e	AA 2	Slightly degraded steppe on loamy soil	Very high	Very high	Fairly slight	Medium	Very high	Low	
D, r	AR 2	Medium dunes fixed by vegetation	Medium	Very high	Very high	Very high	Moderate	Very low	3 Medium
R, n	GD 2	Slightly degraded steppe on calcareous crust	Medium	–	Medium	–	High	Nil	
G, r	SD 1	Highly degraded montane vegetation							
D, c	ra	Agriculture on sand (Saharan)	Slight	Slight	High	High	Moderate	Moderate	
E	AR 3	Dunes fixed by vegetation	Medium	Very high	High	Very high	Moderate	Very low	4 Slight
E v	RA 3	Non-degraded steppe on sandy soil (Saharan)							
A, r or B, r	AA 1	Highly degraded steppe on loamy soil	Slight	Slight	Fairly slight	Fairly slight	Moderate	Moderate	
R, g	SD 2	Slightly degraded montane vegetation	Fairly slight	–	Fairly slight	–	Moderate	Nil	
A, p	aa	Agriculture on loamy soil	Slight	Slight	Slight	Slight	High	Very high	
E	zr	Floodplain agriculture							
Not applicable	ZR 3	Non-degraded floodplain vegetation	Slight	Slight	Slight	Slight	Very high	Low	5 Slight
Not applicable	PZ 3								

* The term «sensitivity» is used to convey a similar idea to that contained in the term «vulnerability», used in the FAO desertification charts.

Fig. 8. Synoptic map of desertification hazards, test zone of Oglat Merteba (Tunisia)

Legend

DEGREE OF SUSCEPTIBILITY OR DESERTIFICATION HAZARDS

very high	1
high	2
medium	3
fairly slight	4
slight	5

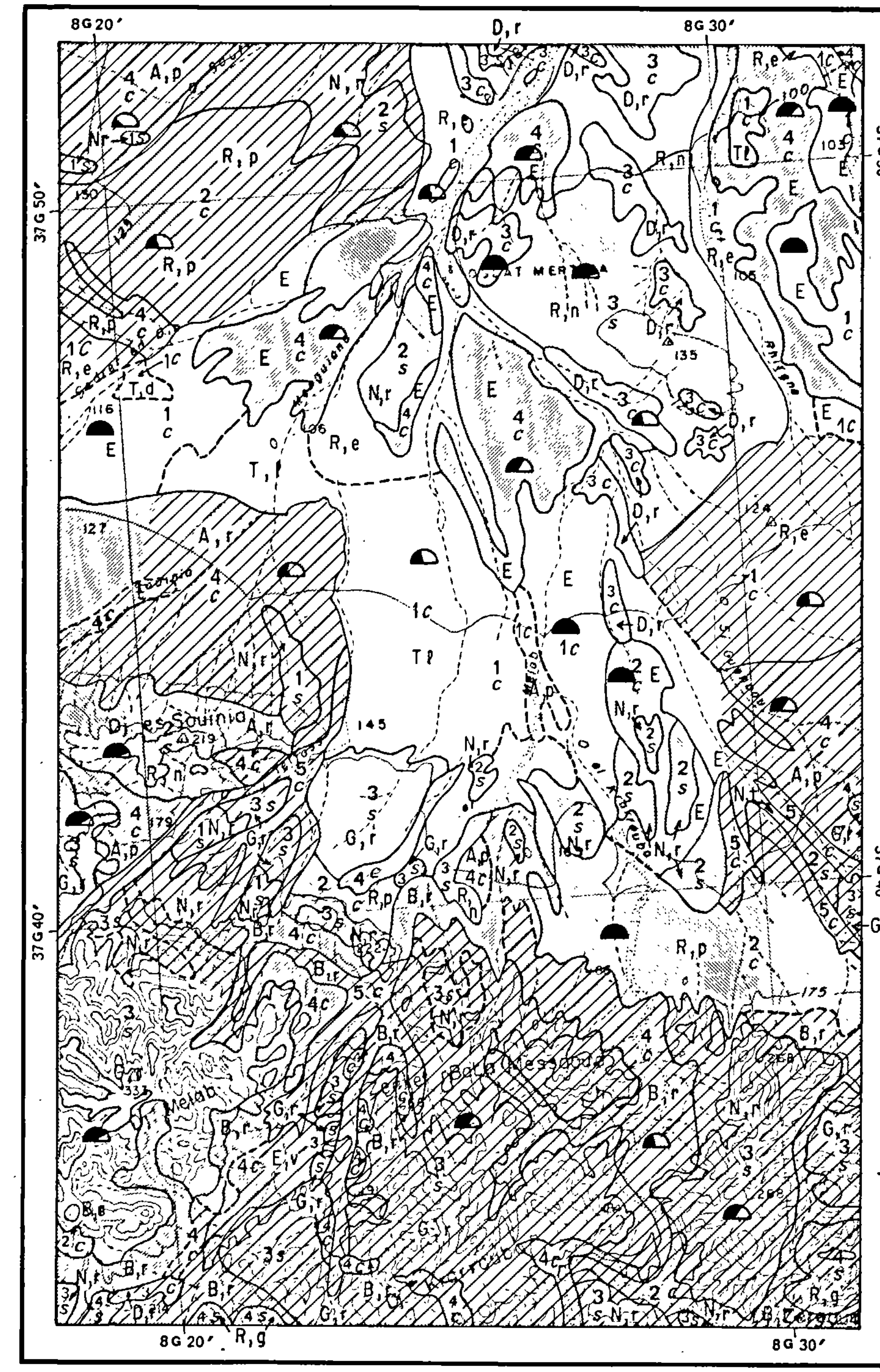
VULNERABILITY OF LAND TO DESERTIFICATION PROCESSES

The associated processes are shown in small letters.
Surfaces subject to:

Regression of the natural plant cover		R, r
Proportion of edible plant material presumed to be still existent on rangelands for some hundred years after degradation (black sector)		
Wind formations	shifting sand sheet	V, v
	shifting dunes	D, d
Deflation on sandy plains	slight	E, e
	high	T, t
Ablation of soils by deflation and water erosion	medium ablation	A, a
	high ablation	N, n
Sealing of soil surface	localized crust	L, l
	generalized crust	P, p
Water erosion	formation of bad-lands	B, b
	stripping of topsoil	G, g

HUMAN AND ANIMAL PRESSURE

Zone with fairly high population density	
Cultivation and eradication of woody species	C
Over-grazing and eradication of woody species	S



been localized mainly within the flood-out areas. Typical pastures of the main geomorphological units (mountains, glacis and sandy plains) may well have been similar to the best natural ranges now found in certain favoured spots within these same units.

Some of the major representative geomorphological units are therefore marked with a semi-circle to show the P1:P2 ratio, calculated on the basis of the data in Figure 2, where:

P1 = average edible plant production (black sector)
P2 = edible plant production in the present best rangeland (whole area of semi-circle).

In the Oglat Merteba study area, the values for this ratio range from 0·37, where the natural vegetation is most highly degraded, to 1 in areas which are still in good condition.

Aeolian formations. Mobile sand film (V, v): Sand accumulation in the form of a thin film affects few ecosystems and never appears to constitute a dominant process in the zone. In any case, sandy steppes where the sand film is relatively immobile and forms an integral part of the ecosystem are not regarded as being affected by this process.

Mobile dunes (D, d): Sand accumulation in the form of unstabilized dunes is at present little in evidence in the study area. It is worth mentioning however, that the unstabilized dunes already established are increasing in height.

Aeolian deflation (E, e): Slight deflation affecting the sand film. Because it reduces their cover in general, this process affects all ecosystems located on sandy soil.

Marked deflation with truncation of soil (T, t): The only ecosystems suffering from the effects of this process are those on the most degraded sandy soils (RK_1, rk).

Ablation of soils by deflation and water erosion (on foothills and glacis). Ablation leading to partial truncation of the soil (A, a): On footslopes with loamy soils this process affects ecosystems in which the self-sown vegetation is already highly degraded (AA_1, aa).

Ablation leading to denudation of crusts or of bedrock (N, n): Shallow soils overlying gypseous or calcareous crusts or pans are subjected, when the vegetation becomes sparse, to the combined and destructive action of wind and water erosion (ecosystems GD_2, GD_1, AZ_2, AZ_1).

'Glazing' of the soil surface. Formation of a localized rain-beat seal (L, l): This minor phenomenon at present affects sandy zones that have been deprived of their top horizons as a result of marked deflation. A small proportion of loam is sufficient to cause surface 'glazing' in these sandy zones and to hinder germination of annual plant species.

General extension of rain-beat seal (P, p): Rain-beat seal very quickly forms on loamy horizons and is therefore more or less general in ecosystems AA_2, AA_1 and aa, although it still does not constitute the dominant degradational process.

Water erosion. Badland formation (B, b): This phenomenon is present on the loamy parts of the majority of the footslopes, where the vegetation is already degraded and where there are no small-scale water management works to slow down the effect of sheet, rill and gully erosion (AA_1).

Denudation of the geological substratum (G, g): In the mountains, 'pockets' of soil lodged in crevices in the parent rock are fairly rapidly carried away, especially if there is no plant cover to protect them.

The various degradation processes currently taking place in the Oglat Merteba study area are listed in Table 13.

Lessons to be learned from the Oglat Merteba study

By virtue of its locality (annual rainfall of 150 mm), its diversity and its type of land use (10 per cent agriculture and 90 per cent grazing), the Oglat Merteba zone may be regarded as representative of the arid and pre-Saharan regions of Tunisia.

The areas that are at present 'desertified' constitute 10–20 per cent of the territory depending on the criterion selected. There is no doubt that this process is still continuing. Desertification is not extremely rapid, being likely to affect no more than 20–30 per cent of the territory (depending on the hypothesis selected) by the year 2000, provided that the pattern is not greatly modified before that date. Nor is it very spectacular (there are no vast dunes yet to be seen), but it takes the form of a continuous reduction in biological productivity.

Account must be taken, however, of the predictable increase in population (at present 2·3 per cent/yr in Tunisia), and of the fact that the people, who are becoming better and better informed, want to see an improvement in their standard of living. There will therefore be a tendency to demand greater production from the environment than at present. The immediate solution is simple: bringing new ground under cultivation raises the productivity of an ecosystem at first and enhances water penetration and storage. In the light of present prices therefore, it produces net profits that are often greater than those obtained from pastoral activity, until the time when soil erosion, frequently by denudation, destroys this productivity.

It can in fact be seen from the causes and processes described that extensive cereal farming in this region is the major desertification factor. It leaves the soil open to erosion and totally eliminates the perennial vegetation, which is unable to re-establish itself easily even in wet years.

There is obviously no question of asking the people to do without the cereal crops which occupy a very important place in their diet, but management should provide for the more rational location of agriculture. Since the ecosystems vary enormously in their regeneration capacity, the tendency should be to locate extensive cereal-farming activities in areas where the natural vegetation has already disappeared and is unlikely to be able to re-establish itself (loamy glacis), until such time as new techniques or new species may make it possible to reconstitute grazing land (annual or permanent). Cereal farming should be banned from fragile, sandy areas where the vegetation generally has good regeneration potential for grazing. Truly profitable cereal farming, in any case, can only be carried out in areas where run-off provides direct watering.

Since rangeland production varies according to the season of the year and from year to year, it is obviously necessary to provide supplementary feedstuffs for the livestock in order to make optimum use of the vegetation, which is their staple food, without degrading it. The nature and location of water points for livestock watering and for irrigation should be judiciously chosen in order to avoid overgrazing.

The practice of uprooting woody plants for firewood should be discouraged in favour of the use of some other fuel.

An optimum level of land-use intensity should be determined on the basis of ecological considerations, within the context of overall management of the area, in order to obtain the maximum from the region's resources without progressively reducing the soil and vegetation capital. The technical measures necessary for management of this kind often constitute a financial burden because, although it cannot be calculated in terms of financial profit, such measures include the conservation and regeneration of the physical and human environment. These management measures must be adapted to the customs of the local population who will have to receive a certain 'ecological education' and adequate assistance from technical specialists to enable them to apply these measures.

Management

Traditional land management and land use in arid and desert areas

The practices traditionally used by the population during the early part of this century made the best possible use of the natural resources and fought against the difficult conditions created by the aridity of the climate. The population of Tunisia's arid areas was scattered and mobile, living essentially from small-scale farming. There were three different systems of land use:

1. The oasis system (e.g. Gabès) based on the use of water from the ground-water reservoir (springs) for the cultivation of date palms together with forage crops and vegetables. The population was sedentary.
2. The extensive system (Medenine) based on extensive stock-breeding of sheep, goats and dromedaries. The population was nomadic.
3. The mixed system (e.g. El Hamma and Oglat Merteba) based on a combination of oasis crops and extensive stock-breeding. The population was semi-nomadic.

In operation, the characteristics of these systems were as follows:

1. Production destined for domestic consumption in the first system and for export (of meat) in the other two.
2. A kind of integration between the first two systems:
   - the oasis farmers and the pastoral stock-breeders of the steppe worked in association for the purposes of sheep-breeding and cereal farming. As far as sheep-breeding was concerned, the joint flocks used the natural ranges of the steppe and, in times of shortage, part of the stock was sent to the oases, where emergency rations were provided pending the return of normal conditions. In certain cases the pastoral stock-breeders of the steppe simply looked after the animals belonging to the oasis farmers in return for payment. As far as cereal farming was concerned, after the first rains the oasis farmer would plough and sow a given area put at his disposal by a colleague from the steppe. In other cases a true association was established between the two parties. The oasis farmer would contribute the means of traction (a mule) whereas the pastoral stock-breeder contributed the land and the labour;
   - the steppe provided considerable quantities of manure to the oases;
   - a large part of the forage produced in the oases was used for fattening the lambs born in the steppe.
3. In the mixed extensive systems, extensive stock-raising predominated. The predominance of stock-raising can be explained not only by the type of environment but also, and more important, by the practice of a self-sufficient economy. Sheep, for example, wc. ,red primarily for meat and wool and secondarily for milk and the products made from it. Goats were bred primarily for milk and secondarily for meat, and also for hair (for making tents and ropes). Lastly, the dromedary was bred for meat and as a draught animal (ploughing and transport). Herding patterns were determined by the climate rather than by the stock-breeder. The distances travelled and changes in herd size depended on the quantity of available food and water.
4. The land was only rarely cultivated for the production of cereals, olives and figs; this made it possible to use the land to meet the population's needs for vegetable products (corn, oil and fruit). In times of shortage in the arid areas, part of the active population would emigrate to the semi-arid areas of the north in search of barley and wheat.

In conclusion, the traditional method of land management and land use was characterized by:

- the practice of small-scale agriculture;
- the use of water on a small scale for cultivating crops;
- a kind of integration between the oases and the steppe, between different arid areas, and between arid and semi-arid areas;
- a way of life which tended to be semi-nomadic.

Socio-economic changes and present trends in land management

Socio-economic changes

Semi-arid regions have undergone numerous socio-economic changes during the past twenty years. The introduction of schooling for all children has resulted in a progressive reduction in nomadism, as well as having its direct effect on the intellectual level of the population. Once begun, this trend towards sedentarization was reinforced by the establishment of a large number of water points and by the setting up of dispensaries.

Socio-economic development in general, and improvements in means of communication and information in particular, have brought about the following consequences, in addition to a very distinct improvement in the population's standard of living:

- the creation of a new demand for foodstuffs, clothing and cultural satisfaction, making it necessary to seek new sources of income as well as to intensify the level of exploitation of the land resources;
- the development of emigration, a phenomenon that scarcely existed in these regions before the 1960s;
- the rural depopulation, prompted by a desire to find more dependable and better-paid work;
- the introduction and increasingly widespread use of the tractor for ploughing and of vans for carrying produce, in place of draught animals.

Finally, the growth in population has aggravated the imbalance between the needs of a constantly growing number of people and the production level of an environment that is in the process of becoming degraded.

Present land use trends and their consequences

The method of land management and land use has undergone profound modifications following these socio-economic changes:

- an irreversible trend towards sedentarization, leading to a greater number of small herds, overgrazing and excessive eradication of woody plants around dwellings and water points;
- uncontrolled expansion of cereal farming and arboriculture, usually at the expense of the best rangeland;
- the development of arboriculture, known as *jessour* arboriculture, using run-off water;
- general introduction of cereal farming in the flood-out areas (*segui*), without special management measures, and subsequent erosion;
- accelerated emigration and rural depopulation;
- reduction in the scale of stock-breeding among small farmers.

These trends can be explained in terms of socio-economic considerations;

- there is no doubt that, economically speaking, cereal farming and arboriculture represent stiff competition to stock-breeding. In fact, according to the results carried out recently in the Gafsa district by the Tunisian Ministry of Agriculture and the Agronomic University of Wageningen (Netherlands), stock-breeding accounts for 8 per cent, 28 per cent and 71 per cent, respectively, of the family income for small farms (7·7 ha and less than 10 head of livestock), medium-sized farms (22·1 ha and from 10 to 50 head of livestock) and large farms (25 ha and over 50 head of livestock). Furthermore, on land that is at present used for grazing but would be suitable for dry arboriculture, cereal farming would provide a gross profit of the order of 10–18 TD/ha as against 20 TD/ha for pistachios, 30 TD/ha for almonds and only 2–3 TD/ha for sheep-breeding. As far as employment is concerned, cereal farming and arboriculture create far more employment than stock-breeding (17, 19 or 42·5 d/ha/yr, depending on the size of the farm, as against only 1–2 d/ha/yr for stock-breeding);
- even in large farms with more than 50 head of sheep and goats, the agricultural family income per person is lower than the average income per person for the whole of Tunisia, and is less than the minimum essential family expenditure;
- the average wage available per working man comes to 447 TD in the towns and only 119 TD in the countryside. This is the fundamental reason for rural depopulation.

Thus stock-breeding on its own provides very little employment and a very low gross income, except perhaps when practised on a large scale. The active population makes up for this by cereal farming and arboriculture on the one hand, and by leaving the countryside and emigrating on the other, leading in time to desertification of the environment and to deterioration of the way of life.

Recommended types of land management

General considerations and management principles

1. The technical surveys carried out to date in the region confirm that arid regions require a pastoral type of land use in order to fight against progressive and often irreversible degradation of the environment.
2. Range management should respect the following principles:
   - measures for range improvement should be combined with measures for improving animal husbandry (diet and selective breeding) and improved health measures (essentially preventive);
   - the stocking rate for livestock should be in balance with range productivity;
   - the range should be managed in a way that allows the perennial vegetation to build up its reserves and the annual vegetation its stock of seeds; this should be achieved by introducing the system known as rotational grazing in place of continual grazing.
3. Range management is not an end in itself, but should be regarded as a means of improving ecosystem production while preserving and if possible increasing its production potential.
4. Any attempt to combat desertification is doomed to failure unless it is integrated in an overall programme of socio-economic development. The steppe-dweller must feel himself to be involved and must participate actively in the action being undertaken. Experience has shown that where he is merely an onlooker, such actions have failed.

5. Range management on its own is not viable, since one of the characteristics of rangeland production is its irregularity from one season to another and from one year to another. The provision of additional feedstuffs is essential in order to make up for shortages and stabilize herd size. This necessitates integrated co-operation within an arid region (e.g. integration of the oases and other irrigated areas with the steppe) and integration between arid and semi-arid regions (by the provision of concentrates for example).
6. The majority of the population in arid regions, as in the past, are still pastoral by inclination; range improvement based solely on the creation of irrigated areas, therefore, is bound to fail because of the lack of skill possessed by this population for irrigation farming. Furthermore, establishing a water point without rational management results in rapid degradation of the surrounding rangeland through overgrazing and uprooting of the woody plants.
7. Sedentarization is a socially irreversible phenomenon, but this does not rule out the possibility of transhumance. This practice, which is no more than a means of adapting to the climatic conditions of arid areas, should be included in proposed management schemes and should be controlled.
8. It is ineffective to forbid the uprooting of woody plants without providing an alternative source of fuel. The present alternative—oil—will soon be outdated because the present trend is towards the use of gas cookers. The uprooting of woody plants is diminishing of its own accord as the standard of living of the population rises. The construction of rural villages equipped with basic facilities (schools, dispensaries, drinking water, electricity, etc.), together with public-information campaigns, is encouraging the use of gas a a fuel in place of wood.
9. The spread of mechanization in arid regions is also an irreversible phenomenon. The unchecked spread of cereal farming and arboriculture cannot be arrested or even slowed down merely by legislation or by public information measures; the only way of solving the problem is to provide alternative solutions. In fact:
   - the income gained from extensive stockbreeding is becoming totally inadequate. An increase in cereal production is becoming a socio-economic necessity and, in this climate, only the sowing of large areas—made possible by mechanization—can solve the problem;
   - trees, particularly olive and fig trees, are practically the only plants that are perfectly suited to the climatic irregularities of the region. Even when the yield is low, there is less variation and no risk of loss of capital;
   - apart from the fact that climatic conditions—in the form of a succession of good years (1969–76)—have been favourable to the extension of mechanization, it is also a fact that this has proved the most profitable form of investment for the emigrants.
10. In general, extreme measures are not advisable in this type of region, where the human environment is as sensitive and as fragile as the physical environment.

Possible forms of action

In order to fight effectively against desertification, a land-management and land-use programme should have the following goals: a significant increase in the annual income of the families concerned; the creation of employment; improvement of the productivity of the environment by better use of water and soils.

The following actions should be undertaken in order to attain these goals:

1. Restoration, in an adapted form, of the integration between extensive steppic agriculture and intensive oasis agriculture. Oases possess very good fodder potential, especially in winter when there is a surplus of irrigation water. The steppe farmers could fulfil the role of breeders, while the oasis farmers would fatten the animals. The data available at present show that it is possible to double the weight of lambs raised for slaughter. This production scheme has proved its effectiveness (experimentally) during a period of shortage, since its provides relief both to the ewes, at a time when they are exhausted from suckling, and to the rangelands, which are generally degraded or in the process of becoming so. This system will be easier to put into practice if State or semi-official bodies or, better still, professional organizations are established. Organizations such as the Office de l'Elevage et des Pâturages (Office for Stockbreeding and Pasturelands) and the Union National des Agriculteurs (National Farmers' Union) could act as intermediaries between the breeders and the fatteners.
2. The introduction of measures for management and improvement of natural rangelands. Several different types of approach may be advocated. For rangelands under the control of the State (training and research establishments and agricultural combines) and for semi-official rangelands (managed by co-operatives), we would suggest a system of areas given over to improvements in grazing, fodder production and animal husbandry. The results obtained in the first trial areas are encouraging. For collectively owned rangelands, an 'intensive' type of management is very difficult to implement because of the complexity of the human and land-ownership aspects. It should be possible however to apply a modified version of the preceding scheme and to introduce management measures of a 'diffuse' kind rather than concentrating the effort on specific points. Here again, the first priority is to bring the least degraded rangelands under management. The areas to be managed will undergo the following procedures:
   - reduction of overgrazing, for example by encouraging an increase in herd productivity. Productivity should be related to the herd itself (kg of meat/female unit/yr) rather than to land area (kg of meat/ha of rangeland/yr). The introduction of a productivity bonus would lead to a reduction in stocking rates on the

rangelands since it is impossible for a breeder to exceed a certain level of productivity for a given area of grazing land without reducing herd size;
— incentives to convert fallow cereal land back to grazing land by introducing a bonus for meat production and by supplying cereals at favourable prices;
— limiting the further extension of cereal farming and arboriculture by the introduction of a meat-production bonus;
— encouraging the planting of fodder crops (*Atriplex* and *Opuntia*) that are suited to arid-zone conditions;
— improvement of the genetic potential of the herds by introducing tested sires;
— improvement of health conditions by preventive-medicine campaigns.

3. The fodder potential, particularly of by-products, should be fully utilized. Stock-breeders should be encouraged to use the estimated annual production of 35000 tonnes of date trimmings and the common dates which are decreasingly being used for human consumption as supplementary feed. From the nutritional point of view, dates are poor in nitrates (4 per cent of total dry weight) but very rich in energizing substances (283 calories in 100 g of dates); they are also rich in vitamin C, calcium and iron. There are also the olive leaves remaining on the cut wood and olive-oil cakes. It has been calculated that if the leaves produced from the pruning of the olive trees in central and southern Tunisia were used as feed for sheep and goats, rather than as fuel, they would provide more than 14 million FU—enough to meet the energy requirements for the upkeep of over 400000 head of sheep and goats. Olive-oil cake can profitably be used to make up from 10 to 30 per cent of an emergency ration for sheep, goats and camels. This by-product has good energy value (0·5–0·7 FU/kg of dry matter), but, like the olive leaves, is poor in nitrates.
4. Extensive measures should be taken for soil and water conservation. These measures are designed not only to combat erosion caused by water but also to create employment and increase annual income. Additionally, they will make it possible to recover large quantities of water (run-off water) that can be used in areas under intensive irrigation for food and fodder crops.
5. The construction of 'green wind-breaks' consisting of a solid line of trees in order to arrest 'the advance of the desert' should not be adopted as a solution. The fact is that desertification is a diffuse process, although not a generalized one. It makes its appearance wherever the equilibrium between the environment (soil and water) and the way in which it is used by man is disturbed. In any event, the protection provided by a green wind-break of this sort, even when its construction is technically and economically feasible, extends—as with all wind-breaks—only for a limited distance, which is in proportion to its height (approximately ten times the height of the trees). Localized afforestation, on the other hand, whenever environmental conditions are favourable to the growth and development of trees, can only be beneficial. It creates employment and improves the income of the population, protects soils against erosion, provides timber and produces better overall biological productivity by more thorough recycling of minerals and organic matter.
6. A mass-information programme should be set up to make the people aware of the problems:
   — information on plant and animal ecology should be incorporated in educational and cultural programmes;
   — programmes for increasing popular awareness should be intensified within the framework of activities carried out by the various committees, organizations and associations concerned with the problem of desertification.

Conclusions and recommendations

It must be emphasized that the main task in halting a progressive desertification of the environment is to define the socio-economic development policy to be advocated for arid regions.

There are two possible alternatives:
— Taking the short-term view, this policy could be based on technical and economic criteria, in which case it must be remembered that studies show that the majority of good-quality ranges are situated in areas that tend to be suitable for cultivation (forestry and cereal crops). In the long term those soils and their vegetation would become degraded at an increasing rate, and the environment would become sterile and therefore unable to support life, resulting in almost total rural depopulation. In other words, the present trend would have to be accepted.
— An alternative policy could be based on socio-economic criteria, which would mean slowing down and if possible arresting rural depopulation; increasing meat production where the locality lends itself to this (meat being a scarce commodity subject to continual price increases); protecting that part of the national heritage represented by water resources, soils and vegetation; and maintaining, or if possible improving, the production potential of that heritage.

The necessary investment will be heavy and will yield little or no return in the short term. In order to obviate this financial difficulty, it could be suggested that part of the underground resources (oil, phosphates and various ores) might be used to make a contribution towards development and improvement of the production potential of the surface resources. Integration of underground and surface resources in this way would be all the more rational in that the present productivity of areas undergoing degradation is low. A considerable effort therefore still remains to be made in order to increase the level of productivity in those areas and thus make the proposed production units economically viable.

The required effort is justified by the following considerations:
— underground resources are limited;
— the biological resources of the land are renew-

able and can offer considerable potential as long as the techniques used to tap them are based on the appropriate results of suitable scientific research.

In connection with this second alternative, the following recommendations, most of which are set out in the reports of the *Desertization Days* organized at Gabès in 1972 by the Ministry of Agriculture of the Tunisian Government, are proposed:

1. Provision of fuel to the population in order to put an end to the destruction of the vegetation. It is essential to convert all wood-burning industrial ovens (bakeries, hammams, lime kilns, etc.) progressively to oil. Even though the use of gas and oil fuels is tending to become more generalized in the towns and villages, the same is not true in the case of scattered and rural populations, which continue to use the vegetation as a fuel. It is recommended that, where this is the case, the use of suitably adapted oil stoves and gas cookers of the 'camping' variety be publicized and encouraged. Alternative forms of energy such as solar and wind energy should also be considered.
2. Trees should be planted around water points, oases and villages, alongside thoroughfares, and in other areas where conditions will allow them to grow and flourish. In addition to providing protection, tree plantations go some way towards meeting the population's fuel needs.
3. As far as extension of dry cereal farming and forestry are concerned, it is recommended that:
   - Ploughing be discouraged in pastoral areas, and implements which break up and crumble the soil be banned.
   - Farming be encouraged in flood-out areas and along the stream courses after suitable modifications have been made (e.g. embankments, weirs, etc.).
   - The conversion to rangeland of fallow cereal land be encouraged wherever the soil and vegetation have not yet reached a technically irreversible degree of degradation. A possible solution might be to introduce a preferential price policy for the benefit of farmers who agree to carry out such conversion, covering the purchase of corn for human consumption and the sale of lambs and kids.
4. There is a need to create employment and raise the level of income for the rural population in order to reduce the intensity of exploitation of the environment. This goal can be achieved by setting up an agro-pastoral programme and establishing industries compatible with the type of area concerned.
5. Genuinely effective rangeland-protection programmes could be put into effect by carrying out integrated management of areas of the largest possible size.
6. The utilization of water resources requires rational planning, with priority given to fodder production.
7. A mass-education programme should be set up, both in the schools and universities and among the peasant population, to support measures to combat desertification.
8. Specialist training might be provided locally for key staff called upon to work in arid regions.
9. Intensified research is needed in order to gain a better knowledge of the potential of each environmental area and the extent of rational exploitation possible:
   - evaluation of water and soil potential (covering both surface water and deep ground water) and studies of ways and means of exploiting them;
   - evaluation of the genetic potential of vegetable and animal biotypes, and of the possibilities of improving that potential and of introducing adapted, productive biotypes;
   - evaluation of fodder potential, including agricultural by-products, and study of the ways of using them;
   - efforts to find new energy sources, such as solar and wind energy;
   - socio-economic studies which could be used to determine the extent to which socio-economic development aims can be made to coincide with the objective of protecting and conserving renewable natural resources.

Bibliography

CENTRE DE RECHERCHES DU GÉNIE RURAL (CRGR). 1972. *Amélioration des techniques d'irrigation et de drainage. Irrigation des cultures annuelles:* no. 5, *L'orge*; no. 7, *Le sorgho fourrage*; no. 9, *La luzerne*. Tunis, Centre de Recherches du Génie Rural. (Projet PNUD/FAO/TUN/70.)

CENTRE NATIONAL D'ÉTUDES AGRICOLES (CNEA). 1975. *Analyse technique sociologique et institutionelle dans le cadre de l'élaboration et de l'exécution d'un modèle de développement pastoral dans le sud tunisien: le cas d'El Hamma et de Gabès*. Tunis, Centre National d'Etudes Agricoles. 27 p. (Rapport général.)

COMBREMONT, R. 1973. *Note sur l'utilisation de l'eau pour la production de fourrage en Tunisie centrale*. Tunis, Centre de Recherches du Génie Rural. (Projet PNUD/FAO/TUN/70/529.)

COMMISSARIAT RÉGIONAL AU DÉVELOPPEMENT AGRICOLE (CRDA). 1973. *Projet des actions intégrées dans le cadre de la lutte contre la désertisation. Oglat Merteba*. Gabès, Commissariat Régional au Développement Agricole.

DESPOIS, J. 1961. Development of land use in Northern Africa (with reference to Spain). In: *History of land use in arid regions*, p. 219–37. Paris, Unesco. (Arid Zone Research 17.)

FLOHN, H. n.d. *Étude des conditions climatiques de l'avance du désert*. Tunis, Office de la Météorologie Nationale. (Rapport á l'OMM.)

——; KETATA, M. 1971. *Investigations on the climatic conditions of the advancement of the Tunisian Sahara*. Geneva, WMO. 32 p. (Technical Note 116.)

FLORET, C.; LE FLOC'H, E. 1973. *Production, sensibilité et évo-*

lution de la végétation et du milieu en Tunisie présaharienne. Conséquences pour la planification de l'aménagement régional de la zone-test d'Oglat Merteba. Montpellier, Institut National de la Recherche Agronomique de Tunisie (INRAT); Centre d'Etudes Phytosociologiques et Ecologiques Louis Emberger (CEPE). 45 p. + maps. (CEPE Doc. 71.)

——; ——; PONTANIER, R.; ROMANE, F. 1975. *Elaboration d'un modèle écologique régional en vue de la planification des parcours des régions arides. Réunion régionale sur les pâturages des zones arides et semi-arides du Nord de l'Afrique. Tunisie, 3–12 avril 1975.* Tunis, Institut National de la Recherche Agronomique de Tunisie (INRAT). 41 p. (mimeo) (English abstract, 14 p.)

——; ——; ——; ——. 1978. *Modèle écologique régional en vue de la planification et de l'aménagement agro-pastoral des régions arides. Application à la région de Zougrata.* Medinine, Institut des Régions Arides; Centre d'Etudes Phytosociologiques et Ecologiques Louis Emberger (CEPE). 74 p. + map.

GODRON, M.; DAGET, D.; LONG, G.; SAUVAGE, C.; EMBERGER, L.; LE FLOC'H, E.; POISSONNET, J.; WACQUANT, J. P. 1968. *Code pour le relevé méthodique de la végétation et du milieu. Principes et transcription sur cartes perforées.* Paris. CNRS. 291 p.

——; LEPART, J. 1973. Sur la représentation de la dynamique de la végétation au moyen de matrices de succession. *16ème Symp Ass. Int. Phytosociol.*, Rinteln über Weiser. 9 p.

——; POISSONNET, J. 1972. Quatre thèmes complémentaires pour la cartographie de la végétation et du milieu. (Séquence de végétation, diversité du paysage, vitesse de cicatrisation, sensibilité de la végétation). *Bull. Soc. Languedoc. de Géog.*, t. 6, fasc. 3, p. 329–56.

HADJEJ, M. S. 1969. *Méthode de sélection appliquée à la race barbarine en Tunisie.* (Doc. FAO/TUNISIE/16/6.) (Mimeo.)

——; 1971. *Résultats préliminaires et problèmes posés par le testage des béliers sur descendance chez la race barbarine de Tunisie.* Institut National de la Recherche Agronomique de Tunisie (INRAT). (Mimeo.)

——. 1974. *Principaux acquis dans l'amélioration de l'élevage ovin en Tunisie.* Institut National de la Recherche Agronomique de Tunisie (INRAT). 16 p. (Mimeo.)

IONESCO, T. 1972. *L'amélioration pastorale et fourragère en Tunisie. Problème technique, humain, politique et legislatif.* Institut National de la Recherche Agronomique de Tunisie (INRAT). (Projet PNUD/TUNISIE/69/001.)

——. 1975. Suggestions pour une stratégie de développement des zones pastorales arides et désertiques du Nord de l'Afrique. *Options Méditerr.*, no. 28, p. 82–8.

——; CABEE, M. 1972. *Démonstration d'aménagement des pâturages dans la région de Sbeitla.* Consultation auprès du Projet FAO/TUN/71/525.

——; HADJEJ, M. S.; FAROUA, H.; FLORET, C.; LE FLOC'H, E. 1976. *Améliorations pastorales à Oglat Merteba. Périmètre d'Ouled Cherib el Grea et Périmètre d'Ouled Khalifa.* Projet PNUD/TUNISIE/69/001. (Etude Technique 10.)

LE FLOC'H E. 1973. Etude de parcours du Sud Tunisien I: carte phyto-écologique d'Oglat Merteba et Mareth (1/100 000). *Ann. Inst. Nat. Rech. Agron. Tunisie*, vol. 46, fasc. 5. 92 p. + maps.

——. 1974. *Notice de la carte phyto-écologique et des ressources pastorales du Périmètre d'Oglat Merteba.* Projet PNUD/TUNISIE/69/001. 24 p. + map (1/25 000).

LE HOUÉROU, H. N. 1959. *Recherches écologiques et floristiques sur la végétation de la Tunisie méridionale.* Alger, Université d'Alger, Institut de Recherches Sahariennes. 510 p. + maps. (Rapport spécial.)

——. 1969*a*. *Principes, méthodes et techniques d'amélioration fourragère et pastorale en Tunisie.* Rome, FAO. 261 p.

——. 1969*b*. La végétation de la Tunisie steppique (avec référence au Maroc, à l'Algérie et à la Libye). *Ann. Inst. Nat. Rech. Agron. Tunisie*, vol. 42, fasc. 5 et 6.

——. 1973*a*. *Contribution à une bibliographie des phenomènes de désertisation, de l'écologie végétale, des pâturages et du nomadisme dans les régions arides de l'Afrique et de l'Asie du Sud-Ouest.* Rome, FAO.

——. 1973*b*. Peut-on lutter contre la désertisation? *Symp. Int. Désertis. Nouakchott.* 15 p. (Mimeo.)

LONG, G. 1954. Contribution à l'étude de la végétation de la Tunisie centrale. *Ann. Serv. Bot. et Agron. Tunisie*, vol. 27, p. 1–388.

——. 1975. Pour une stratégie de la recherche, dans le cadre du Projet 3 du MAB, appliquée aux zones arides au nord du Sahara. *Options Méditerr.*, no. 26, p. 39–50.

MONCHICOURT, C. 1906. La steppe tunisienne chez les Fraichiches et les Madjeurs. *Bull. Dir. Agr. Comm. et Col.*, p. 36–76, 159–69.

PONTANIER, R.; ZANTE, P. 1976. *Étude pédologique de la zone d'Oglat Merteba.* Tunis, Ministère de l'Agriculture, Direction Ressources Eaux et Sol; ORSTOM, no. 507. 60 p. + maps.

RAPP, A. 1974. *A review of desertization in Africa: water, vegetation and man.* Stockholm, Secretariat for International Ecology (SIES). 77 p. (SIES Report 1.)

SCHWAAR, D. 1965. *L'évolution du milieu entre 1949 et 1963 dans une région test de la Tunisie centrale. Étude détaillée réalisée par photo-interpretation.* Rome, FAO. 11 p. (FAO/PNUD/TUN/9.)

SHERBROOKE, W. C.; PAYLORE, P. 1973. *World desertification: cause and effect. A literature review and annotated bibliography.* Tuscon, University of Arizona. 168 p. (Resource Information paper 3.)

SKOURI, M. 1969. Amélioration de l'élevage dans le sud tunisien. *Séminaire de Gabès sur l'élevage.*

ZANTE, P. 1975. *Projet d'aménagement pastoral d'Oglat Merteba. Création de périmètres irrigués à réserves fourragères.* Tunis, Ministère de l'Agriculture, Direction Ressources Eaux et Sol; ORSTOM, no. 499. 28 p. + map.

2 Desertification in the region of Coquimbo, Chile

Case study presented by the Government of Chile

Acknowledgements

Unesco would like to express its thanks to the Instituto de Investigaciones Agropecuarias (INIA) of Chile, which was responsible for the preparation of the case study, and to the scientists who collaborated in writing the text: S. Bonilla E., INIA; E. Hajek G., Laboratorio de Ecología, Instituto de Ciencias Biológicas, Universidad Católica de Chile; M. Peralta P., Facultad de Ciencias Forestales, Universidad de Chile; J. Gasto C., Facultad de Agronomía, Universidad de Chile; D. Contreras T., Facultad de Agronomía, Universidad de Chile; J. Rottmann S., Departamento de Conservación del Medio Ambiente, Corporación Nacional Forestal; N. Bahamondes N., Museo Nacional de Historia Natural; R. Hernández A., Departamento de Ciencias Antropológicas y Arqueológicas, Facultad de Ciencias Humanas, Universidad de Chile; W. Mundaca E., S. Marín A., A. Pinto M., Universidad Técnica del Estado; and X. Baeza A., INIA.

Assistance was also provided by UNDP, FAO, WMO and the Inter-American Bank of Development.

Introduction and general description

This case study on desertification had to be carried out in a short period (end of June to September 1976). It is a multidisciplinary study, with contributions from distinguished Chilean specialists who were already familiar with the region and who had expressed concern regarding the problems of this part of the country. A broad individual knowledge was the starting-point for the preparation of this monograph, to which was added data obtained after a brief period of intensive interdisciplinary work in the field.

Several reasons justify the choice of the district analysed:

— the district is representative of a large transitional region between the hyper-arid desert of the north and the productive irrigated valleys and plains of the middle part of the country;

— comparative studies, made at different periods, on the natural resources and arable lands of the region of Coquimbo, as well as on the rural population, point to a great breakdown in productivity of the ecosystems, particularly during the last two centuries;

— since the beginning of Spanish colonization, much of this region has been subject to a type of land-ownership, as well as to communitarian social structures, unique in Chile;

— except for a short period when exportation was the main goal, the agricultural and livestock-breeding activities have been largely influenced by mining activities in the region. The pressure exerted by man on the natural resources has paralleled the increase in mining activities;

— developmental programmes of agriculture and livestock-breeding have been conceived to yield profit on a short-term basis, and no attention has been given to measures tending to preserve natural resources. The programmes have also been of short duration and have not lived up to the expectations of the rural population;

— all these factors, and others beyond the scope of the present study, have brought about a critical situation for the local population, whose survival is threatened. The region was recently declared a 'zone of extreme poverty' by the Chilean Government.

As a result of the limited time in which the work was done, it has been necessary to generalize various concepts. However, the present work can be used as a reference for other more detailed studies, or as a guide for stopping various actions and eventually reversing the destructive processes.

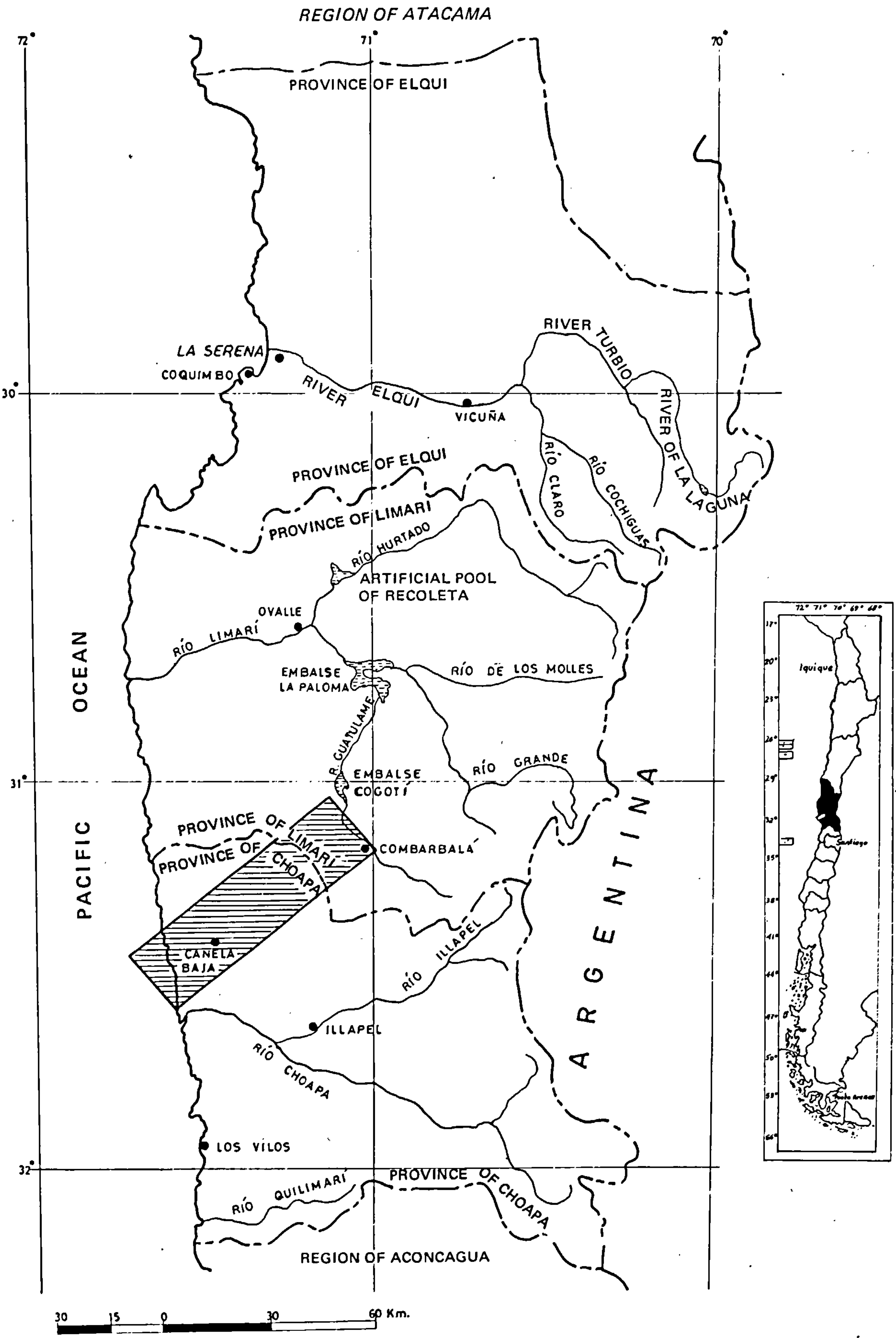


FIG. 1. Region of Coquimbo

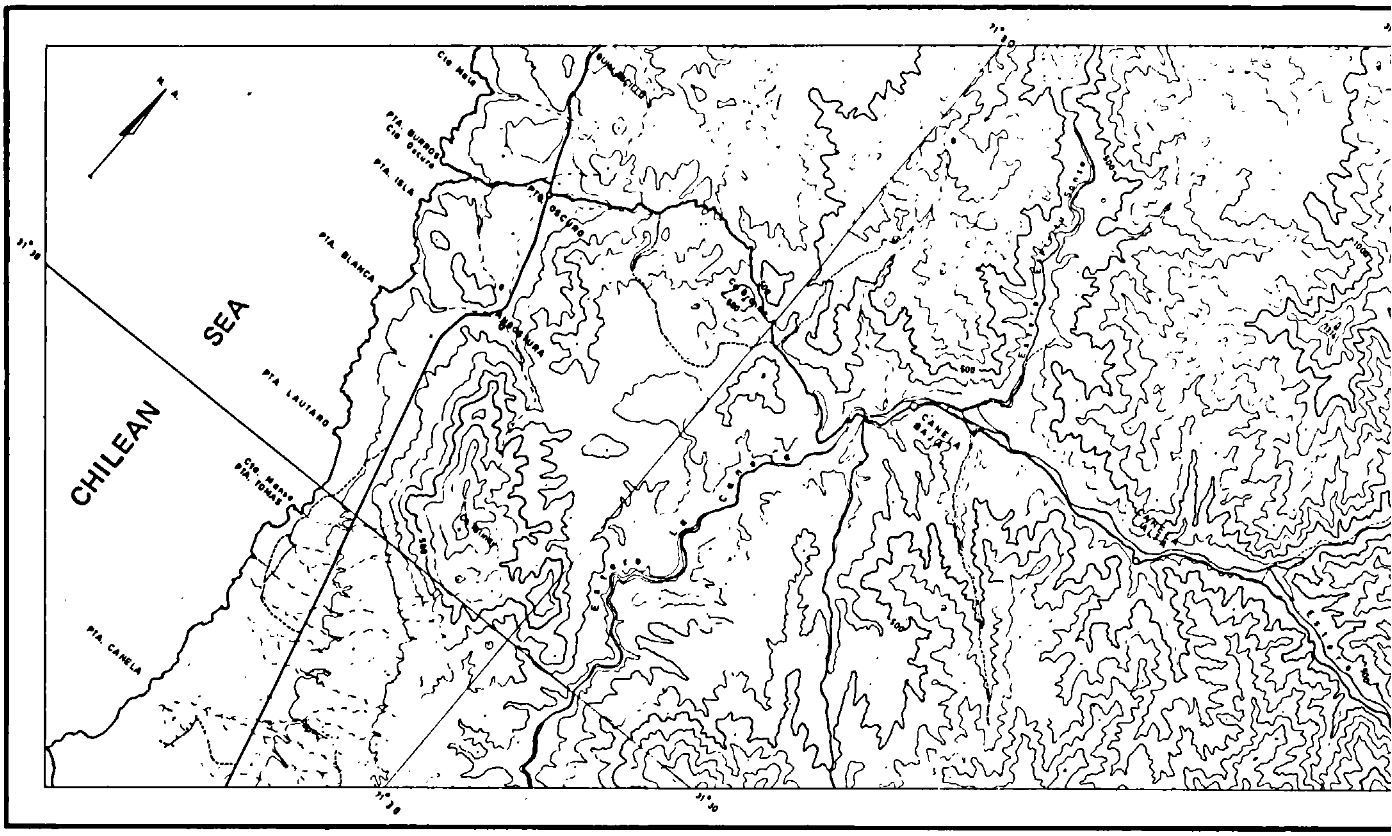


FIG. 2. District of Combarbalá

The study area is situated in the region of Coquimbo, 31°–32° S. It forms a rectangle 72·5 km long and 20 km wide, oriented SW–NE from the Pacific Ocean to the Cordillera de los Andes (Fig. 1).

The climate is predominantly of the arid-mediterranean type, with rains in the winter and drought during the warmer months. This mediterranean climate is controlled by the south-east Pacific anticyclone and by the cold Humboldt current.

The topography consists of many rugged ranges (Fig. 2). Many deep ravines cross the district in a north–south direction and drain a small amount of water into a few creeks and rivers during the rainy period. There are small areas of gentle slopes in the littoral terraces and in intermont valleys, and there are smooth hill ranges in the plains.

The majority of soils are derived from granitic, volcanic and sedimentary parent materials. They are predominately light-textured and have lost large quantities of organic matter as well as their surface structure, vegetation cover and fertility. They are now left exposed to the direct action of rain and the subsequent loss of topsoil. Erosion is evident throughout the entire district and is particularly accentuated near the places where man has settled.

The vegetation has deteriorated completely, so that in many landscape units no traces of the climax state remain. The changes have led to reduced productivity and reduced development of human activities.

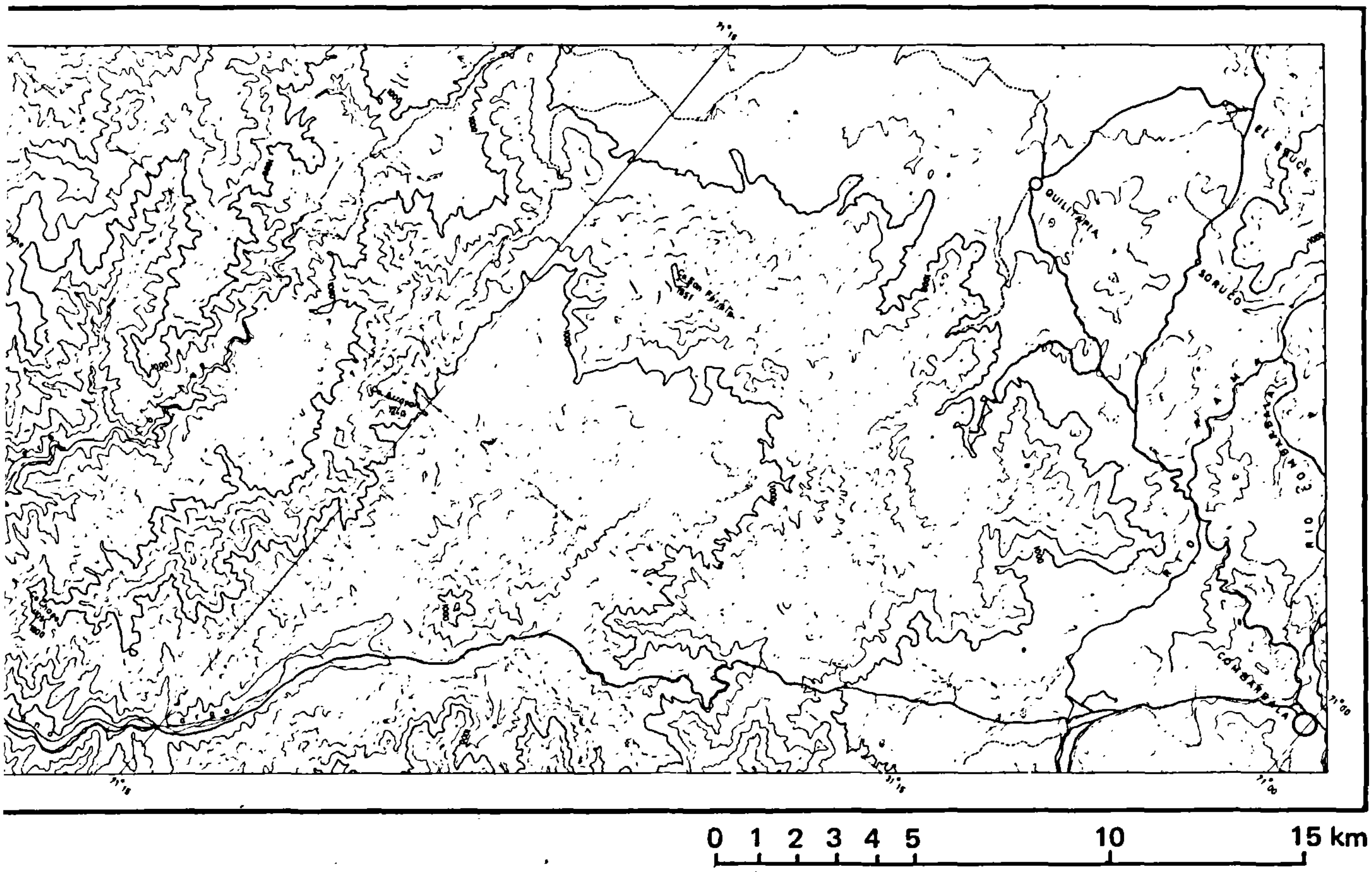
The population of the district has undergone fluctuations which correspond roughly with the droughts. It has a growth rate which is lower than average for Chile due to the continuous emigration of the active population. This phenomenon has created a distortion in the population distribution by sex and age, with accompanying effects on family structure as well as on production in the zone.

A major part of the arable land has been subjected to the traditional system of land-ownership and to the community social structures called agricultural communities. These have had their effect on the degree of degradation of natural resources and on the deterioration of living conditions of the rural population.

Detailed description of the district under study

Regional climate

Any study of the climate must take into account the neighbouring regions and establish the relationship with the general climate of the whole area. It is therefore necessary to make frequent references to the regional climate. On the other hand, the limited number of meteorological stations in the district makes it necessary to use readings from nearby stations.



The area is characterized by a subtropical belt of high pressures, forming the south-eastern anticyclone of the Pacific Ocean. The resulting mediterranean climates are dominated by the anticyclonic condition as well as by cold ocean currents. These areas of high pressure inhibit the passage of fronts over the areas, and enhance the vertical stability of the air. In summer they occupy zones far from the Equator (35°–31° S.) according to Miller *et al.* (1977) and Schneider (1969), and frontal activity is shifted poleward; in winter the nuclei of high pressure move towards the Equator (25°–28°, op. cit.) and the fronts pass nearer the Equator and cross the mediterranean regions. The winter fronts are the main sources of precipitation. Increased precipitation inland is also due to orographic uplift of the air as it moves over the foothills and mountains. Atmospheric stability decreases the frequency of convective rains and contributes to an inversion caused by the penetration of colder marine air beneath a layer of warmer air. In Chile, at least in this district, the inversion layer can be from 400 to 700 m thick (Miller *et al.*, 1977) and can even extend up to 1000 m (Antonioletti *et al.*, 1972).

Regional bioclimatology

The region under study is situated in a latitudinal zone tending to have a mediterranean-type climate, characterized by precipitation during the cold months and drought during the warm months. Aschmann (1973) defines a mediterranean climate as one having one month with a mean temperature below 15°C, and not having air temperatures lower than 0°C in more than 3 per cent of the whole year. As for precipitation, at least 65 per cent of the total should fall during the six winter months (May–October).

Using various bioclimatic criteria, several climatic regions have been identified in Chile (di Castri and Hajek, 1961, 1976; di Castri, 1968). Di Castri's map (1968) divides the country into fifteen regions, embracing tropical, desertic, mediterranean, oceanic and continental traits. For the region of mediterranean climate six subdivisions have been distinguished, following Emberger (1955): perarid, arid, semi-arid, subhumid, humid and perhumid. Some comparative studies have also been made on specific Chilean bioclimatic regions (Nazar, 1969; di Castri, 1973) relating them to bioclimates in other parts of the world (Nazar *et al.*, 1966).

The regions of mediterranean-type climate in Chile occur between 25° and about 39°S, with an extension to about 42°S in the east.

The district under study is included in the arid mediterranean zone. In Figure 3, the relation of the climate of this district to other Chilean bioclimates is shown. This zone has been defined as having a dry period of eight to nine months, with three or four subhumid months in winter and an absence of cold periods. Biological activity is concentrated during the winter, except in the littoral hills where thick masses of fog remain throughout the year. There are

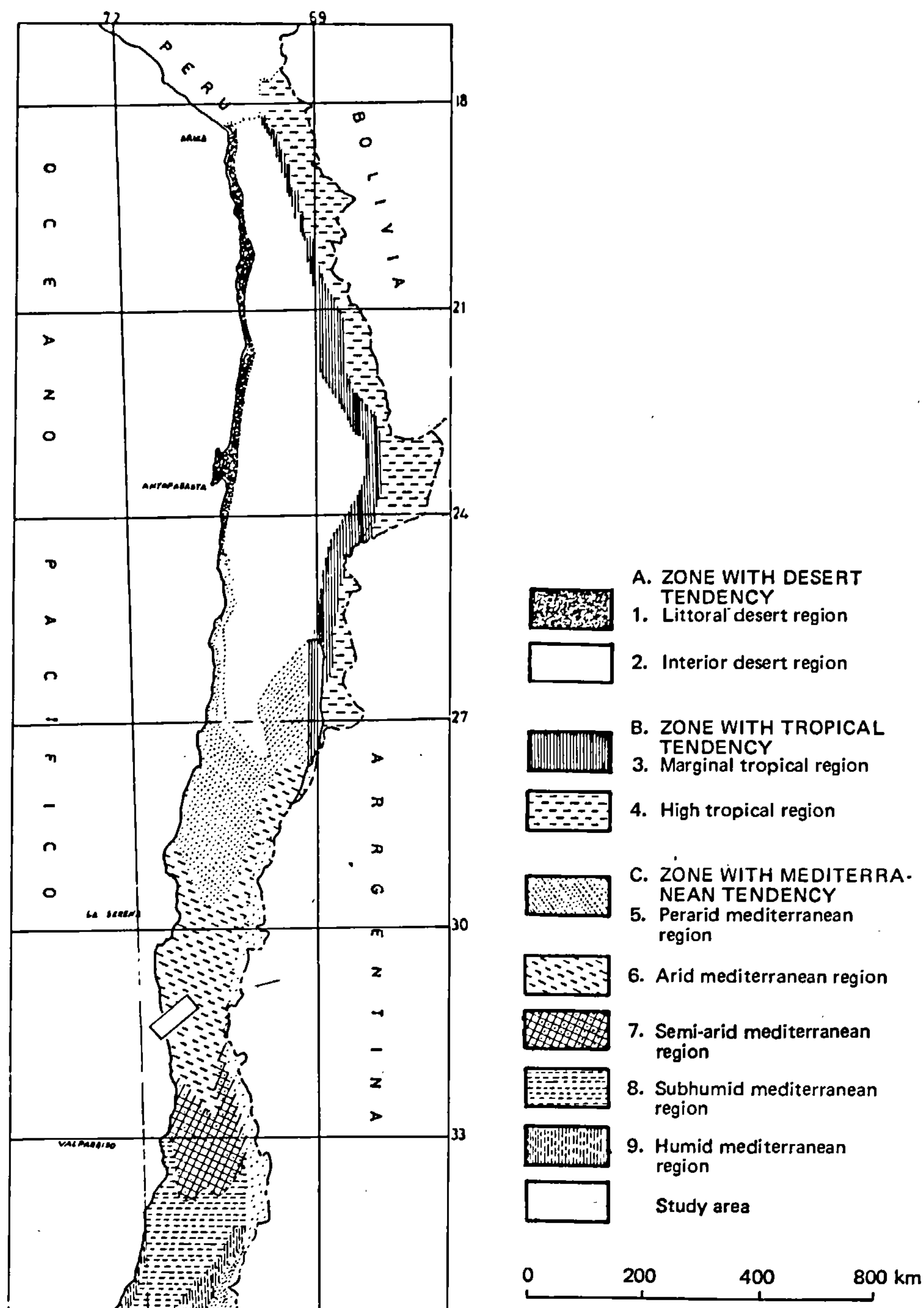


FIG. 3. Location of the study district in the climatic regions of Chile (from di Castri, 1968)

some climatic differences between the littoral and the interior parts of the region, although marine influences penetrate deeply along the transversal valleys. On the coast, the mean temperature is 14°C, the mean maximum temperature 18·3°C, the mean minimum temperature 11·5°C; the relative humidity is 82 per cent, with a mean rainfall of 115 mm. Further inland these values are 15·5°C, 24.0°C, 8·5°C, 65 per cent and 145 mm respectively. The rainfall increases to 100–300 mm in the southern part of the region. The main disadvantage of the climate, apart from drought and general aridity, is the extreme annual variability of rainfall and the alternation of favourable years with years of serious drought (di Castri, 1968). Tables 1–3 contain climatic data for the stations of the region.

Figure 4 shows two latitudinal sections (di Castri and Hajek, 1976), along which the thermic and pluviometric gradients can be traced, as well as the duration of dry and humid seasons.

TABLE 1. Bioclimatic indices for stations of the region (di Castri and Hajek, 1976, supplemented by more recent calculations)

Station	Annual aridity indices				Thermal indices		
	Lang	de Martonne	Emberger	Thornthwaite P/E	Periods of vegetative activity (months)	Thornthwaite T/E	Thermic concentration in summer (%)
La Serena	8·61	5·13	30·25	8·52	12	80·10	30·23
Punta Tortuga	6·97	4·15	30·71	6·45	12	79·49	29·50
Ovalle	8·81	5·32	20·7	9·10	12	82·50	31·49
La Paloma	9·67	5·88	22·18	10·17	9·6	83·93	32·12
Combarbalá	15·41	9·60	31·95	17·27	9·3	88·97	31·82

Station	Monthly aridity indices of de Martonne[1]											
	January	February	March	April	May	June	July	August	September	October	November	December
La Serena	0	0·3	0·4	1·1	11·7	21·8	15·7	12·0	3·2	1·7	0·4	0·2
Punta Tortuga	0	0·4	0·3	1·1	11·0	16·4	11·0	8·9	2·4	1·3	0·4	0·4
Ovalle	0	0·4	0·3	1·0	15·3	23·6	15·4	11·7	11·7	1·3	0·4	0·5
La Paloma	0	0·9	0·8	2·0	15·6	19·5	20·5	15·7	4·2	1·5	0·4	0·5
Combarbalá	0·1	2·2	1·2	4·5	29·4	29·9	26·1	27·7	4·9	3·3	0·3	1·4

1. Arid month: index lower than 10. Semi-arid month: index between 10 and 20. Humid month: index higher than 20.

Figure 5 illustrates the distribution of the mediterranean climate in Chile. The localities of La Paloma and Combarbalá, both in the arid region, have been added to the original figure.

Main characteristics of the regional climate

Precipitation

In this district, the patterns of rainfall can be explained by the seasonal movements of the Pacific anticyclone and the ensuing penetration of the fronts coming from higher latitudes. Schneider (1969) points out that the peculiarity of the climate in the Norte Chico of Chile can be explained by examining the rainfall both from the point of view of its concentration in winter, and also its variability in amount, from one year to another. There are very few rainy days and several months can pass without rain.

Figure 6 shows that the rainfall is concentrated between May and August. The concentration attains a value of 82 per cent in Canela Alta and even 89·3 per cent in Ovalle. Table 2 points out some other characteristics of rainfall in the district.

Figure 7, drawn according to Almeyda and Saez (1958) with modifications from Huber (1975), shows the isohyets for the four seasons as well as for the whole year. However, Schneider (1969) does not agree to a seasonal division. This is confirmed and explained by di Castri (1973), who notes the shifting character of the beginning and the end of seasons in Chile, compared with California.

The spatial distribution of precipitation is

TABLE 2. Some additional characteristics of regional rainfall from 1931 to 1966 (Oficina Meteorológica de Chile, 1965; Schneider, 1969)

La Serena	Ovalle	Combarbalá	Puerto Oscuro	Illapel
Irregularity coefficient				
2·48	2·55	1·55	1·76	1·38
Maximum precipitation in 24 hours				
100·2 May	120·3 May	160·0 May	—	88·0 July
80·9 June	73·3 June	149·0 February	—	78·0 August
57·0 July	59·0 July	119·0 August	—	77·6 June
54·3 February	52·0 February	106·0 July	—	77·5 May
Days with precipitation from 0·1 mm to 1·0 mm				
8·8 (47·0%)	1·0 (9·3%)	1·0 (6·8%)	—	1·3 (7·5%)
Days with precipitation from 1·0 mm to 10·0 mm				
6·7 (35·8%)	5·8 (53·6%)	5·7 (38·5%)	—	8·9 (51·5%)
Days with precipitation of 10·0 mm or more				
3·2 (17·2%)	4·0 (37·1%)	8·1 (54·7%)	—	7·1 (41·0%)

TABLE 3. Precipitation and its variability in the region (from Gastó, 1966)

	Ovalle	Combarbalá	Canela Alta	Puerto Oscuro	Illapel
Number of recorded years	52	43	25	53	50
Average					
Mean (mm)	133·8	261·9	197·9	202·1	215·9
Medium (mm)	120·4	241·0	185·0	179·3	203·4
Years with values lower or equal to the mean (%)	59·6	58·0	56·0	62·3	56·0
Deviation					
Maximum (mm)	367·5	594·3	426·0	518·5	500·2
Minimum (mm)	22·9	20·0	55·0	48·0	16·5
Range (mm)	344·6	574·3	371·0	470·5	483·7
Minimum of maximum (times)	16·0	29·1	7·9	10·8	30·3
Limit of the classes (mm)					
Without rainfall	0·0	0·0	0·0	0·0	0·0
Very dry	48·2	96·4	74·0	71·7	81·4
Dry	96·3	192·8	148·0	143·4	162·7
Normal	144·5	289·2	222·0	215·2	244·1
Rainy	192·6	385·6	296·0	286·9	325·4
Very rainy	240·8	482·0	370·0	358·6	406·8
Intensely rainy	0	0	0	0	0
Percentage of years in each class (%)					
Without rainfall	0	0	0	0	0
Very dry	11·5	4·7	4·0	9·5	4·0
Dry	25·0	20·9	32·0	22·6	30·0
Normal	26·9	44·2	28·0	35·8	32·0
Rainy	21·1	18·6	28·0	13·2	18·0
Very rainy	5·8	0·0	0·0	7·5	12·0
Intensely rainy	9·6	11·6	8·0	11·3	4·0

evident from Figure 7, which shows the isohyets drawn by Huber (1975). The annual 200 mm isohyet almost cuts the study area into two.

Rainfall variability can be analysed on the basis of work by Gastó (1966). According to this author, the study area is in the mediterranean arid zone. On the basis of the relationship between actual and mean precipitation, he classifies the years into seven categories, the 'normal' group being that in which the annual precipitation is 80–120 per cent of the mean. The criteria employed were as follows:

Years	*Percentage of the mean*
Normal	80–120
Very dry	0·1–40
Dry	40–80
Rainy	120–160
Very rainy	160–200
Extremely rainy	Over 200

The number of years being expressed as a percentage, the results are expressed as the percentages of years: no rainfall, very dry, dry, normal, rainy, very rainy and extremely rainy years (Table 3).

Water supplied by the coastal fogs and by dew is very important in the study area, but unfortunately we do not have any quantitative information on this. The supply from fog is particularly significant on the coast, and that from the dew is more important in the interior, in places where air with a high moisture content condenses during the night through radiation cooling.

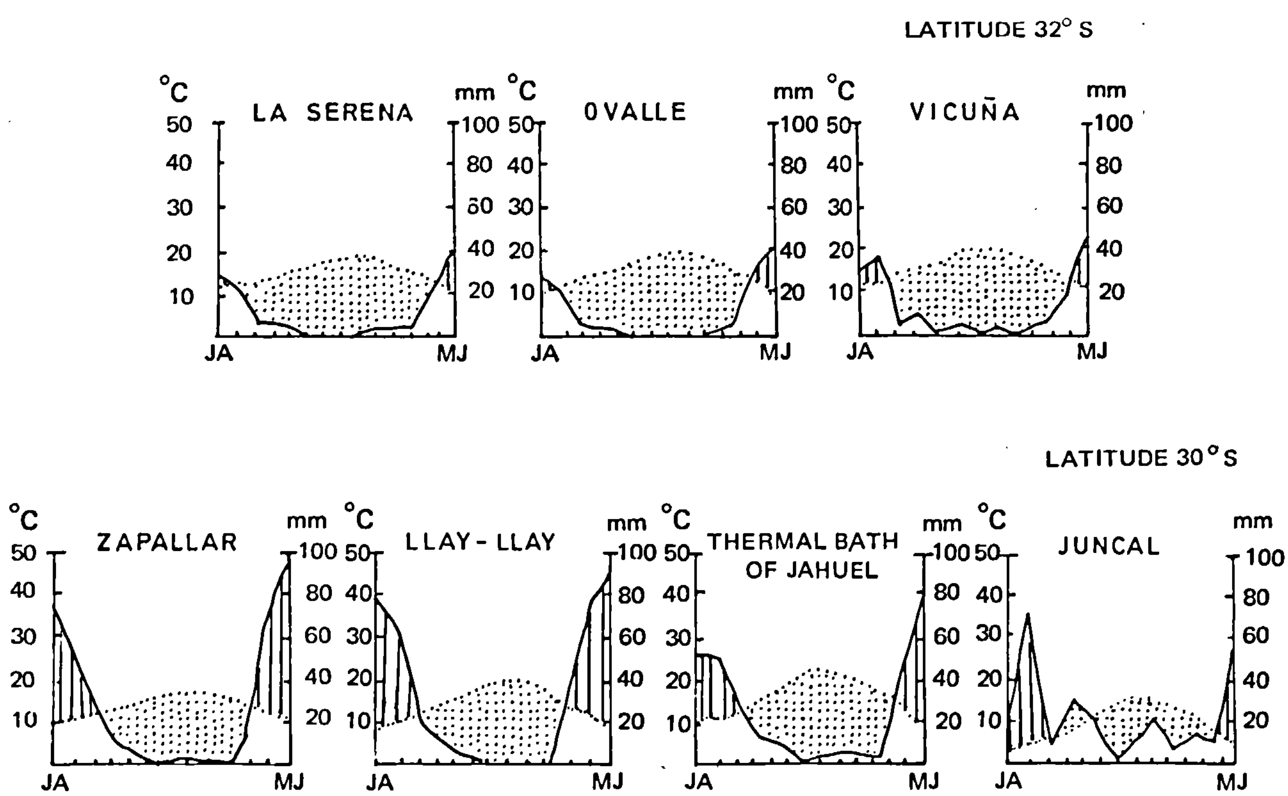


FIG. 4. The Gaussen–Walter diagram in latitudinal sections, 30°–32°S. (from di Castri and Hajek, 1976)

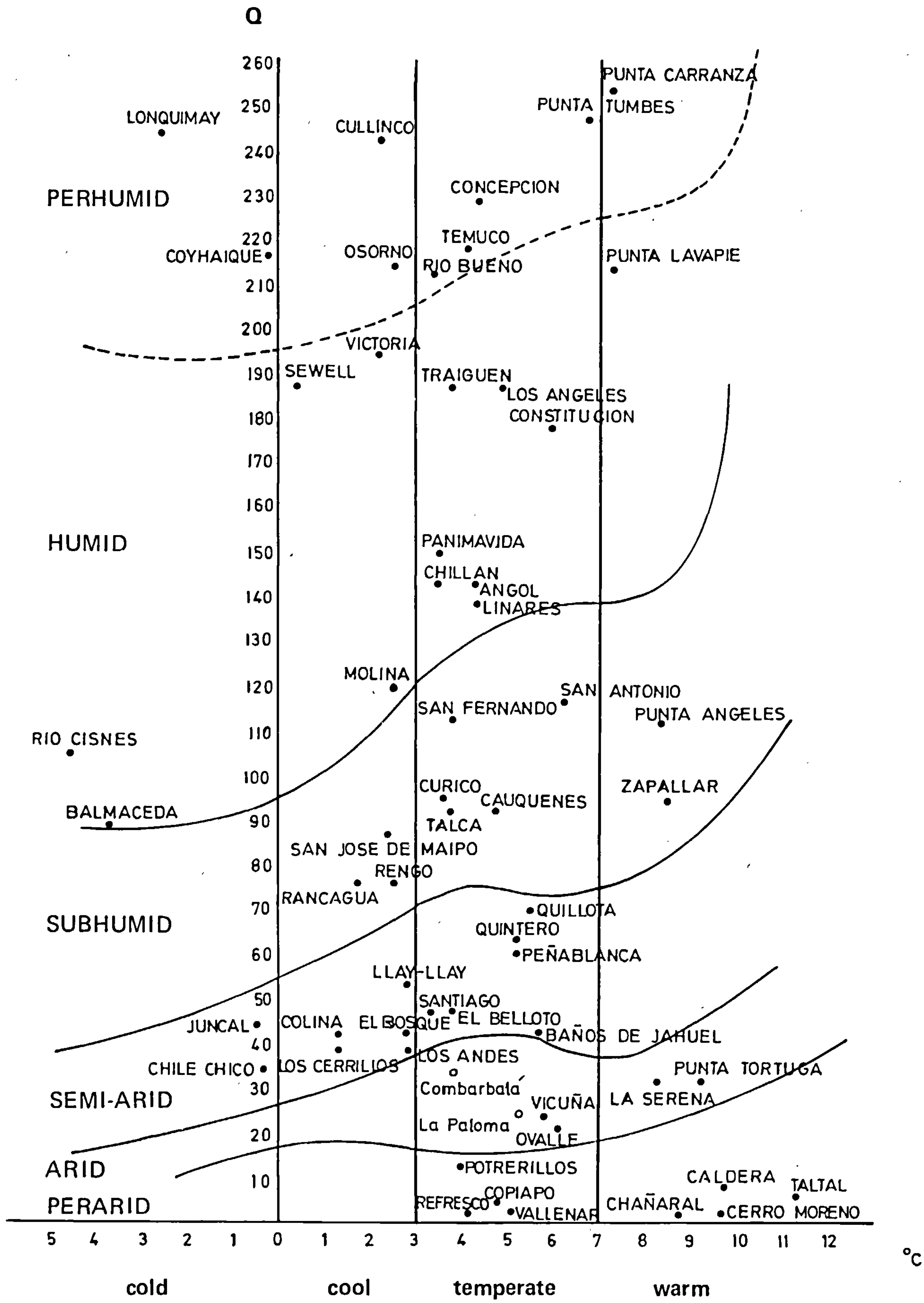


FIG. 5. The mediterranean climate of Chile according to Emberger principles (from di Castri and Hajek, 1976 including the localities of Combarbalá and La Paloma)

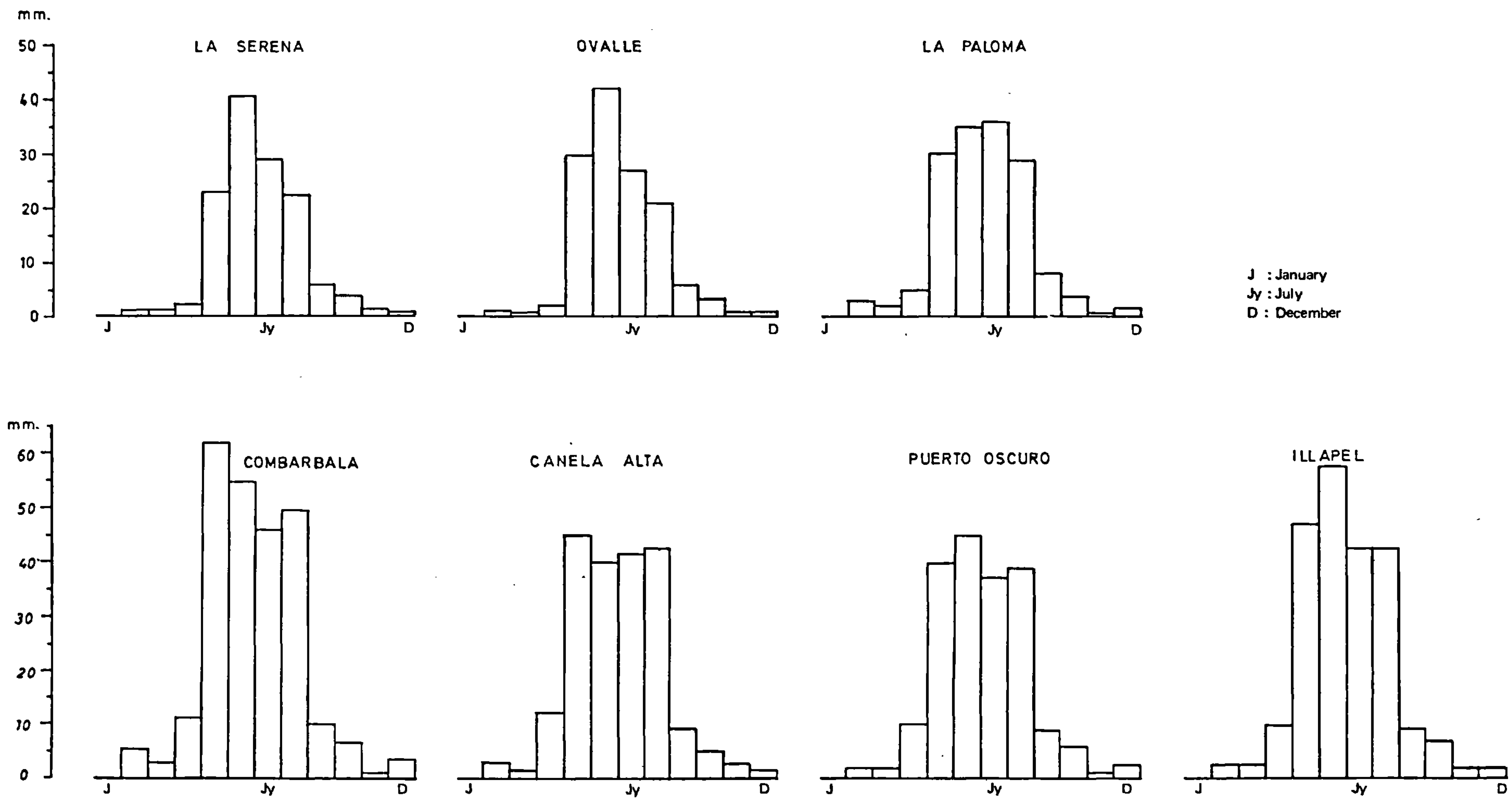


FIG. 6. Monthly distribution of precipitation (mm) in stations of the district and of neighbouring areas

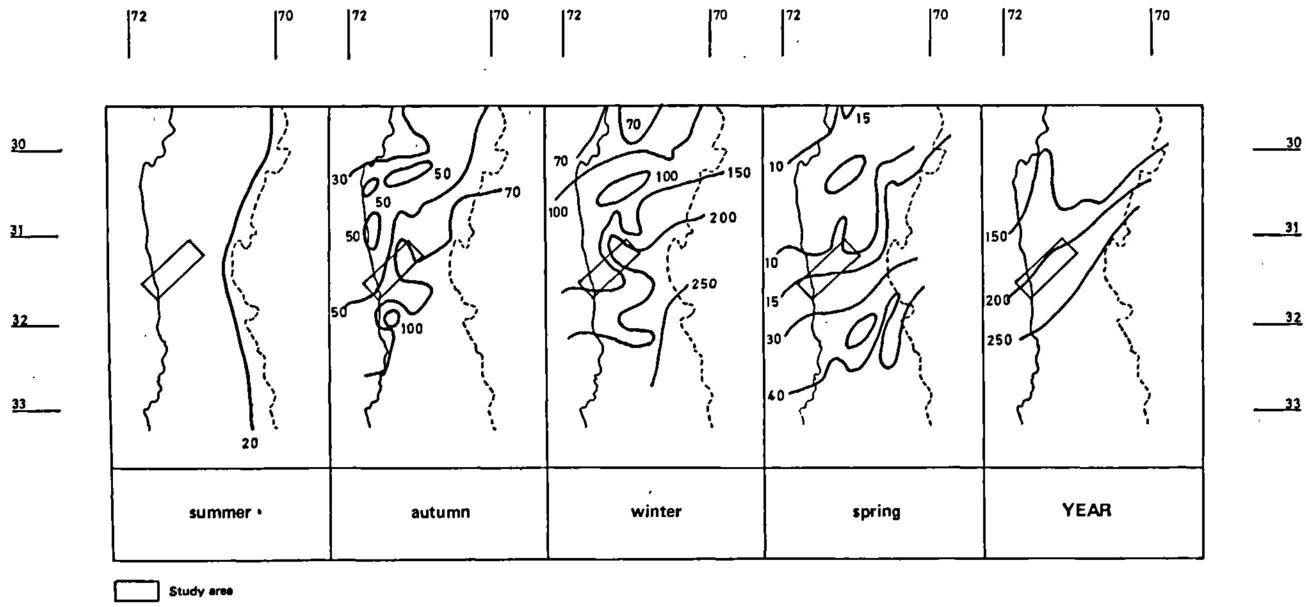


FIG. 7. Spatial and seasonal distribution of precipitation in the region (from Antonioletti *et al.*, 1972; Huber, 1975)

Temperature

The main factors determining temperatures in the district are: the Pacific anticyclone, which produces a subsidence of the air affecting the entire region; the cold Humboldt current, which brings about thermal anomalies by modifying the meridional distribution of temperatures; and finally, the orography, which acts through the altitudinal decrease of temperatures. The negative temperature anomaly in relation to latitude reaches 3·7°C at Punta Tortuga (Antonioletti *et al.*, 1972). A temperature inversion is characteristic of the region; this is found at 1 000 m altitude (Schneider, 1969). The available data, which do not apply exactly to the district itself, indicate the following:

Altitude (m)	*Percentage of the mean*
0	14·4
1000	15·2
2500	8·9
3000	5·2
3750	0·2

A positive gradient of about 0·6°C occurs through the first 1 000 m, decreasing from this point upwards. The normal decrease in temperature with altitude only occurs above the level of temperature inversion.

Figure 8 shows the temperature regime of some stations in the region and others near by. Two groups of stations can be distinguished. The first consists of those on the coast, with very small ranges and with extremely uniform temperatures. The stations of La Serena and Punta Tortuga could well be considered as representative of the study area if the temperatures were a few degrees lower. The second group comprises the stations of the interior, such as Ovalle, La Paloma and Combarbalá, which all display similar characteristics. They show large amplitudes in their maxima, minima and mean monthly temperatures. Combarbalá, at 910 m, stands out from the rest, with a mean maximum temperature above 30°C in summer and close to 20°C in winter.

Figure 9 shows the spatial distribution of temperatures in the region and also their seasonal distribution.

Analysis of these two groups of stations reveals the existence of several temperature regimes in the region: the regime of the coast, a transitional regime below the level of the temperature inversion, the cold regime of the mountains, and the mountain polar regime. Only the first two are present in the study area.

The appropriate thermal indices are shown in Table 1.

Winds

No data on winds are available for the district. Data from Punta Tortuga, La Serena, and Los Andes (the most distant from the area) indicate a dominance of westerly winds at the coast, while winds from the south-east are more important in the interior (Oficina Meteorológica de Chile, 1964). The entire district is included in a zone of high pressure with a mean of 1016 mb (Schneider, 1969). In general the winds have a strength of 2–4 degrees on the Beaufort scale, with calms occurring on almost 20 per cent of observations. In summer, there exists a sea-breeze, but this is not followed by a corresponding land-breeze because of the coldness of the ocean. It is important to note the presence of local winds caused by the irregular relief of the district, but these cannot be discussed on the scale of this study.

Relative humidity

There are few data on the relative humidity of the district except for the stations of La Serena, Punta Tortuga on the coast, and Ovalle in the interior. However, conclusions can be drawn about the relative humidity if monthly temperature variations are taken into consideration. A wide range in temperatures should lower the general relative humidity and

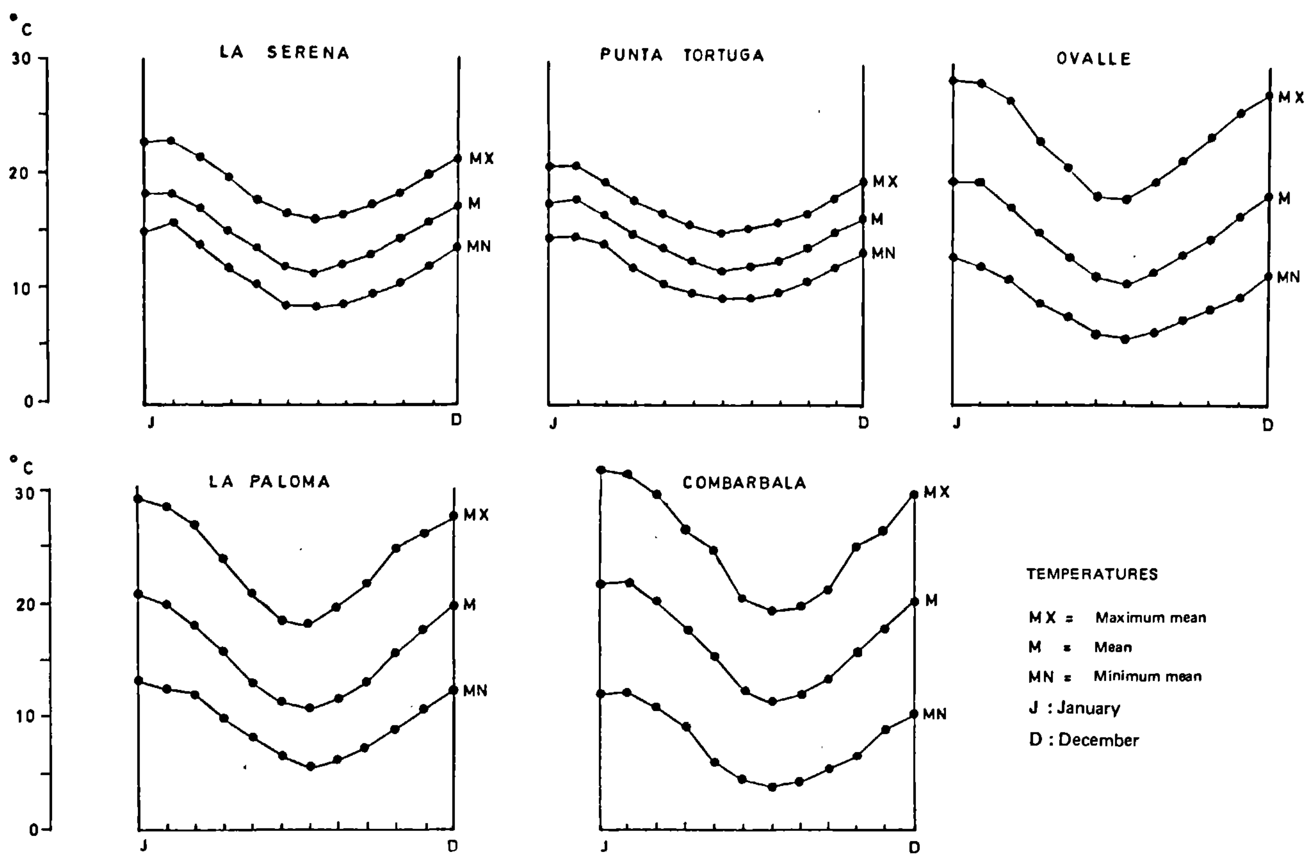


FIG. 8. Temperature variations in stations of the district and of neighbouring areas

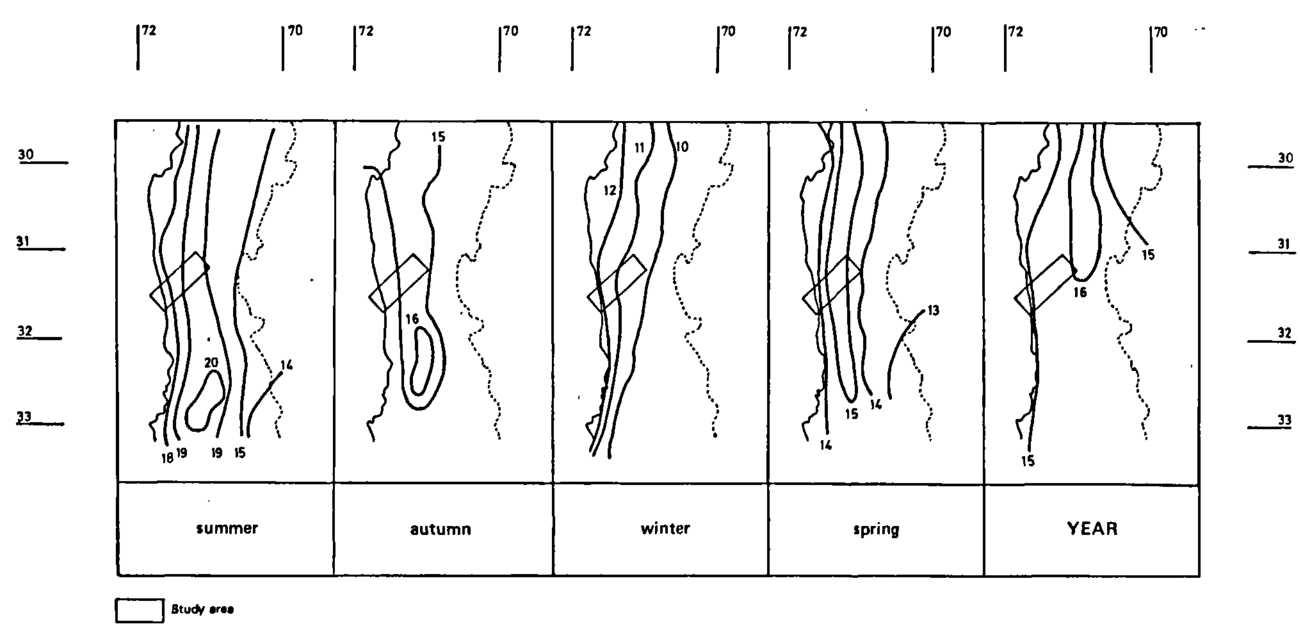


FIG. 9. Spatial and seasonal distribution of mean annual temperatures (°C) in the region (from Huber, 1975)

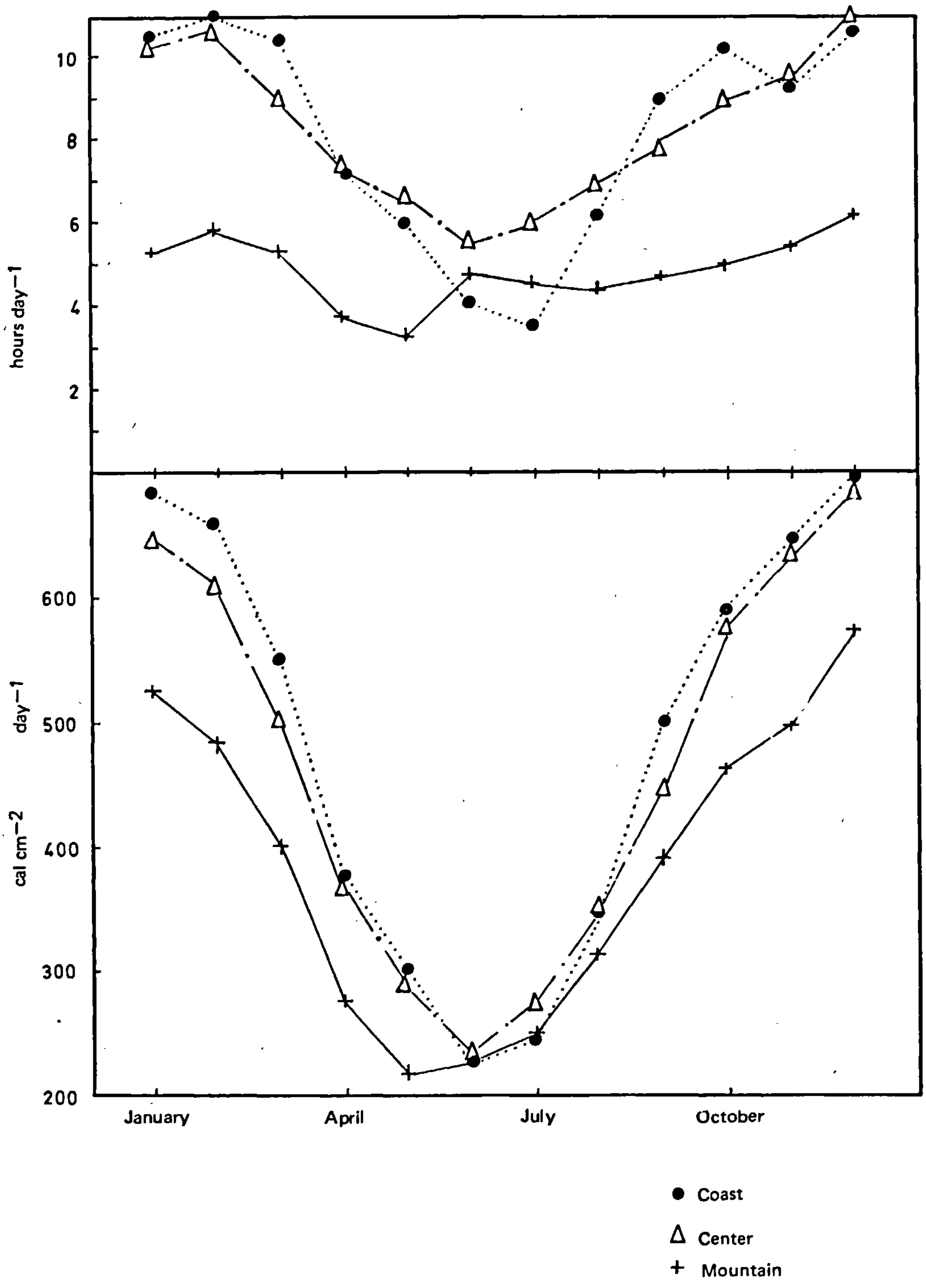


FIG.10. Annual record of sunshine hours and total radiation as recorded in stations on the coast, in the central region and in the mountains at 30°–31°S. (from Dobosi and Ulriksen, 1970)

vice versa. Table 4 shows relative humidity data for some stations, but these do not cover the entire region. These data show that the coastal zone, represented by La Serena and Punta Tortuga with a mean annual relative humidity between 80 and 83 per cent, is to be distinguished from the interior, represented by Ovalle and Vicuña (further north) with mean annual values of 71 and 61 per cent respectively. The annual variation in relative humidity is small on the coast as well as in the interior, but the values for the interior are lower. This is principally due to air masses heavily charged with water vapour penetrating into valleys lying perpendicular to the coast, i.e. in the direction of the prevailing winds.

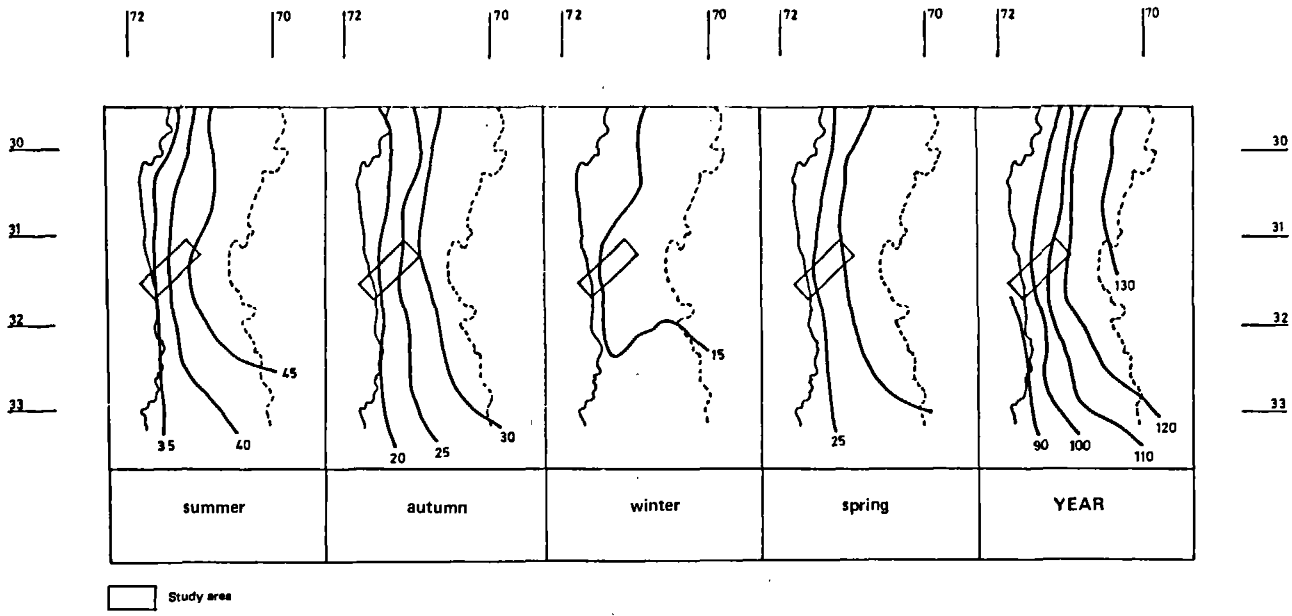


FIG. 11. Spatial and seasonal distribution of potential evapotranspiration (mm) according to Turc (from Huber, 1975)

Solar radiation

There are few data on solar radiation. Figure 10 shows the daily sunshine hours and the total radiation intensity (= total solar radiation = direct plus diffuse solar radiation) measured at three stations—on the coast, in the centre, and in the mountains—between latitudes 30° and 31° S. (Dobosi and Ulriksen, 1970). It was not possible to obtain the numerical data used to draw the graphs in the work cited, but they have been estimated from Figure 10. Therefore, their accuracy is not guaranteed.

Again the difference between the coast and the interior is evident as well as the higher values in the mountains, owing to a lack of cloudiness and fog. In winter, the angle of the sun results in lower values in the mountains.

Evapotranspiration

Blaney and Criddle's equation (1950) which gives water-consumption needs was used; information was also obtained concerning differences between crops and types of vegetal cover (Chang, 1968). The equation of Turc, as it was applied by Huber (1975), appears in Figure 11. In Blaney and Criddle's equation, we have used values of the K coefficient equal to the proportions of 0·85, 0·75, 0·65, 0·50 and 0·25 of the annual water-consumption needs. At the scale of the study, it was not possible to define K values for the different stages of the vegetative period. In any case, on the basis of the temperature regime, the area studied can be considered to have a potential for vegetation growth throughout the year (di Castri *et al.*, 1962).

It has not been possible to calculate other equations, which may be more efficient because they take account of a fuller range of meteorological data (Penman, Bowen, etc.), owing to the small number of stations and lack of records.

A survey of evapotranspiration in the district indicates the existence of two groups of stations, coastal and interior, within each of which the stations resemble each other to a great degree. However, La Paloma is clearly different from others in the interior zone in that it has values very close to those of stations on the coast.

As happens in all arid regions, the water balance in all the stations is characterized by an equality between precipitation and real evapotranspiration; there is also a marked water deficit, which is smaller in Zapallar, the southernmost station in the group under study.

Climatic variations as a factor of desertification

The insufficiency of climatic records makes it difficult to prove whether the district is tending towards a more humid or more arid climate. Schneider (1969) quoting Pizarro and Rivas (1965) points out that 'it

TABLE 4. Relative humidity (percentage) in La Serena, Punta Tortuga, Ovalle and Vicuña

Station	January	February	March	April	May	June	July	August	September	October	November	December	Year
La Serena	77	78	80	82	82	81	81	81	80	80	78	77	80
Punta Tortuga	81	82	83	84	84	84	84	85	83	82	81	81	83
Ovalle	74	65	69	73	76	78	78	76	73	69	66	64	71
Vicuña	61	62	65	66	63	61	61	61	60	60	57	58	61

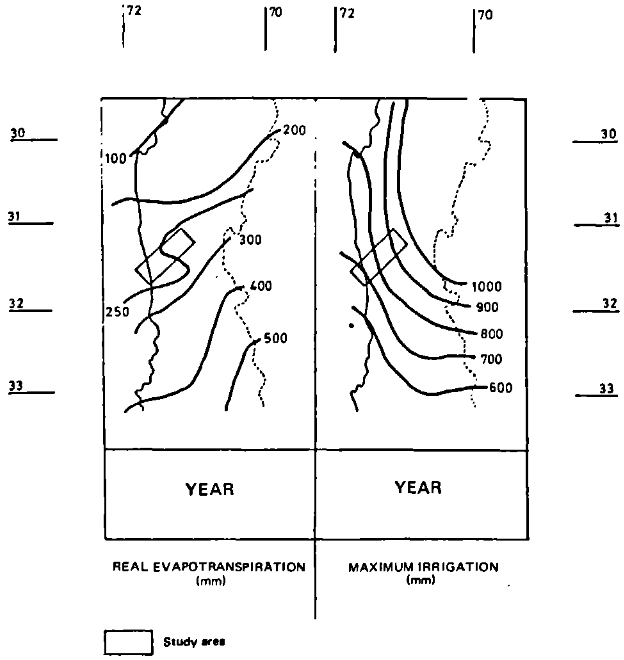


FIG. 12. Real evapotranspiration and maximal irrigation (mm): spatial distribution and annual values (from Huber, 1975)

is inappropriate to refer to a tendency in the long term because any fluctuations could well obey large cyclic variations which should be superimposed on other long-term tendencies lasting for geological periods. Undoubtedly it is more exact to speak of a descending movement in the precipitation level.'

A decrease in precipitation has in fact been recorded in the district, as is shown by Schneider's (1969) figures that follow below. There also appears to be a shift in the seasonal rainfall distribution.

La Serena	1869–1964	mean	125·3 mm	
(coast)	1871–1900	mean	148·2 mm	100·0 %
	1901–30	mean	128·3 mm	86·5 %
	1930–60	mean	104·7 mm	70·5 %
Ovalle	1897–1964	mean	143·0 mm	
(interior)	1901–30	mean	152·6 mm	100·0 %
	1931–60	mean	125·8 mm	82·0 %

	Summer	*Autumn*	*Winter*	*Spring*
La Serena	*(%)*	*(%)*	*(%)*	*(%)*
1871–1900	0·07	13·6	77	9·3
1931–60	3·26	28·7	59·4	8·6

In this context, a quotation from Antonioletti *et al.* (1972) is enlightening:

> . . . with the knowledge actually available it is not possible to decide whether there exists a tendency toward an arid climate or not. However, facts from the past can now shed some light on the problem: paleoclimatic research is conclusive in pointing to the existence of periods with a more humid climate in the Quaternary (Paskoff, 1970) and also to the existence of general climatic oscillations; some chronicles written in periods preceding the establishment of meteorological stations tell about protracted droughts and excessive rainfalls in the central part of Chile (Vicuña Mackenna, 1970). If these data are put together, one could conclude that the decrease in precipitation in the Norte Chico is a simple oscillation due to the marginal arid characteristics of the region. Whether this oscillation is part of a tendency towards a more arid climate on a long-term basis—a century, for instance—seems at present to be an unanswered question. . .

Figure 14 is included as a supplementary contribution to this problem and represents precipitation back to the year 1010 in the district of San Felipe (Miller *et al.*, 1977), as far as it can be reconstructed from the growth rings of a stand of *Australocedrus chilensis.* Dotted lines correspond to estimations based on a smaller number of specimens. Precipitation appears to follow a 100-year cycle. This means that the beginning of a 100-year period of precipitation less than the mean level is to have been expected in the sixties.

On the other hand, Figures 15 and 16 show the results of two bioclimatical studies of a drought period in 1968 (Hajek *et al.*, 1972; Hajek and Valenzuela, 1976). On the Emberger climograph one can see a displacement of the station plot either towards more arid or towards more humid conditions (Figs. 15 and 16). These displacements impose stress on the adaptation mechanisms of many organisms. Moreover, an association between drought phenomena and below-normal mean temperatures has been observed by Hajek *et al.*, 1972. However, the limited time-range of these observations does not allow them to be used for forecasting.

Physical resources

Geology and soils

The district contains rock strata formed during several geological periods (Instituto de Investigaciones Geológicas, 1968; Moos *et al.*, unpublished[1]). The oldest rocks date back to the Devonian period and are best represented in the littoral terraces. The granites of the Jurassic and Cretaceous and the volcanic and sedimentary rocks of the Lower Cretaceous are the most abundant. Some marine sedimentary rocks, intercalated with volcanic rocks, both from the Lower and Medium Triassic are also present (Fig. 17).

Detailed petrographic and mineralogic studies are lacking, particularly in contact zones; emphasis has therefore been put on the lithologic affinities as well as on the differences in age of the strata. In general, the tonalites of the Jurassic give rise to a good textural differentiation in the red clay-rich B soil horizons with strong blocky prismatic structures. The granites and granitic diorites of the Cretaceous give less colour and differentiation of the B horizons. It is likely that the great climatic variations in the past and the marine or continental influences in different parts of the area have all determined the evolution of the soils of the district. The chaos of rocks resulting from mechanical weathering is better represented in the interior areas than the coastal zones. It gives rise to typical isolated tors, which are certainly the remnants of the land surface existing at the end of the Pliocene. These formations also appear, although less often and less obviously, in the

1. Moos, Roeschmann and H. Thomas, Mapa geológico de la costa de la región de Illapel, Instituto de Investigaciones Geológicas.

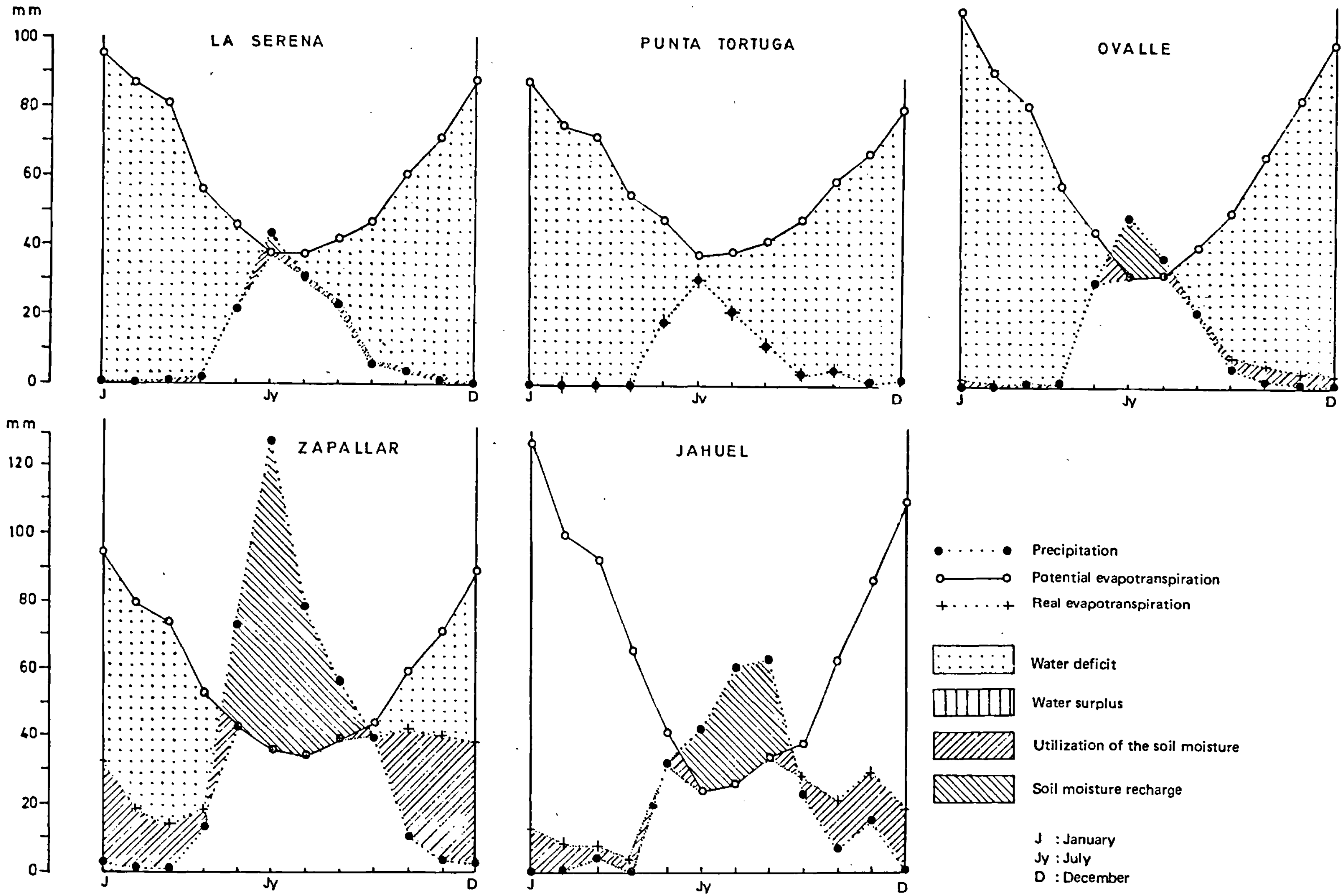


FIG. 13. Water balance as recorded in stations near the district

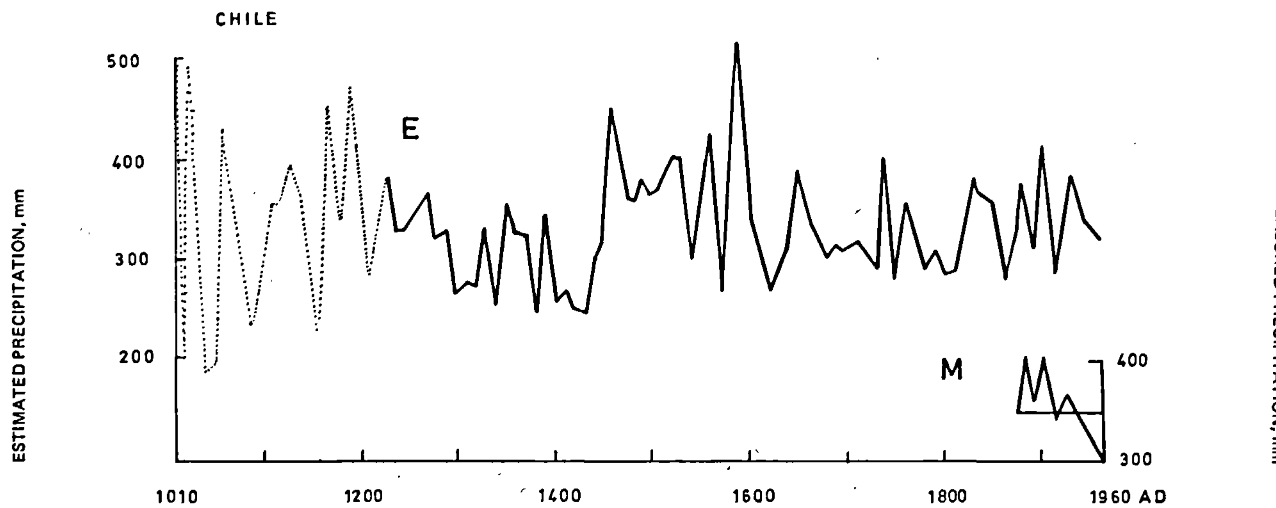


FIG. 14. Precipitation estimated from annual-growth-ring increments (dendrochronology) of a stand of *Australocedrus chilensis* (from Miller *et al.*, 1977)

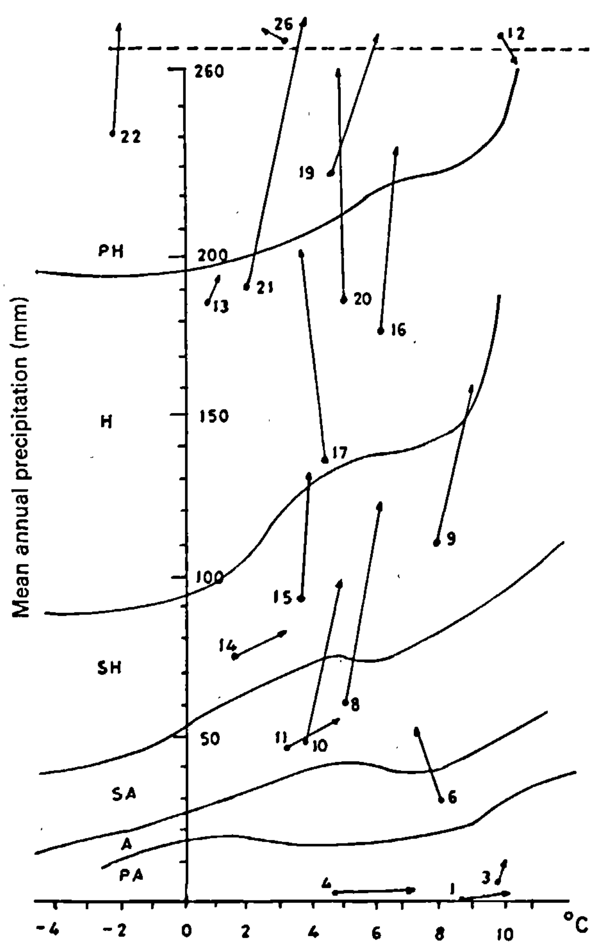


FIG. 15. Emberger climagram: 1965 displacement of pattern of stations studied (Station 6: La Serena)

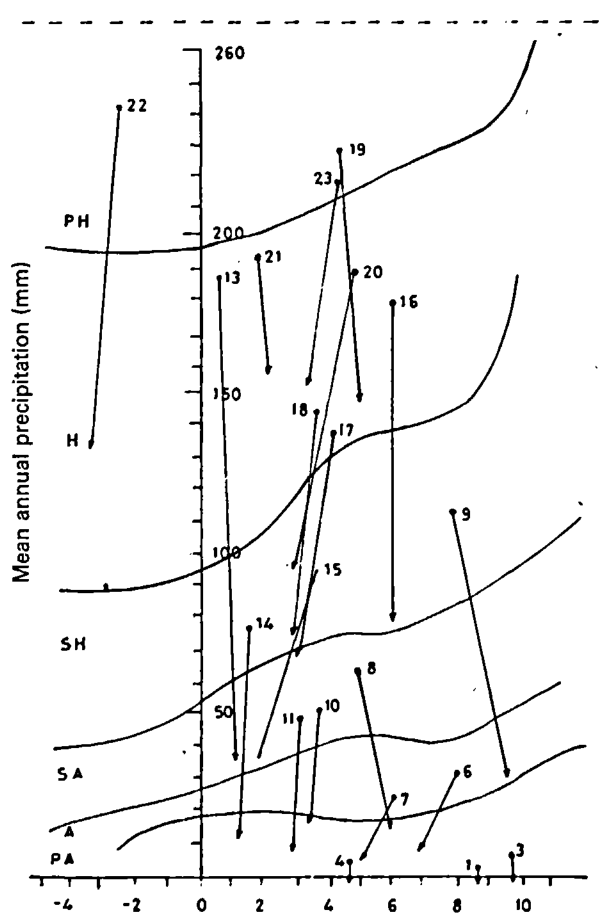


FIG. 16. Emberger climagram: 1968 displacement of pattern of stations studied (Station 6: La Serena) (from Hajek and Valenzuela, 1976)

district of volcanic rocks, forming typical soils on isolated hills.

The volcanic and sedimentary rocks have given rise to different groups of soils on either side of Colihue Creek. Those soils on the eastern side display thin clayish horizons, with colours strongly influenced by the underlying rocky stratum. Those of the western side are uniformly brownish in colour, are more permeable and have a more granular texture.

The soils are more regular on the marine terraces covered by clay and gravel, because of the uniformity of the deposits and also because of the constant supply of sodium ions from both fog and drizzle. In some areas, such as Huentelauquen, sand coming from the mouth of the Choapa River has also been added.

Petrographic and mineralogic studies are needed to make a precise identification of the taxonomic units connected to lithology. In any case, the rock strata clearly differentiate the soils of the district and the landscape has probably taken its present configuration during the great pluvial periods of the Pleistocene. More recent pluvial periods have left fewer traces; there are therefore only a few alluvial surfaces with non-functional cone deltas.

Geomorphology

The geomorphological landscape of the district can be classified into three well-differentiated areas:

Littoral terraces. These result from the rise and fall of sea-level associated with the glacio-eustatic phenomena. The terraces are fairly uniform, constituting one single, inclined plane broken by ravines. In the northern area the terraces are even more inclined, being limited inland by crystalline rocks. In this area, rocky colluvial material has been mixed with littoral deposits from the Quaternary. In the terraces, on the other hand, the sediments belong to the Pleistocene.

Great Central Massif. This massif corresponds to the outcrop of granitic and volcanic rocks, which although of different age have undergone similar geologic and climatic processes. The Quaternary paleoclimates have remained similar to the present climates, at least in the central part of Chile (Tricart, 1967).

Surface run-off has developed a terrain of rounded hills ('*cerros*') which are dissected by deep ravines with a few narrow alluvial terraces containing angular colluvium. Differences in bedrock are easily seen. The hilltops are more rounded on granitic surfaces and some districts have smooth hills enclosing valley plains (Puerto Oscuro and Los Tomes). Near the coast the granite has broken down into a sandy material called *maicillo*, in which one notes the occasional presence of rounded stones of fresh parent material and lodes of aplite. Degradation processes have progressed more slowly further inland, where blocks of rock are found both at the surface and in the soil profile. The abundant vertical lodes of aplite and lamprophyre are more resistant to weathering, and stand out like ruined stone walls.

The rivers and ravines are very sinuous in areas of volcanic rocks. Terrains on sedimentary and volcanic rocks also produce landscapes of hills dissected by deep ravines, which occasionally form narrow alluvial-colluvial terraces. Here, the hills have sharp crests, with many rocky outcrops.

The small alluvial fans of Recent formation may correspond to humid conditions during the Holocene. During the Tertiary, all this region was profoundly weathered under tropical climates; the rock outcrops underwent rubefaction, particularly the granite, which was later transported and contributed material to the marine terraces (Dreckmann, unpublished[1]). This could explain the sequences of clayey gravels and stones found in these terraces. Something similar could have happened to the volcanic and sedimentary rocks of the Central Massif, where the clay-rich deposits in the plains are mixed with angular materials of blocks and stones. Clays in the littoral zone have formed prismatic horizons under the action of sodium. In the drier plains, some montmorillonites have presumably been produced, giving these soils vertisol characteristics.

Region of plains and Quaternary deposits. At the end of the Pliocene, all this region was probably in process of pediplanation, and during the Pleistocene it underwent great modifications leading to the present landscape pattern. The more pluvial conditions of this period modelled the landscape and displaced great superficial deposits which were later washed out of the area, leaving remnants in districts that at the present time constitute the plains. These angular sediments covered local faults and even a part of the batholith. The granitic materials became uncovered in some districts, leaving isolated hills as remnants indicating ancient levels modified by erosion.

Recent alluvium is only scantily represented. The majority of the river terraces of Canela Creek and the Pama River are small and are mixed with other colluvial materials and with younger fans of small torrents. However, as these soils are permanently or occasionally irrigated, they are the most productive in the area. Although small, other alluvial districts, such as valleys between the mountains, provide important potential areas for cultivation during years with enough precipitation.

Modern dunes are infrequent in the south-west corner of the district. They are mobile and advancing slowly. These dunes are formed by material brought down to the sea by the Choapa River, returned to the shore by wave action and spread out over the land by the dry, dominant wind from the south-west.

Soil characteristics

In the present study the soils have been grouped according to their parent materials and also to their physiographic position (Fig. 18).

The soils of the district have undoubtedly undergone a general, noticeable decrease in productivity

1. P. Dreckmann, Bases físicas y biológicas para un planeamiento de los sistemas de explotación de los recursos naturales de la región litoral del Norte Chico.

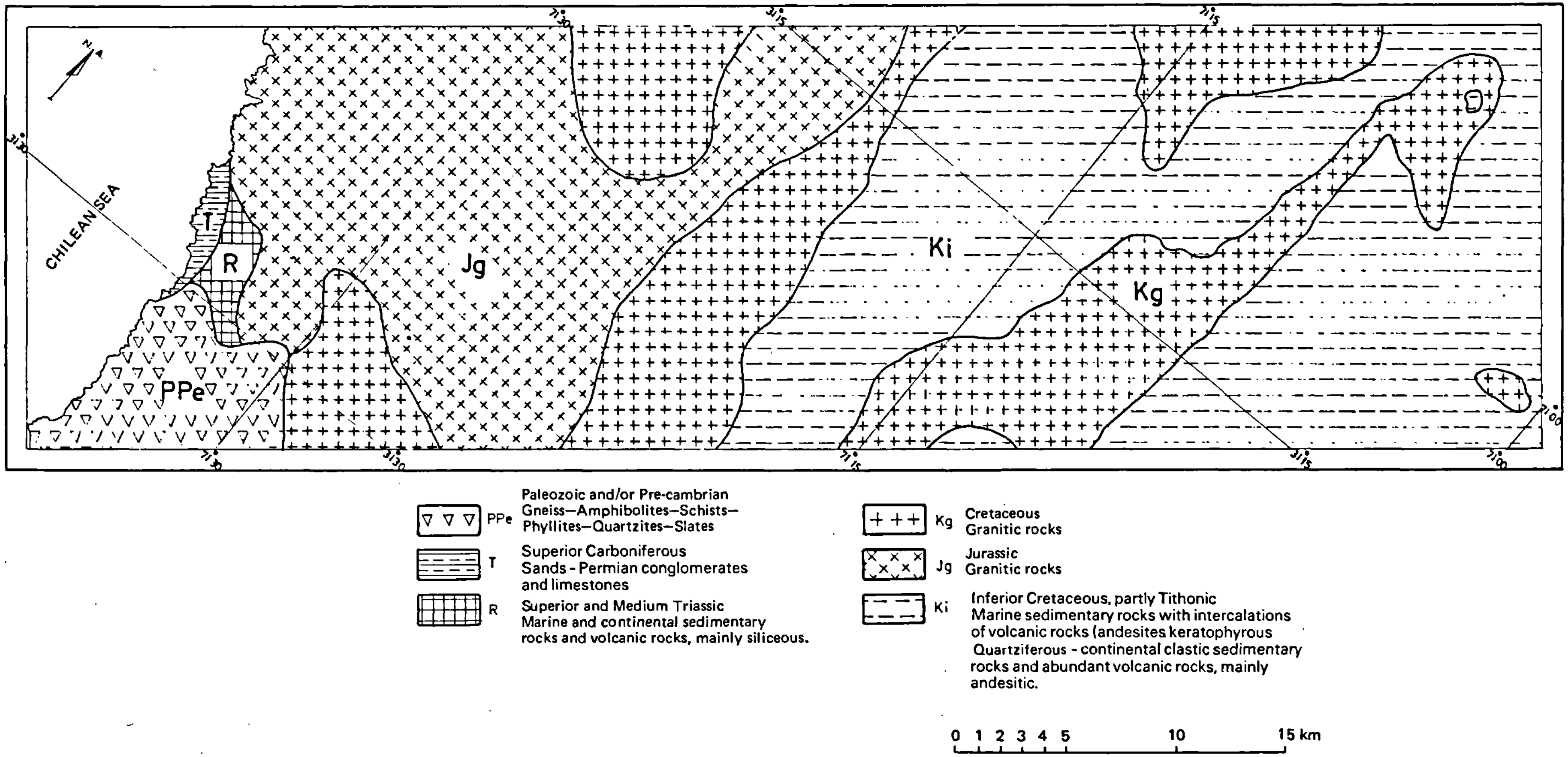


FIG. 17. Geology map, District of Combarbalá, 1976 (from Instituto de Investigaciones Geológicas, 1968)

resulting from an important loss of fertility. It is possible to distinguish two groups of factors responsible for this process of degeneration, namely anthropogenic factors and factors dependent on soil characteristics. The negative influence of population pressure on the environment, the prevailing land-ownership system, and the exhaustive exploitation of resources will be discussed in detail elsewhere.

Except for relatively small areas, like the littoral terraces, alluvial terraces, intermont valleys, soils of the plains and their associated smooth hills, most soils occur on steep rugged slopes. This, together with the removal of vegetation, enhances run-off and increases erosion. The soils have lost their structure in the upper horizons owing to rapid mineralization of the scanty organic matter and compaction by cattle-treading.

Exposure is extremely important with regard to the effective use of precipitation and to soil erosion in the region. The north and north-west exposures are the most arid, the soils being eroded and displaying a more xerophytic vegetation, evaporation is more intense there and the soil organic matter content is lower. The south and south-east exposures have opposite characteristics.

In general, all the soils have a very low organic matter content both in terms of incorporated material and the superficial horizon. This affects the structure of the upper horizon and the potential water storage and infiltration. Only in granitic soils of intermont valleys and on gentle slopes is humus incorporated to a depth as great as 8 cm. This also occurs in a less degraded area on the slope of La Viuda, facing south.

In general, most soils have medium and light textures, always with large quantities of stones. This condition could affect the water-retention capacity of the soil, but it is also likely that it facilitates the penetration of water down through the rock fissures. Some roots and rootlets, probably in search of moisture, were observed in these fissures. Heavy textures are found in the soils of the plains, in the littoral terraces, in some soils formed from volcanic rocks and in some granitic soils on smooth slopes. Water-holding capacity of the soils is limited because of lack of depth.

Several soil types have almost completely lost their structure. The granitic soils in particular are strongly compacted in the lowermost horizon. In the plains, columnar soil structures with relatively firm blocks probably produce massive structures. In the clay littoral terraces, the soil structure is prismatic, with a high content of sodium ions. This means that the soils are highly dispersed on wetting.

The soils with lowest fertility are those derived from granitic rocks, due to the nature of the parent material and the high quantities of quartz, particularly sand, in the soil profile. The soils derived from volcanic and sedimentary materials and the vertisols of the plains have low nitrogen contents. The predominantly andesitic rocks produce normal quantities of nutrients when there is enough humidity. Phosphorus is not likely to be lacking as most soils have an adequate pH, except for the strongly alkaline littoral terraces.

Soil erosion

Soil erosion is active in the study area and is extremely serious in some places, particularly near human settlements. It is difficult to evaluate with any precision.

A stony erosion pavement, a usual indicator of the degree of degradation of a soil submitted to wind and water action, characterizes many eroded soils on the central and southern coasts of Chile, as well as on the foothills of the Cordillera de los Andes. However, in the district under study it is difficult to pick out this pavement effect because stones are very common in these soils, both on the surface and in the profile. The chaos on some granitic hills is clear evidence of mechanical erosion. Erosion has exposed a large quantity of stones at the surface, but it is known that in semi-arid climates a great part of the soil materials undergo only partial chemical weathering, with most of the material undergoing only mechanical weathering. Moreover, constant cultivation of the soils has brought a great quantity of stone and gravel materials to the surface, which are not easily distinguishable from those exposed by a loss of soil.

The pedestalling of plants, considered as another index of sheet and gully erosion, is uncommon in the zone, except in those most severely affected places,

A valuable index of erosion is change in the colour of soils, indicating that much of the upper horizons has been lost over extensive areas. Soils originally brown and greyish-brown are now reddish or reddish-brown, colour found mainly in the B horizon.

Sheet erosion is frequently observed on granitic soils, leading later to gully erosion. The process is not so clear in other soils, particularly those derived from volcanic materials, where only occasional shallow gullies are observed.

There is little sedimentation in the creeks and river beds in spite of their gentle gradient. Some sedimentation can be seen along the course of the Llano Largo Creek, but it is insufficient to correspond to the intense erosion or strong alluviation one might expect in semi-arid zones. This does not mean that erosion does not take place: almost all soils derived from granitic materials undergo intense erosion.

The profiles of the rest of the soils have been strongly modified through loss of the organic components, and partial loss of the superficial organic horizon. This has diminished both the productive capacity and the protective surface layer exposing the soils to the impact of rainfall and to the action of run-off.

The soils of the more level surfaces of the littoral terraces show strong sheet erosion and frequent formation of gullies. This results from the swelling of the clay prisms and the dispersive action of sodium, both of which diminish the permeability and increase run-off. The length of the slopes, however gentle, enhances this vulnerability.

Aeolian erosion is active only in the south-west part of the district, and is of little importance. It is more significant a few kilometres further south, in the area of Los Vilos.

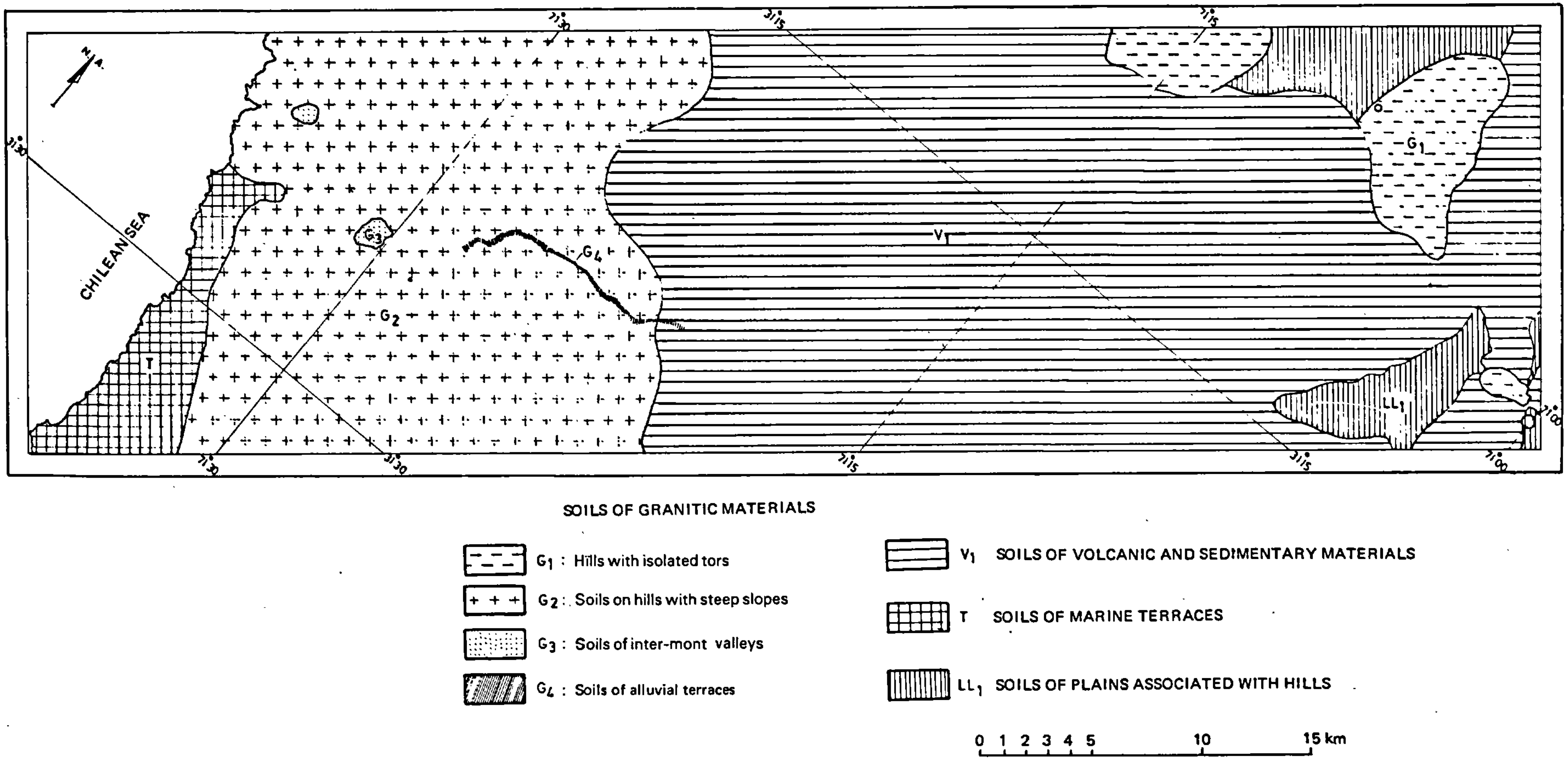


FIG. 18. Generalized soil map, District of Combarbalá, 1976

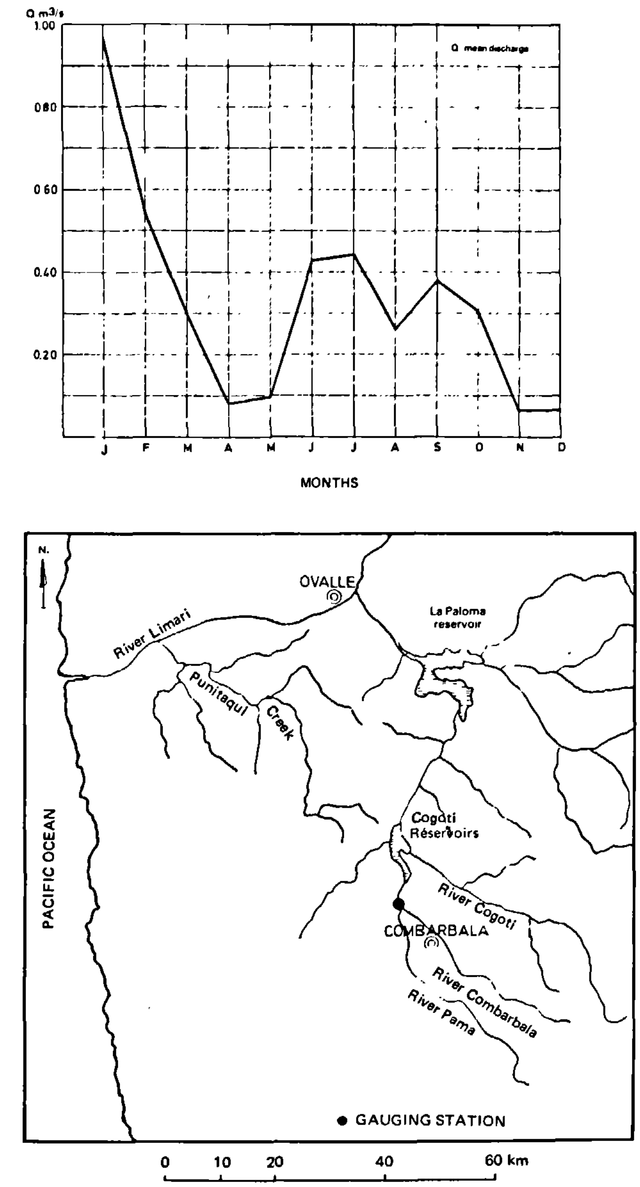


FIG. 19. Mean monthly discharges of the Pama River at Combarbalá

Surface hydrology

The surface drainage of this area consists of ravines with steep gradients draining into creeks with more regular seasonal flow which then join perennial rivers. The two principal rivers, the Pama and the Combarbalá, cross the north-east extremity of the district and flow into the artificial Cogotí reservoir.

The most important creek is called La Canela, and it irrigates the narrow belt of alluvial soils of Canela Alta and Canela Baja. Its main tributaries are Colihue, Llano Largo and Espíritu Santo Creeks. La Canela Creek drains into the Choapa River in the area of Huentelauquen.

These rivers and creeks have extremely irregular regimes. During droughts, as in 1977, the streams dry up leaving only a trickle. The Combarbalá and Pama Rivers are supplied by rain-water as well as by snow-melt water from the high mountains, have a more regular regime and irrigate the low-lying lands that surround the town of Combarbalá. The flow of the Pama River, at the time this study was done (autumn 1976), was interrupted at several points forming a line of rock outcrops.

Measurements of the Pama (Fig. 19) and Combarbalá Rivers show a mean annual discharge of $0{\cdot}32\,m^3/s$. The Dirección General de Aguas (Chilean Water Board) considers both rivers to have a similar, rain-dependent regime. Observations made during an 11-year period show that 70 per cent of the discharge in one year comes from May to August. The highest flow of $133\,m^3/s$ was registered in 1958, on 4 June. This river supplies about 30 per cent of the volume collected in the Cogotí Reservoir; its mean annual discharge is $10091520\,m^3$.

Mineral resources[1]

Both metallic and non-metallic deposits occur in the area and are classified into small and medium-sized mining categories (Fig. 20).

The metallic deposits include ores of gold and copper which have some commercial value, and also iron and manganese mines of lesser importance. Copper mining is a relatively important resource of the zone; it has been estimated that the total reserves would reach 500000 tonnes of sulphate ores, with a copper content of 1·5–2 per cent. Most of the reserves are concentrated in two main deposits.

In the batholith of the central region, ores occur in breccia columns near the village of Soruco and the hamlet of Quilitapia. Other ores are derived from contact metamorphism, near the boundary between the batholith and the Cretaceous calcareous lutites at San Fermin hill, south-west of Quilitapia. Of some importance also are deposits distributed along the systems of fractures in the volcanic rocks. These occur near the slope of La Viuda, on the road from Combarbalá to the Pan-American Highway. Minor deposits occur as veins, both in batholiths as well as in volcanic rocks, in Quilitapia, Cerro Llampangui, Quebrada Los Rulos, etc.

There are also some mineralized deposits with copper-oxide ores associated with fractured sedimentary rocks. However, they are very irregular and of minor importance.

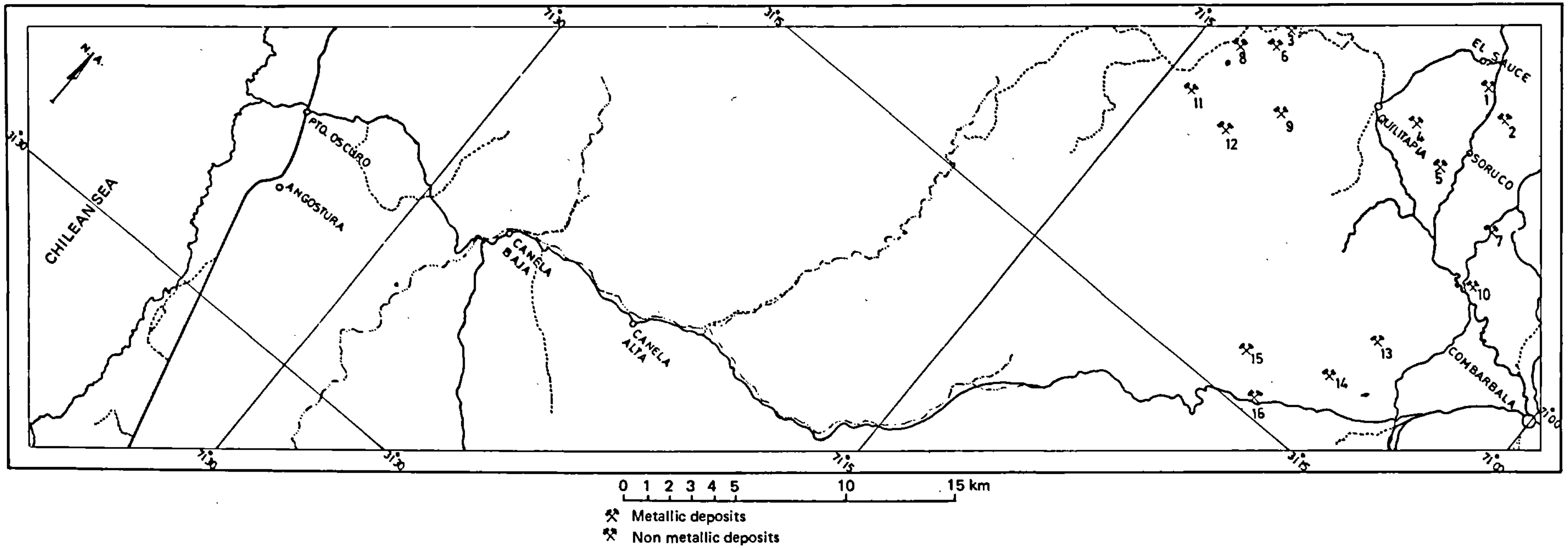
In the coastal batholith there are veins of gold ore which were exploited at the beginning of the century. Their occurrence is very irregular and there are no reserves, nor are there short-term geological expectations to justify any greater research.

The beach sands near Huentelauquen contain titanium and small quantities of gold but their importance has not been estimated.

The exploitation of non-metallic minerals is sporadic. There are large deposits of quartz (batholith of Quilitapia), although the reserves are unknown and they are only exploited following occasional requests.

There are some vertical deposits of pottery clay west of Quilitapia, and a reserve of hundreds of

1. Most of the information presented here has been given by the industrial mining engineer, Sr Claudio Canut de Bon, Executive Director of the Sta Rita Mining Society Limited, subsidiary of ENAMI, P.O. Box 50, La Serena.



N°	Names	Mineral veins	N°	Names	Mineral veins
1	Vanguardia	Kaolin	9	Las Tres A	Cu. Au.
2	Despreciada	Kaolin	10	La Parralina	Cu. Ag.
3	Carmela Santa	Cu. Ag.	11	Zuez	Fe.
4	Polaca	Cu. Au.	12	Flor Del Dosque	Cu. Au. Ag.
5	Lana Corina	Cu.	13	Blanca Azucena	$Ca.CO_3$
6	Lumbrerita	Cu. Au.	14	La Pascua	Cu. Au. Ag.
7	María	Kaolin	15	Afrodita	Cu. Au.
8	Ximena	Cu. Ag.	16	Chingay	Au.

FIG. 20. Map of metallic and non-metallic deposits, District of Combarbalá, 1976

thousands of tonnes has been detected, but they are not at present exploited. An investigation of the properties and marketing possibilities is needed.

There are also small irregular deposits of an ornamental rock worked by the craftsmen of Combarbalá. It is a volcanic rock type, with some clay alteration, but has not been classified. It has been tentatively called the 'Rock of Combarbalá', or Combarbalita, as a trade name. It has beautiful colours and becomes smooth and shiny on polishing. Ornamental objects and tools are manufactured from it in ten workshops, and some institutions such as the Instituto Nacional de Capacitación Profesional (INACAP) are now planning to export these works of craftsmanship.

In general the mineral deposits, except for two or three, have not been developed on a regular basis. Present production has not reach profitable levels at the regional plant of the Empresa Nacional de Minería (National Mining Enterprise, ENAMI), situated 5 km from the city of Combarbalá and working on sulphate ores of copper by the flotation method (capacity of 10000 tonnes per month). This plant buys copper and gold minerals from regional miners.

Investments are now being made for development and exploration. Better studies of the reserves are required, together with more investigations and geological work to create profitable enterprises. A subsidiary of ENAMI, called the Santa Rita Mining Society Limited, has been established in Combarbalá. It processes copper-oxide minerals by leaching processes, and has buying rights over this type of ore. In addition, this enterprise has a flotation plant which stimulates mining development. The two processes together treat 4000 tonnes of ore per month.

Vegetation and ecosystems

Concept of successional changes

The aim of this section is to describe the ecosystems in their present state, to establish the degree of degradation, and to propose alternative measures leading to the improvement of present conditions.

The successional theory of vegetation proposes a regular sequence of changes in the components of ecosystems, leading either to retrogression or progression. Reconstruction of the succession, although founded on fragmentary ecological evidence, has allowed hypotheses to be made about the direction, stages, processes, timing, cause and other characteristics of these changes. The quality and frequency of the ecological evidence in the district are variable. Sometimes, however, there are sufficient data to sustain hypotheses of a lesser or greater degree of certainty. Nevertheless, it is possible to generalize by saying that intensive degradation of regional natural resources has accelerated mainly during the last two hundred years. In the majority of cases, there still exist areas in the degraded districts where human intervention has been relatively minor. This allows us to establish the sequence of change and to describe the whole successional process (Olivares and Gastó, 1971).

The ecosystem successional theory has also allowed transformation schemes to develop, directed towards reversing the destructive processes and to generating successional progressions which lead to more stable and more productive disclimaxes, rendering them more useful to man. It is necessary to make more efficient use of the scanty rainfall during these stages of regeneration in order to reduce the negative effect of annual rainfall variability.

A conceptual framework, allowing for the establishment of the basis of changes, must be a prerequisite to any ecosystem transformation analysis. Accordingly, it has been necessary to define very precisely the original ecosystem intended to be transformed, defining the state, and choosing among different optimal alternatives the most profitable state for man (Armijo *et al.*, 1976).

Landscape units

This method was used to divide the district under study (Rodríguez, 1959–60) according to the ecotypical characteristics (Hills, 1961) of the landscape units indicated in Figures 21 and 22.

Coastal dunes

Present situation. Dune formation began after the erosion of the soils of the interior. Intense land use, without any effort at conservation, has accelerated erosion, particularly during the last two centuries. Part of the sediment conveyed to the sea by the rivers and creeks during rainy periods is later deposited on the shore and dispersed by the predominant southwest winds (Börgel, 1965*a*) forming littoral dunes. In general these are bigger on the northern sides of the mouths of the main river channels.

The dunes have five well-defined geomorphic zones (Fig. 23). Sand transported in the sea is deposited on the lower shore. During the dry season, the prevailing winds displace the sand to the area of embryonic dunes where the presence of *Ambrosia chamissonis, Carpobrotus chilensis, Cristaria glaucophylla,* and *Sphaeralcea obtusiloba* diminishes the grain velocity and allows the sand to accumulate about the vegetation. The level of the soil is raised, and the aridity of the newly formed edaphic climate provokes the death of vegetation. Subsequently, the sand hillock is destroyed and the sand particles are transferred to an upper area of the dunes deprived of vegetation. This slope facing the wind is smooth, due to the high speed of the inshore winds. On reaching a certain crest height the protected area develops a slip face, slowing down the velocity of the wind. Colonizing species establish then among which *Baccharis concava* and *Muehlenbeckia hastulata* predominate, stabilizing the soil and accelerating the weathering of the sand particles. As the dune gets older, there appear other species such as *Azara celastrina, Sphaeralcea obtusiloba, Chenopodium paniculatum, Lithraea caustica, Colletia spinosa, Nassella* spp. and *Piptochaetium* spp. In more advanced stages, the phanerophytes diminish under the competitive action of hemicryptophytes, and in the climax stage the plant cover is made up only of perennial grasses.

Where the dune is established on saline, swampy

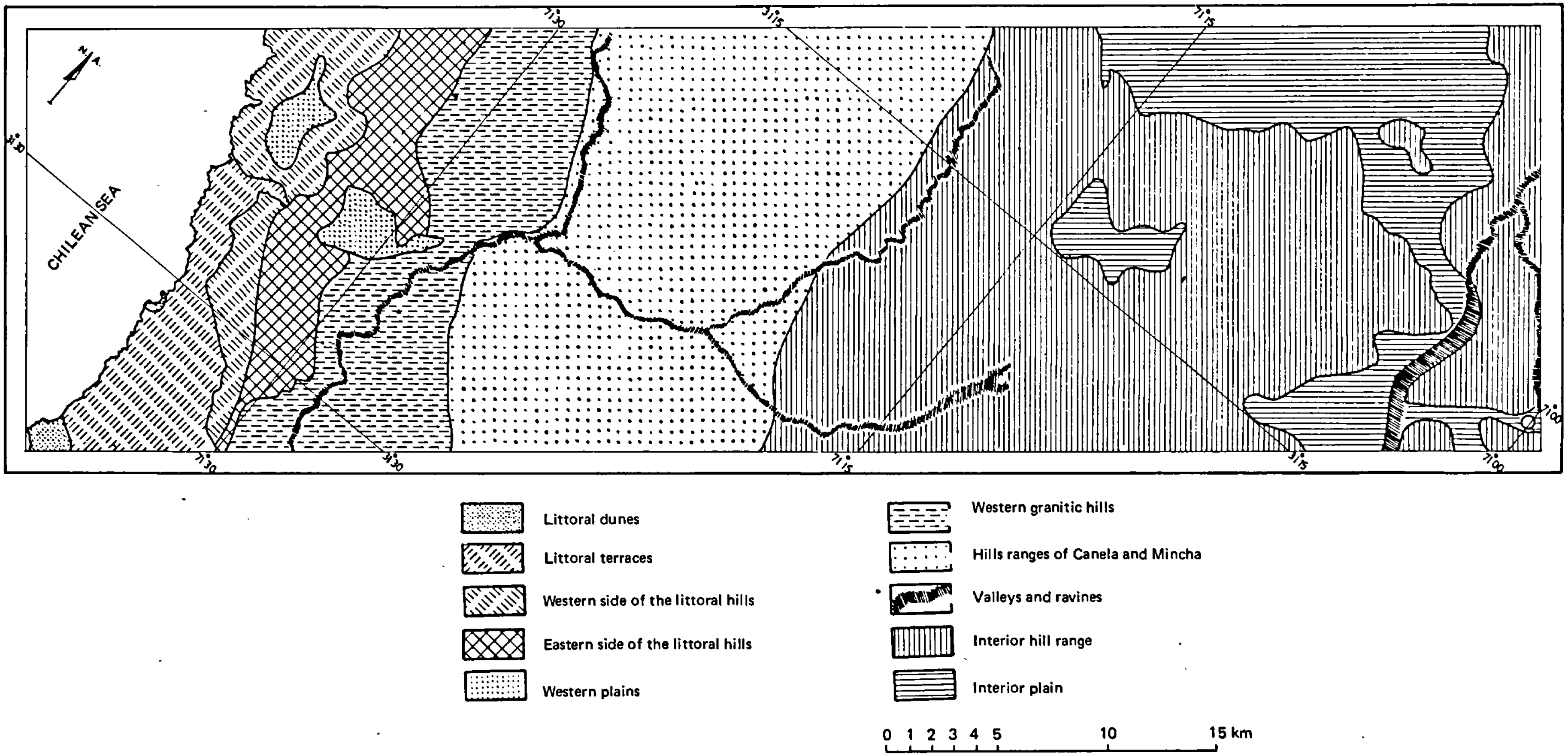


FIG. 21. Map of ecological and landscape units, District of Combarbalá, 1976

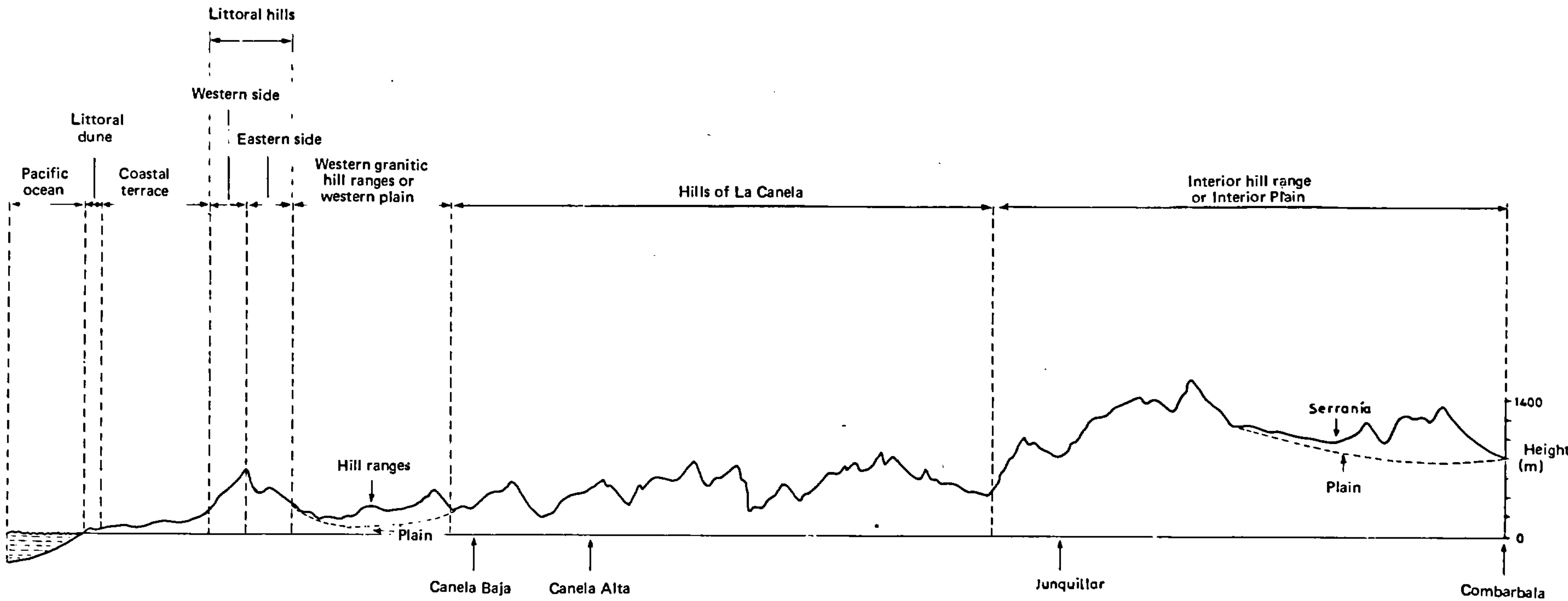


FIG. 22. General profile of landscape units

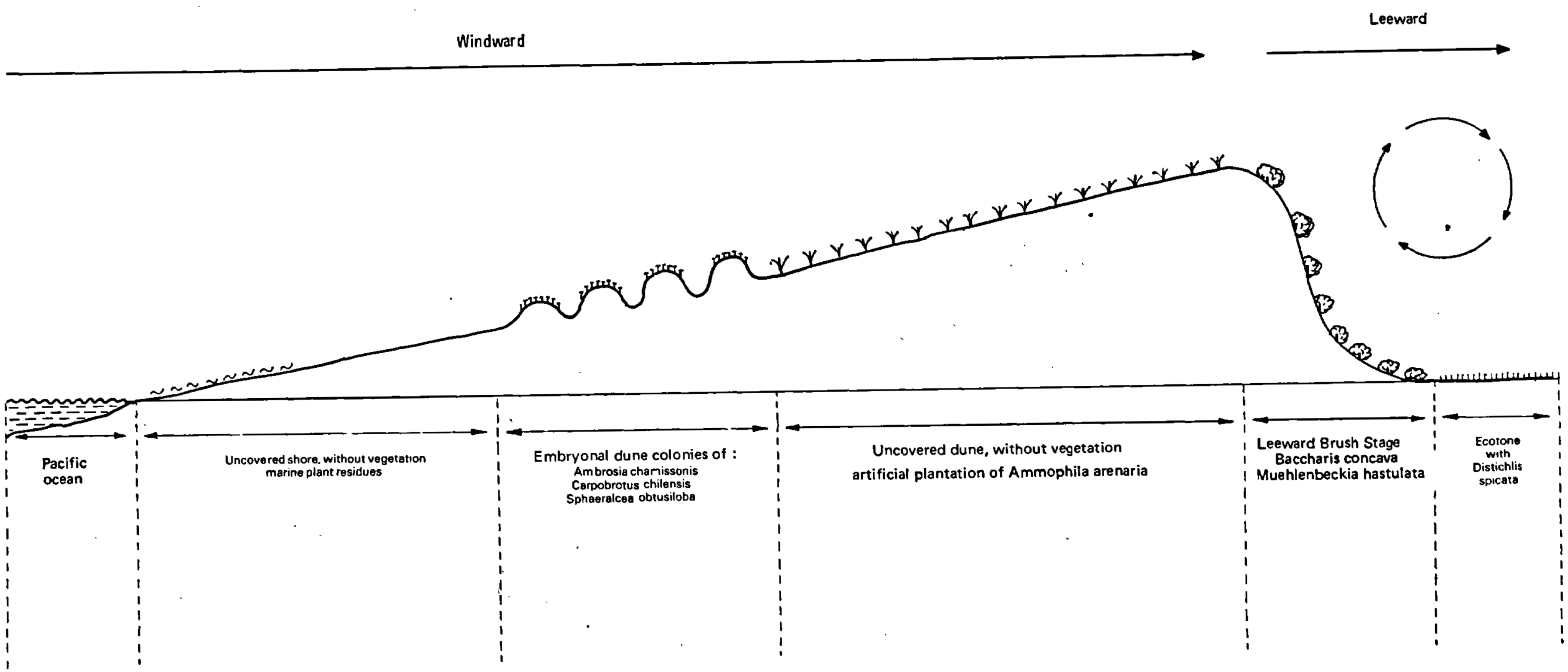


FIG. 23. General profile of a coastal dune

soil, a community dominated by *Distichlis spicata* can be established on the lower part.

Climax situation. As we are dealing with a community of recent origin, with progressive stages, the climax state is now known. The evolutionary process can be accelerated and *Ammophila arenaria* established. This reduces the movement of sand grains and enhances sand settling, and the development of species of greater biomass; species which accelerate pedogenesis. In this way, favourable conditions are produced for the establishment of communities belonging to more advanced stages.

Coastal terraces

Present situation. The vegetation found in the most degraded areas (terraces of Huentelauquen) consists of single-layered communities in which the therophytes of the genus *Plantago*, and frequently the hemicryptophyte *Dichondra repens*, predominate. Periodic ploughing eradicates the woody species, increases the risk of erosion, and generates the retrogressive process. This is followed by a population decrease of the most demanding animal species. Cereals are cultivated in years of good rainfall, but the soils are soon abandoned and used for livestock, particularly goats.

Cereal productivity is low. Usually, 15–20 kg of seed is sown per hectare and in many years the yield is only a little more than three times the sowed grain; these lands are thus considered to be of marginal quality (Workman and Hooper, 1968).

The cultivated areas are delimited by permanent fences and are utilized by cattle after the harvest. This sequence of cultivation, abandonment of soil working followed by free grazing, leads to a degradation both of the ecosystem and of cereal productivity. The fences deteriorate and later disappear because maintenance and replacement costs are very high in relation to productivity.

All these soils were originally of a better quality, with physical and fertility characteristics which allowed cultivation (Albrecht, 1956). The extension of cultivation is always towards those places that have been abandoned generally for more than twenty years. There are no areas where agriculture is a recent innovation. The degraded and abandoned areas are finally invaded by columnar cactus (*Trichocereus chilensis*) which generally exceeds densities of 10–50 plants/ha. The nanophanerophytes include sparse populations of *Cassia coquimbensis, C. acuta, Bahia ambrosioides, Chorizante* sp., *Nolana* sp. and others. *Margyricarpus setosus* prevails among the chamaephytes; isolated *Nassella, Piptochaetium, Dichondra, Trifolium* and others prevail among the hemicryptophytes. All of them display a high resistance to grazing.

The therophytes are the most important life form in terms of density and adaptability to years with favourable precipitation. The species composition reflects the degraded state of the ecosystem, which has very low productivity and the worst potential as rangeland. This life form appears to be stable as a result of ecosystem degradation (Fig. 24).

Areas covered by old dunes with deep soil and high humidity-retention and infiltration capacities are covered by *Atriplex semibaccata* (Lailhacar, 1962, 1966; Kartzov and Lailhacar, 1965), a species introduced from Australia at the end of the nineteenth century and now adapted to the district. It has greater vigour and higher productivity than the older ecosystems of the district.

Climax situation. The climax stage corresponds to a single layer of perennial grasses dominated by species of the genera *Hordeum, Nassella, Piptochaetium* and others which are found at present only as remnants. Originally, the pasture was used for the winter pasturing of wild *Camelidae*, particularly guanacos. This allowed the preservation of a relatively high biomass of hemicryptophytes, which have a low palatability, and thus the preservation of the habitat. In the ravines and districts altered by small digging mammals and other destructive animals were species subordinate to hemicryptophytes.

Grazing by domestic *Camelidae* near watering areas initiated the degradational process, although the hemicryptophytes continued to dominate. The low stocking rate practised during that period did not lead to any generalized degradation of the climax rangelands. The human population of the province of Coquimbo was only 15 000 when the Spanish conquerors arrived, decreasing to 5 000 some years later; each family had about two or three domestic guanacos (Encina, 1940–52; Correa, 1938). On the other hand, the wild *Camelidae* were small in number, forming mobile herds. They therefore did not contribute to overgrazing of the climax rangelands. Primitive man did not have a better attitude towards conservation of his environment, but his destructive impact on the ecosystem was less: population density was lower and the use of draught animals and iron technology and the cultivation of arable lands were not known (Guthrie, 1971).

Retrogressive change. The district of Huentelauquen was occupied by man in the Prehispanic period, but no degradation took place in the ecosystems of the cultivated lands (Helbaeck, 1959). There was an abundant, economically valuable flora, providing food nutritious for man (Jiles, 1963; Ortiz, 1969).

The degradation of the littoral terrace ecosystem began later in the sixteenth century, with the introduction of sheep, cattle and goats. The increase in livestock numbers was initially slow, as water was lacking and transport difficult. The main destructive agent was the introduction of draught animals associated with the cultivation of arable lands.

The sparse human population from the sixteenth to the eighteenth centuries probably cultivated only the valleys and ravines with irrigation. At the beginning of the nineteenth century the increasing human population may have caused an excessive destructive pressure in such a way that at the end of that century it was necessary to extend cultivation to the better arable lands, without irrigation. The opening of the Pan-American Highway on the coast at the beginning of the 1950s introduced an exploitive type of cultivation, thus encouraging the desertification process (Börgel, 1965*b*).

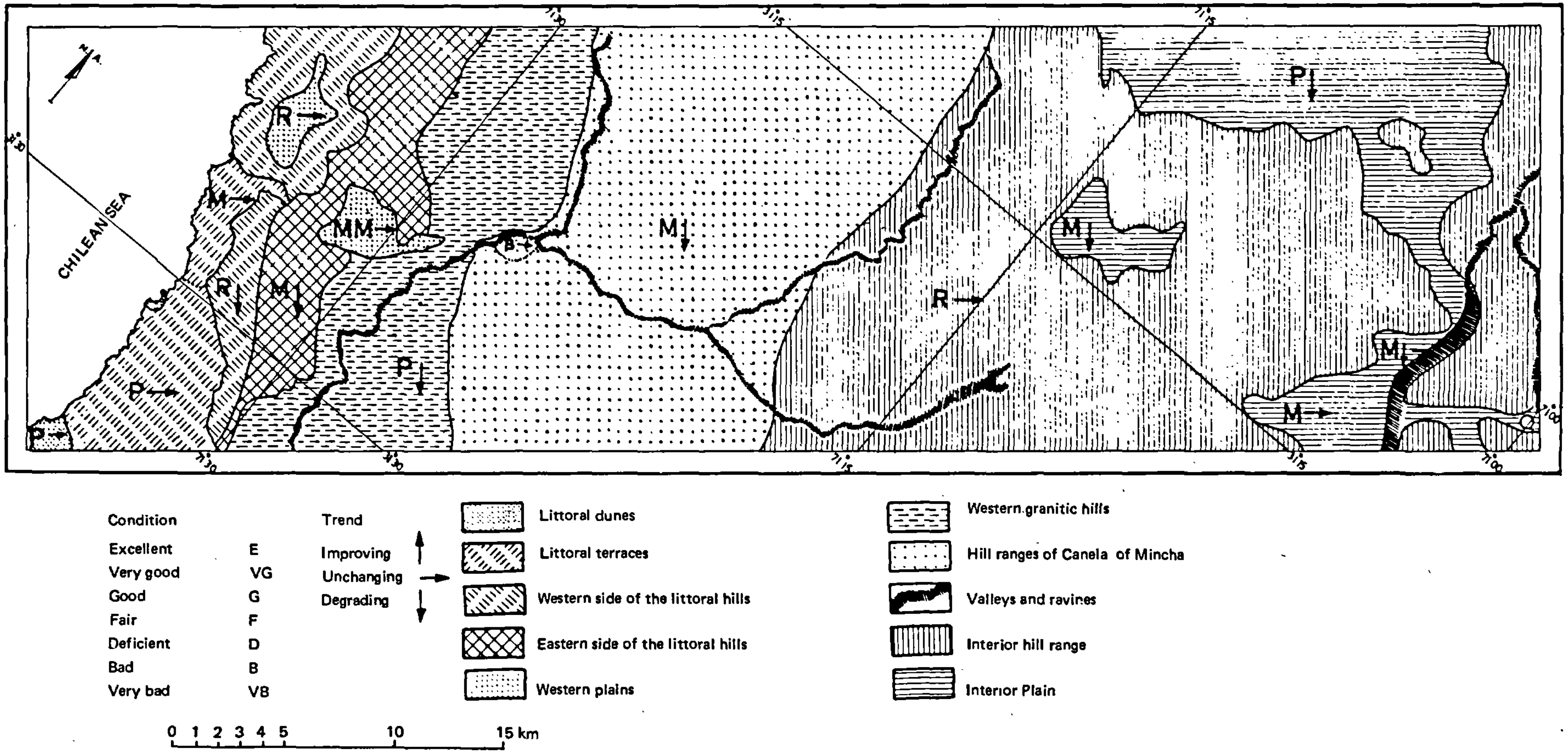


FIG. 24. Map of the condition and trend of rangelands

The characteristic stages of this breakdown can be described as follows:

— climax ecosystem of hemicryptophytes, dominated by grasses from the genera *Nassella, Piptochaetium* and *Hordeum*;

— reduction of the hemicryptophyte biomass, leaving intervening areas unoccupied;

— invasion of these areas by woody species, whose establishment is limited by excessive competition with hemicryptophytes;

— the most important species during the ensuing retrogressive stage are bushes of nano- and microphanerophytes, such as: *Azara celastrina, Maytenus boaria* and *Lithraea caustica* for the microphanerophyte stratum; *Baccharis concava, Sphaeralcea obtusiloba, Chenopodium paniculatum* and *Colletia spinosa* for the nanophanerophytes associated to *Muehlenbeckia hastulata, Baccharis linearis, Cestrum parqui, Ephedra andina, Schinus polygamus, Adesmia microphylla, Senecio bahioides,* and others. Among the important chamaephytes are: *Margyricarpus setosis, Cardionema ramosissima, Atriplex semibaccata, Geranium corecore, Cotula* sp. and others; a majority of them are intensively utilized by cattle. Among the therophytes. *Trisetobromus hirtus* and *Erodium cicutarium* are found, and particularly species of the genera *Adesmia* and *Plantago.* Among the hemicryptophytes *Nassella pungens, Bromus uniloides* are conspicuous and other species of the genera *Hordensa* and *Piptochaetium;*

— more palatable species predominate and attain better growth in areas free from grazing and cultivation, particularly perennial species, such as *Margyricarpus* sp., *Sphaeralcea obtusiloba, Baccharis linearis* and *Chenopodium paniculatum.* Continuous grazing reduces the strength of these species, increasing the development of other less palatable species which then exterminate them (Humphrey, 1958);

— harvesting of firewood from bush dominated by *Azara celastrina* and *Lithraea caustica* leads to the establishment of a low cover of brush devoid of tree species, dominated by *Baccharis concava, Puya chilensis,* and *Bahia ambrosioides.* Continual harvesting of firewood leads to sparse brush with continuing losses of biogeochemical nutrients. Productivity decreases as does the stability of the annual species and only poor quality species remain. *Puya chilensis* starts to invade from higher areas. Continual overgrazing and firewood harvesting lead to a community where the annual species are degraded, associated with unpalatable or less palatable chamaephytes;

— the ecosystem is also degraded by ploughing in successive, damaging stages. Periodic cultivation, soil erosion and lack of care in preserving the pioneer communities of the post-cultivation stage, lead to loss of topsoil. When the soil is abandoned, invasion by *Trichocereus chilensis* ensues, accompanied by small chamaephytes and nanophanerophytes, such as *Cassia coquimbensis, C. acuta, Nolane* sp., and *Chuquiraga.* The annual species are less important at this stage, and most of the soil surface is covered by an erosion pavement of stone which acts as a protection against further degradation;

— in arable lands, abandoned at intermediate stages of breakdown and later overgrazed, there appear communities of chamaephytes dominated by *Atriplex coquimbana,* which has interesting characteristics as a browse species.

Western slope of the coastal hills

Present situation. This unit occupies a gradient extending from the piedmont up to a maximum height of 700 m (Fig. 25).

The piedmont area has deeper soils with better characteristics than those of the medium and high slopes. Its typical community is a low, blackish brush, dominated by *Bahia ambrosioides,* which grows in more favourable environments exposed to the southwest, and is associated with *Baccharis concava. Puya chilensis* gradually increases in areas exposed to the north, until it reaches an equilibrium with *Bahia ambrosioides.* Populations of *Adesmia microphylla, Fuchsia lycioides, Cassia coquimbensis* and *Muehlenbeckia hastulata* are also present in the nanophanerophyte layer. The therophytes include *Erodium cicutarium, Plantago tumida, P. rancaguae, Adesmia angustifolia, A. tenella, Medicago hispida, Oxalis* sp. The microphanerophytes are represented by occasional specimens of *Schinus latifolius* and *Lithraea caustica.*

In some restricted areas of this district there are communities of *Cassia coquimbensis* and *Baccharis concava,* and also *Erodium cicutarium.* Some isolated specimens of *Piptochaetium caespitosa* are found among the hemicryptophytes. In some limited districts of the piedmont there are occasional communities of *Baccharis concava* and *Muehlenbeckia hastulata,* together with some isolated specimens of *Pictochaetium* which dominate the hemicryptophytes; *Trifolium megalanthum* is also abundant. *Erodium cicutarium* and *Trisetobromus hirtus* must be mentioned among the therophytes. In other areas of soil subject to sheet and gully erosion there is a single-species cover of *Baccharis concava,* associated with some herbaceous layers of minor importance. In the districts close to the Pan-American Highway the upper soil horizons have been removed up to 1·5 m in depth, leaving the soil completely devoid of vegetation.

The middle part of the slope displays a greater variation in nanophanerophytes, mainly *Gochnatia fascicularis, Myrceugenia obtusa, M. correaefolia, Escallonia purverulenta, Eupatorium salvia, Podanthus mitique* and *Fuchsia lycioides.* Moreover, *Oxalis gigantea* becomes more abundant and so do the hemicryptophytes as well as *Nassella pungens,* which in some places forms a continuous cover.

In the upper areas of the slope, with greater effective precipitation (Kummerow, 1966), the microphanerophyte layer begins to dominate, represented mainly by *Azara celastrina, Myrceugenia correaefolia,* and *M. obtusa.* Some nanophanerophytes are found, mainly *Baccharis concava, Bahia ambrosioides* and *Fuchsia lycioides.* The hemicryptophytes of the genus *Melica* and *Nassella pungens*

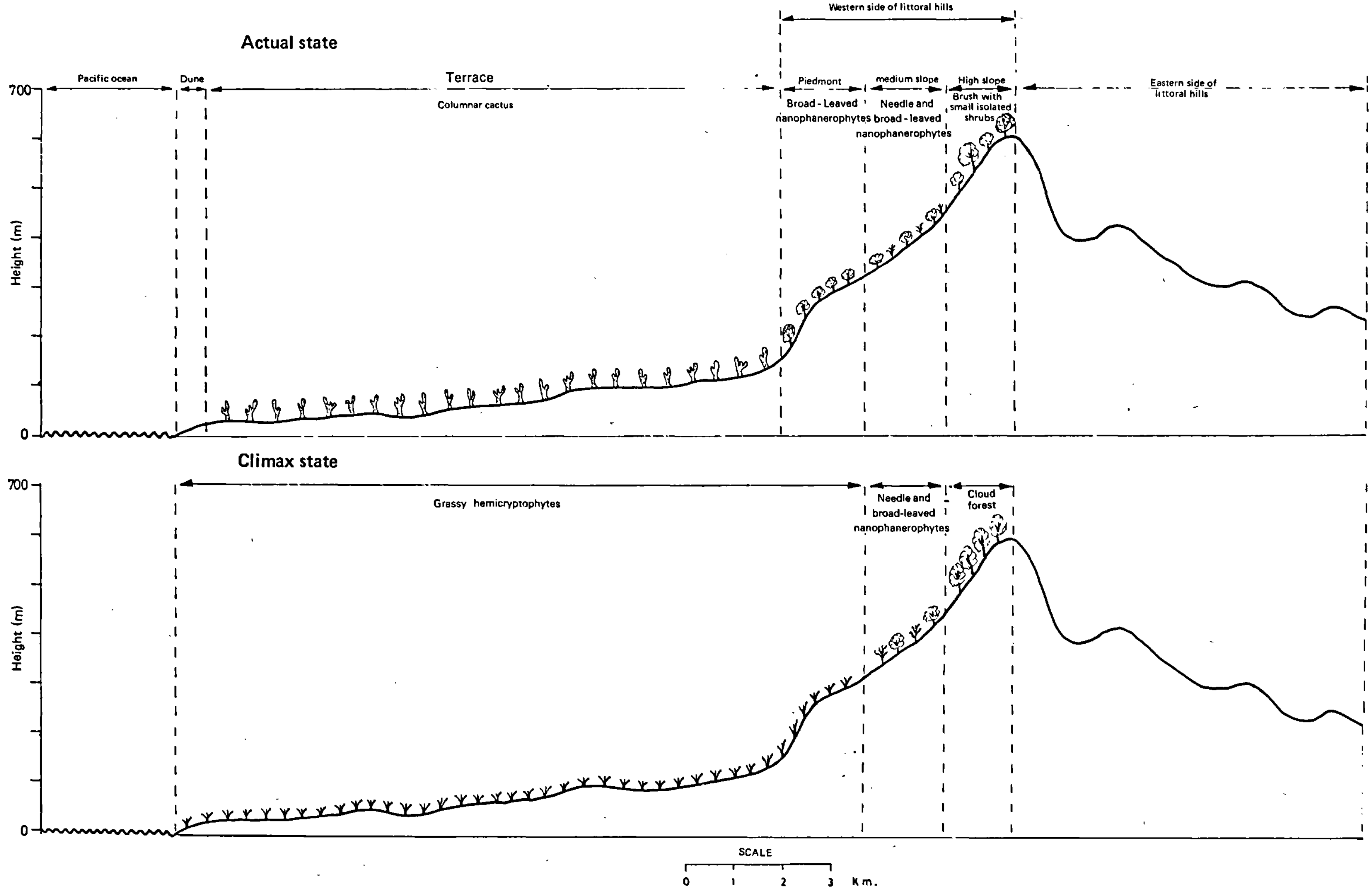


FIG. 25. General profile of the western slopes of the coastal hills and terraces, showing actual and climax states

are less important than in the preceding area because of the greater density of phanerophytes.

Other conspicuous species on the slope sequence, particularly when exposed to the north, are *Puya chilensis* and *Trichocereus chilensis*. There are also *Lobelia polyphylla, Adenopeltis colliguaya, Baccharis linearis* and *B. concava*.

Climax situation. The climax stage in the piedmont corresponds to a range of hemicryptophytes similar to the one described for the coastal terrace, dominated by a continuous cover of species of the genera *Nassella, Hordeum* and *Piptochaetium*.

The climax stage in the middle part of the slope corresponds to a two-layered community of grass hemicryptophytes and nanophanerophytes, in which *Gochnatia fascicularis, Bahia ambrosioides, Baccharis concava, Myrceugenia obtusa* and *Fuchsia lycioides* predominate. Originally, they constituted a sparse cover predominated by perennial grasses.

The climax stage of the upper part of the slope corresponds to a low forest composed mainly of *Azara celastrina, Myrceugenia correaefolia, Schinus molle* and others. The density of these species used to be greater than that found at present, with less numerous nanophanerophytes and hemicryptophytes.

Retrogressive change. The piedmonts around settlements, submitted to intensive agriculture, have undergone great transformation.

Overgrazing of the climax pastures after the introduction of domestic livestock during the sixteenth century has led to populations of invasive nanophanerophytes in the surrounding areas. The persistence of this process reduced the hemicryptophyte layer to a few remnants with isolated specimens growing at the base of brush species which protected them from overgrazing. This process finally ends in dense bush on a stabilized soil with good fertility characteristics.

The increasing need for agricultural produce compelled men to cultivate these soils intensively. The soil was ploughed using draught animals, thus intensifying ecosystem disturbance and enhancing degradation. Cultivation was stopped when yields fell and the land was grazed by cattle for a short period before being abandoned. New land was then cleared and cultivated and subsequently abandoned, causing a general degradation of land on slopes of 10–30 per cent.

The successional regeneration of the abandoned ecosystems is slower than degradation. This has caused these areas to be completely abandoned by man probably more than fifty or sixty years ago. Four well-characterized communities have developed, dominated by:

— *Cassia coquimbensis—Baccharis concava*, in districts abandoned more than thirty years ago, characterized by gentle slopes;
— *Cassia coquimbensis—Muehlenbeckia hastulata*, in cultivated districts at a certain distance from the farmyards and therefore not so intensively utilized;
— *Baccharis concava*, on intensively grazed abandoned slopes (*lluvias*);
— *Plantago tumida—Dicondra repens* in intensively utilized areas.

Colonization by vegetation has been slow in those places where the soil was removed for constructing the motorway. There are some isolated specimens of *Baccharis concava, Bahia ambrosioides*, and *Cassia coquimbensis*, all of them demonstrating their pioneer characteristics.

In the areas surrounding the ravines, where the piedmont is more favourable to vegetation and is also more accessible, communities dominated by *Schinus latifolius* and *Lithraea caustica* were formed, which were intensively harvested. From this same period there are some isolated specimens, but there is no natural regeneration of the species.

The middle and upper parts of the slopes have been slightly transformed by moderate grazing and less intensive clearing.

Eastern slope of the coastal hills

Present situation. The present ecosystem is a mosaic of communities which vary according to the intensity of past land use, the physiographic position and the time elapsed since the beginning of human intervention. The areas exposed to the east which have not been cultivated form a brush comprising two layers. The upper one consists of small microphanerophytes dominated by *Azara celastrina* and a vigorous population of *Fuchsia lycioides*. The nanophanerophyte layer is dominated by *Oxalis gigantea*, with intercalated populations of *Eupatorium salvia, Adesmia microphylla, Baccharis concava, Cassia coquimbensis, Podanthus mitique, Bahia ambrosioides* and *Carica chilensis*. There are also some conspicuous although sparse populations of *Puya chilensis, Trichocereus chilensis*, and *Lobelia polyphylla*. On hills with steeper slopes, or on those exposed to the north, *Puya chilensis* and *Trichocereus chilensis* are more abundant.

The soils of the ecosystems which have only recently been cleared for cereal cultivation still have good physical and chemical characteristics. However, the majority of arable lands have been repeatedly over-exploited and then abandoned, and are highly degraded.

Those districts abandoned ten to twenty-five years ago have a sparse vegetation dominated by *Muehlenbeckia hastulata, Baccharis concava* and *Heliotropium stenophyllum*. Occasionally, some young specimens of *Bahia ambrosioides* and other perennial grasses are found; among the invasive chamaephytes and nanophanerophytes *Atriplex semibaccata, A. repanda, Eupatorium salvia, Sphaeralcea obtusiloba, Chenopodium paniculatum* and others are abundant.

In overgrazed districts abandoned more than twenty-five years ago there is a dominance of *Bahia ambrosioides* and *Gutierrezia paniculata*. Occasionally, some specimens of *Baccharis concava, Adesmia microphylla, Trichocereus chilensis, Haplopappus foliosus, Atriplex semibaccata* and *A. coquimbana* are found. The continuous utilization of these more palatable species prevents the acceleration of the process of ecological succession.

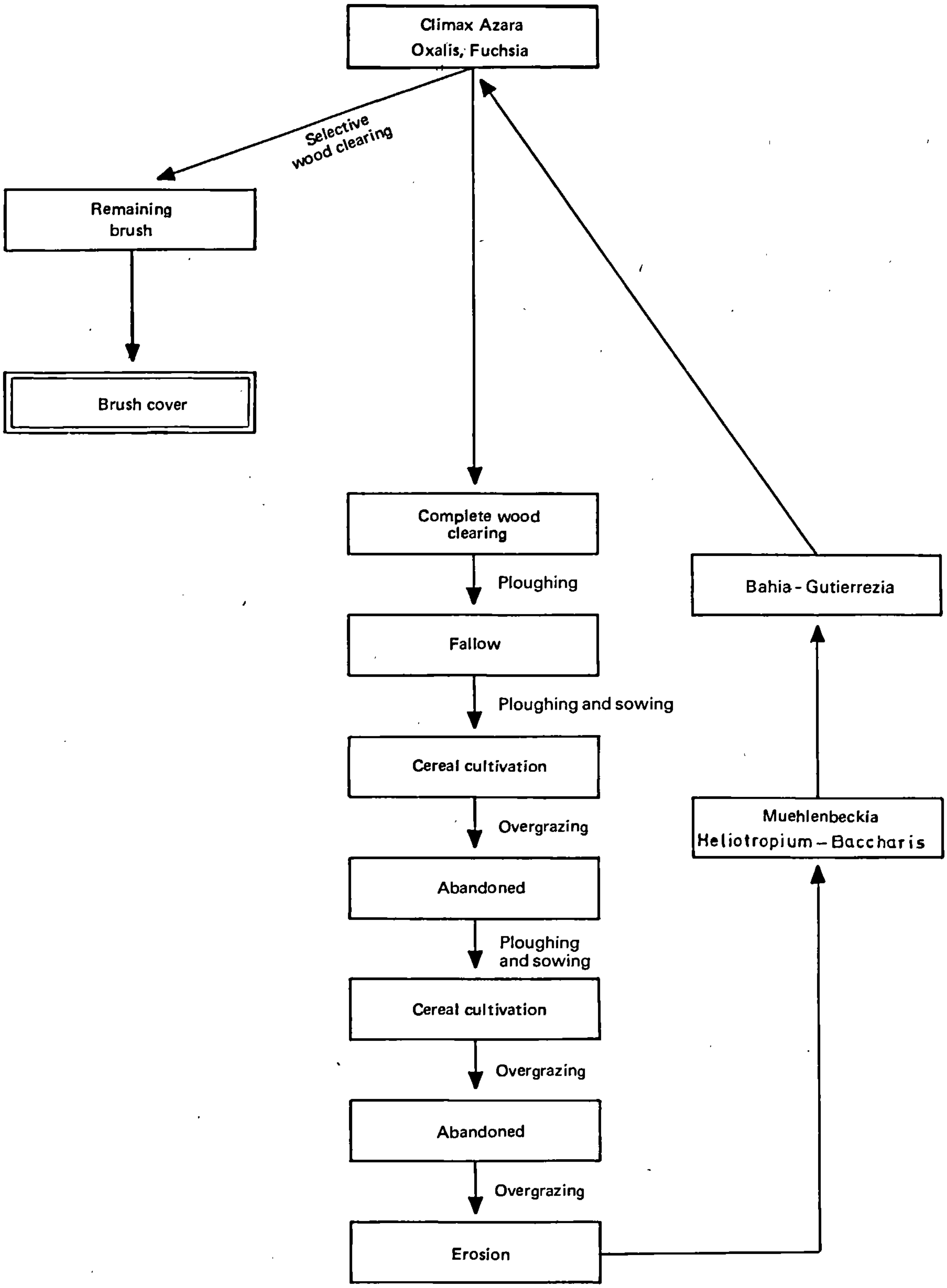


FIG. 26. Stages of retrogression of ecosystems in the western slopes of the coastal hills

Climax situation. The original vegetation described above corresponds approximately to the climax vegetation. Tree-felling, firewood-gathering and utilization by cattle have never been excessive. The steep slopes and the abundance of species of low palatability make the movement of cattle difficult and each forage unit costs a large amount of energy (Cañas and Gastó, 1974). The climax vegetation differs from the present one only in the proportion in which some populations are represented, particularly those which have little value as firewood or forage.

Retrogressive change. This follows two main pathways: that of cultivation and that of selective clearing with simultaneous utilization as pastureland (Fig. 26).

Transformation into brush starts with the manual clearing and burning of the woody species. In spite of the excessive slope, the ground is then ploughed using draught animals and then left fallow in order to sow cereals in winter. This practice, together with the action of rainfall, first of all causes sheet erosion and the formation of gullies. The loss in soil fertility, organic matter, and the original upper soil horizons reduces the yield of cereals and the land is then abandoned. A community of invading pioneers is formed after a long period of time, in which *Muehlenbeckia hastulata, Baccharis concava* and *Heliotropium stenophyllum* predominate. The successional progression of this community leads in forty or fifty years to the *Bahia–Gutierrezia* stage. The vegetation communities of these successional stages are all of low grazing value, although of high stability. The stages occurring between these and the climax stage are unknown. The successional process could be accelerated if goat and sheep overgrazing were eliminated.

Western granitic hill ranges

Present situation. This unit is characterized by its physiography of gentle hills attaining 300–400 m and its granitic origin. It is an area which has long been cultivated and there are no indications of the climatic ecosystem.

The high vulnerability to erosion of the cultivated soil rapidly reduced productivity and a large percentage of the land was abandoned.

The present resident population carry out small-scale irrigated subsistence agriculture in the narrow valleys with a natural water supply. Other people have settled alongside these areas, with the result that the ecosystem is also used for goat-breeding and continuous annual cultivation. Both these latter activities are practised with a complete absence of conservation measures.

The most frequent species are: *Baccharis linearis, Muehlenbeckia hastulata, Bahia ambrosioides, Gutierrezia paniculata, Haplopappus foliosus, Anthemis cotula, Cassia closiana, Senecio sinuatilobus, Adesmia microphylla, Fluorensia thurifera* and *Fuchsia lycioides*; all of which, except the last, are indicative of the pioneer stages of secondary successions.

The intensity of human intervention in the ecosystems gives a mosaic pattern to the landscape units, in which ploughing, cultivated and retrogressive abandoned areas alternate with sparse patches showing more advanced successional stages. A high degree of degradation has been reached resulting in the absence of such resources as firewood and pastures near the settlements, and the inhabitants have to find these farther afield.

Hill ranges of Canela de Mincha

Present situation. This unit is characterized by its hilly physiography, with average slopes of 20 per cent or more, corresponding to the first outliers of the Interior Hill Range. The major part of this unit is intensively utilized for cultivation with grazing–forestry rotations except in the very rocky areas and in those places with excessive slopes. Those areas are over-utilized for grazing and the harvesting of firewood.

Wheat, barley and cumin are sown for a period of ten to twelve years; the land is then abandoned for twenty or more years during which the sparse vegetation undergoes high grazing pressures. Cereals are sown on fallow land prepared with the first rainfall of the season, using approximately 15 kg/ha of seed; three to ten times this quantity is later harvested. In very favourable years the yield can be higher, but in the majority of cases, the amount of seed used is only barely recovered.

Because of the intense system of land use, there is no indication, even fragmentary, of the climax stage, nor is it possible to hypothesize about the changes that have taken place. Among the existing vegetation communities, pioneer species of secondary successional stages predominate, such as: *Haplopappus glutinosus, H. foliosus, Gutierrezia paniculata, Muehlenbeckia hastulata, Heliotropium stenophyllum, Cassia closiana, Anthemis cotula, Cestrum parqui, Adesmia microphylla* and *Bahia ambrosioides.* In the less important layer of therophytes, *Erodium cicutarium* and annual *Adesmiae* predominate. Palatable species such as *Fuchsia lycioides* and *Muehlenbeckia hastulata* are intensively grazed by cattle. The columnar cactus *Trichocereus coquimbensis* and *Eulychnia sp.* stand out in the landscape, together with specimens of *Puya berteroniana.*

Cassia coquimbensis, Eupatorium salvia, Proustia pungens and perennial grasses are abundant on areas exposed to the north. *Llagunea glandulosa, Lepechina salvia, Eupatorium salvia, Fuchsia lycioides* and *Gymnophyton polycephalum* are found on southern aspects. In the more protected places there are some perennial grasses and other palatable plants such as *Atriplex repanda.*

The abundance of threshing floors and abandoned houses suggests that these ecosystems once had a higher productivity. However, in spite of a marked decrease in productivity, the degree of erosion is low due to the intrinsic characteristics of the soils.

Areas with very steep slopes and abundant stone cover exposed in the north were not cultivated in the past. Here the dominant community is *Trichocereus coquimbensis* associated with *Opuntia ovata, Heliotropium stenophyllum, Fluorensia thurifera* and *Puya berteroniana. Lobelia polyphylla* is occasionally

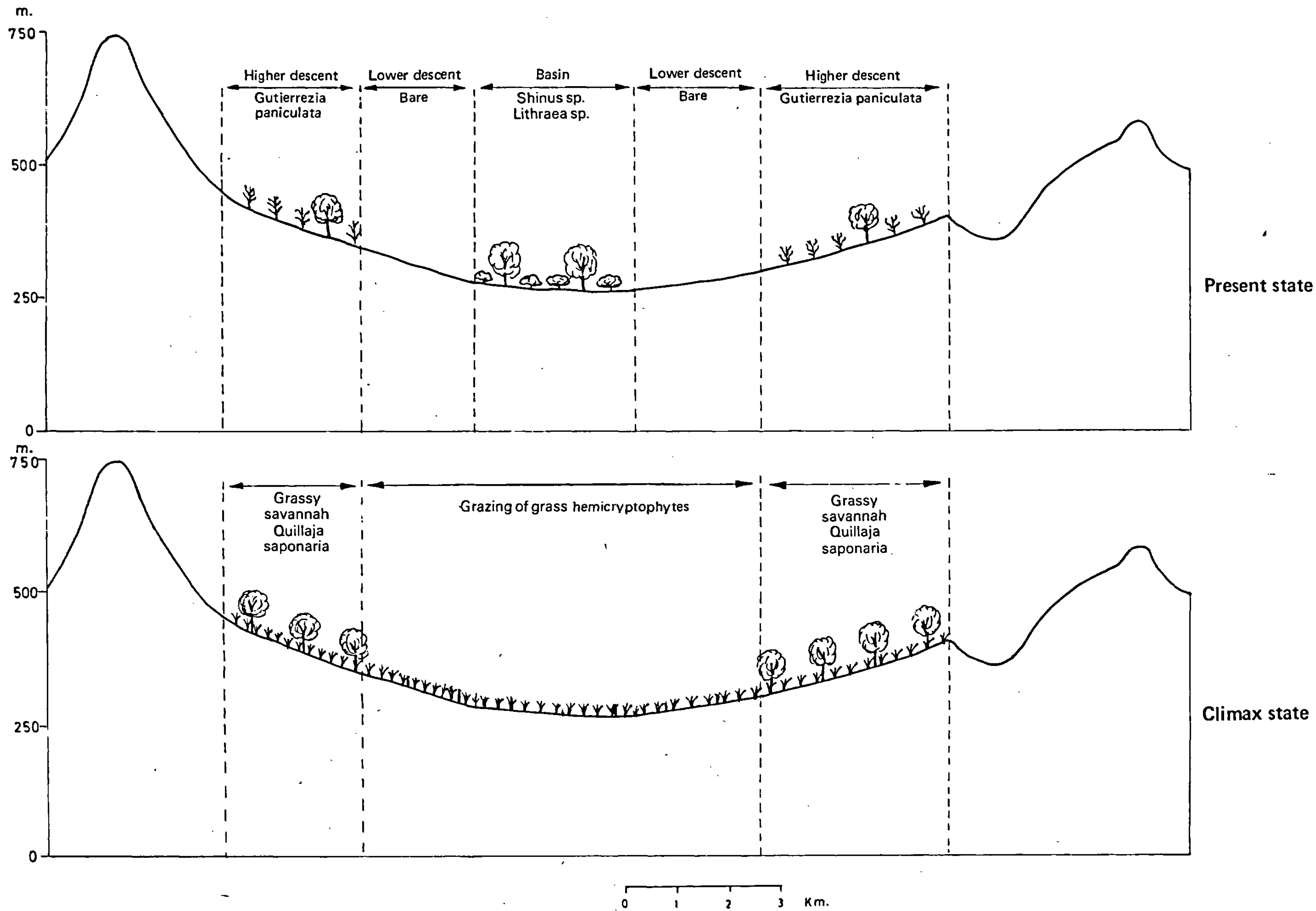


FIG. 27. General profile of the western plain and its present and climax states

found, which is another indicator of degradation. The therophyte layer is poorly developed.

Western plains

Present situation. This unit is geomorphologically defined by its occurrence in intermont valleys, reaching up to 700 m (Fig. 27). The plain is level, with deep soils, therefore having a high productive potential. The climate is different from that of the Interior Plain, with less pronounced thermic variations and a higher relative humidity because of its proximity to the sea.

In areas with higher run-off, a discontinuous forest of *Schinus latifolius, Baccharis linearis* and *Schinus polygamus* predominates. This is a mosaic of trees, intermingled with shrubs and with open spaces dominated by therophytes and hemicryptophytes. Other existing species are *Quillaja saponaria, Maytenus boaria, Azara celastrina, Acacia caven, Gutierrezia paniculata, Solanum tomatillo, Nassella pungens, N. chilensis,* and *Melica* sp. There are areas with a single layer of poorly developed therophytes, due to the dominance of species of *Plantago.* The vegetation has disappeared from those districts lying under fallow or with arable lands destined for cereals.

A continuous cover of *Schinus polygamus*, practically devoid of undergrowth, is often found in depressions in the plains. The microphanerophytes form a discontinuous cover of isolated specimens of *Schinus latifolius* and *Lithraea caustica.*

In the higher margins there are isolated well-developed specimens of *Quillaja saponaria,* which are mostly in decline and lacking younger plants; an indication of successional retrogression of this population.

Climax situation. The more advanced successional stage corresponds to a continuous range of perennial grasses, dominated by species of *Nassella, Piptochaetium* and *Hordeum* (Fig. 27). The standing biomass is relatively high and the annual growth can be consumed without damage to the stability of the vegetation. The soils are chemically stable because of the high above-ground and root biomass, as well as efficient, closed biogeochemical cycles.

In the lower sectors of the ravines and slopes, where they join the plain, the soils are deeper and more humid. Here, broad-leaved microphanerophytes are at their best, such as the pure forest of *Quillaja saponaria* and *Cryptocarya alba*, with other layers of less importance.

Retrogressive change. Increasing and long-lasting grazing pressure has destroyed the perennial grasses typical of the climax (Fig. 28). These plants were not replaced by woody species but by annual mediterranean species coming from the Old World such as *Erodium cicutarium, Bromus mollis, Medicago hispida,* etc. On the other hand the simultaneous over-exploitation by cultivation and livestock leads to the establishment of annual ephemerals, particularly those of the genus *Plantago,* indicating the degraded state of the rangeland.

The opposite happens in the basins. The increase in available water has produced an invasion by almost pure communities of *Schinus polygamus* and other species of high palatability. The adjoining areas upslope were occupied by mixed communities of grasses and nanophanerophytes; *Atriplex repanda* formed extensive communities until its extermination by intensive cultivation.

Some areas with good quality soils were sown with *Olea europea,* which still grows vigorously, although its cultivation has been abandoned because of its low yield as a consequence of the limited local water supply.

The low erodibility of the soil has enabled it to remain in a state of incipient breakdown, whereas the vegetation has already been exterminated. This breakdown follows a quite definite sequence. In the lower, more sloping areas, deep gullies are formed and later colonized by *Muehlenbeckia hastulata.* The less degraded places are colonized by *Schinus latifolius,* and *Salix chiliensis* grows where the gullies are more than three metres deep and have a better water supply. The almost vertically walled gullies are of recent formation, indicating present-day erosion, although the presence of mature trees in the gully bottoms indicates that the process began more than fifty years ago. The abandoned houses in the cultivated areas also testify the existence of a past period in which forestry and agricultural activities were at their best.

The over-utilization of the forest of *Quillaja saponaria* and *Cryptocarya alba* brought about the invasion by *Schinus latifolius,* a pioneer nanophanerophyte of rapid growth which invades territories left by the microphanerophytes of the climax stage. This stage still remains, giving the landscape a savanna appearance with *Schistus latifolius* in the tree layer, and *Plantago tumida, P. rancaguae,* and *Erodium cicutarium* in the therophyte layer.

Interior plain

Present situation. There are now three units in the ecosystems of the Interior Plain: the brush of *Acacia caven,* the plains with *Gutierrezia paniculata,* and the plains of *Fluorensia thurifera—Trichocereus chilensis.*

The *Acacia caven* brush covers a large portion of the country (Matte, 1968), but is found mainly in the north-east of the district under study. This community develops on plains, or level areas devoid of micro-relief, and also on gentle hills broken by small ravines and valleys. These soils are highly attractive for annual cultivation as well as for cattle. As they are surrounded by hills and mountains, they are influenced by the neighbouring higher ecosystems, particularly in relation to run-off and the deposition of sedimentary particles. The annual precipitation approximates 250 mm (Oficina Meteorológica de Chile, 1965).

The dominant layer of *Acacia caven* forms a discontinuous thin cover of vigorous specimens. However, woodcutting for firewood and for fence-building, and continuous browsing by goats, has reduced the soil to a thickness of only a few centimetres. The lower layer of therophytes is poorly developed and lacks vigour, with a marked dominance of *Plantago,* and secondarily of *Erodium*

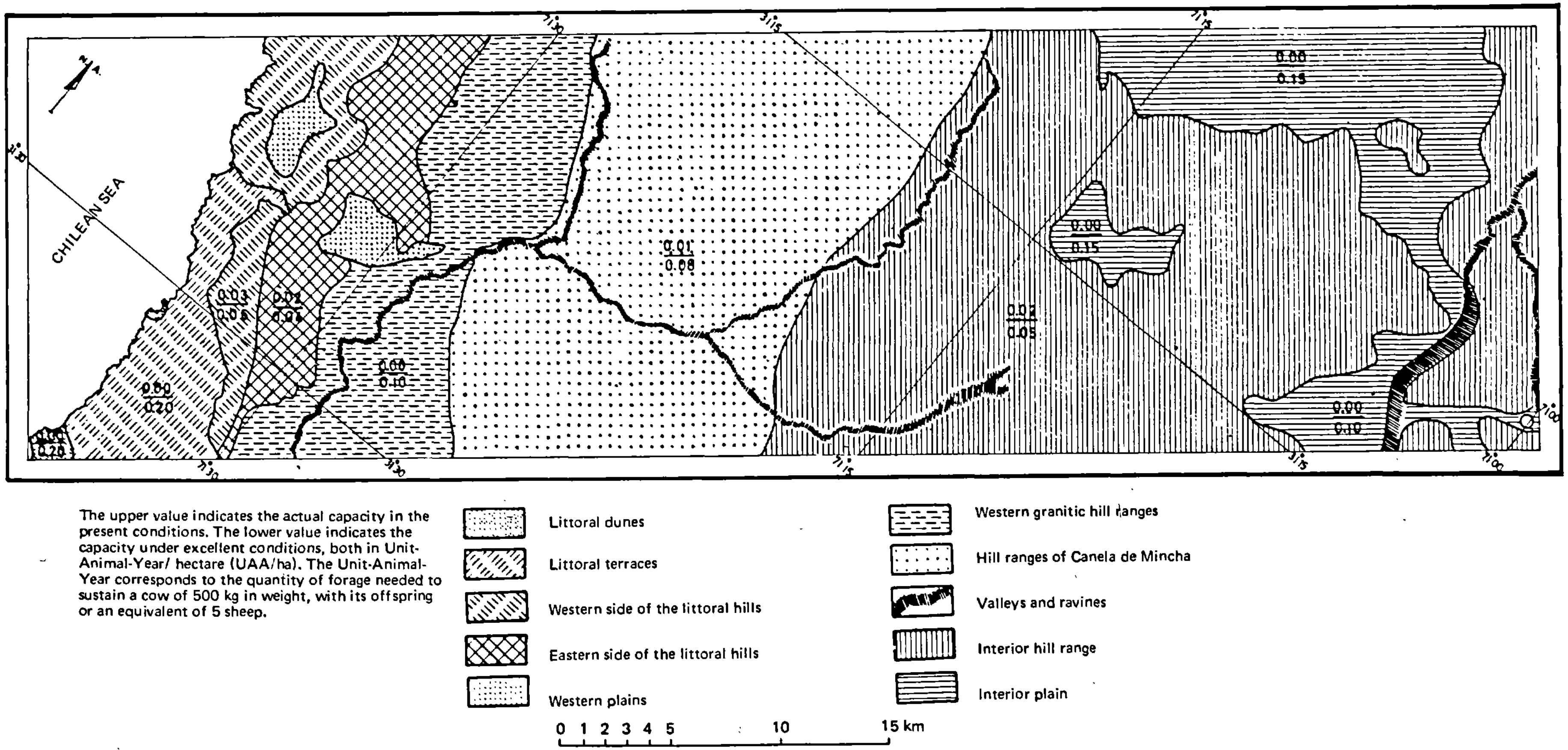


FIG. 28. Map of calculated carrying capacity of rangelands in their present condition and at maximum capacity, District of Combarbalá, 1976

cicutarium, Adesmia angustifolia, and *A. tenella.* This layer is often parasitized by several species of *Cuscuta.* In some limited areas it is possible to find other bushy species such as *Ephedra andina, Porlieria chilensis, Solanum tomatillo, Trevoa trinervis, Baccharis linearis, Schinus polygamus, Proustia cuneifolia, Cassia coquimbensis, Prosopis chilensis, Fluorensia thurifera* and *Margyricarpus setosus.* This landscape unit is ordinarily known as *espinal*, and it has species similar to those found in the Central Plain to the south, even where the rainfall is higher than 800 mm.

In some areas there is an erosion pavement of angular or slightly rounded stones. In these districts protected by stones, by logs or by stony walls, some perennial grasses of a high palatability are frequently found, intensively utilized by goats.

The plains dominated by *Gutierrezia paniculata* constitute heavily damaged environments on the poorest quality ground. This nanophanerophyte forms a continuous cover, with some occasional isolated specimens of *Trichocereus chilensis.* The layer of therophytes is dominated by *Plantago tumida* and *P. rancaguae,* and to a lesser degree by species of *Erodium* and *Adesmia. Margyricarpus setosus* is found as a subordinate species.

The plains dominated by *Fluorensia thurifera* and by *Trichocereus chilensis* correspond to the ecotone between the Interior Hill Range and the Interior Plain. Their development is better in the mountains. The abundance of stones has rendered this land unattractive for cereal cultivation; therefore only limited areas remain with remnants of cereal species.

Climax situation. The scanty and fragmented evidence makes it difficult to elaborate a well-supported hypothesis about the climax origin of this ecosystem. However, a few preserved areas indicate that the original vegetation cover might correspond to a grassland dominated by perennial grasses of *Nassella, Stipa, Piptochaetium* and *Hordeum,* forming a continuous cover of high stability with regard to climatic fluctuations, and having a high cattle-carrying capacity (Figs. 28 and 29). Probably, there were also some isolated therophytes of *Adesmia, Plantago,* and *Trisetobromus*, but of a subordinate, non-vigorous character.

Its low-lying location renders this ecosystem highly vulnerable to invasion by plants from surrounding less-favourable environments. This natural process probably allowed the development of plant populations that did not correspond to the climax of the plain.

Retrogressive change. The level landscape and the presence of valleys with available water rendered this entire ecosystem highly attractive to man. The first mechanism of plant retrogression was the very intensive use of rangelands by cattle introduced by the Spanish colonizers. The abundance of wild mammals and birds, particularly guanacos and partridges, provided an adequate food supply of animal origin (Hidalgo, 1972). Moreover, the combined utilization of the valley and the grasslands in the Cordillera favoured the maintenance of natural resources.

As the human population increased, there was an increasing use of the vegetation by cattle and removal of firewood, together with cultivation. The intensification of livestock-breeding led to the replacement of cattle by sheep, and finally by goats. The productivity of the ecosystems gradually decreased to the present level.

Another form of retrogressive change of the ecosystem started with the introduction of draught animals by the Spanish colonizers. This increased the cultivation of arable lands, which reached its maximum during the second half of the last century and the first half of the twentieth century. Extensive areas were cultivated during this century after the massive introduction of agricultural machinery. As a result, the soils have been impaired by the simultaneous effects of cultivation, overgrazing and wood clearing, until they have finally been abandoned. The present rate of ecosystem degradation is low because the most vulnerable elements have already practically disappeared (Fig. 30).

A narrow piedmont is found between the Interior Plain and the Interior Hill Range. The slopes are gentle, almost level or slightly undulating, rendering the area very suitable for cultivation and grazing. Intensive utilization of this area has practically exterminated the original vegetation. The most characteristic elements are the sparse populations of *Acacia caven*, which give these areas a savanna-like appearance, with a layer of therophytes dominated by species of *Plantago.* In other districts there are specimens of *Lithraea caustica*, sometimes of high density. The original vegetation was probably dominated by this broad-leaved tree, which was slowly replaced by *Acacia caven. Cestrum parqui* can also be abundant, indicating ecosystem degradation, and occasional populations of *Ephedra andina* display less vigour and reduced size due to overgrazing.

Valleys and ravines

Present situation. This unit crosses all other units in the district (Fig. 21). Its characteristics vary according to location, the mesoclimate and the geomorphologic setting. It is situated in the lower parts of the hills, which supply it with sediment and surface waters. There are frequent watercourses, which run the whole year in the lower and intermediate parts of their profiles, and which are seasonal in their upper courses. The availability of water diminishes from the channel outwards towards the periphery of the catchment basin, thus creating a vegetation gradient ranging from hydric communities dominated by grasses, sedges and rushes in saturated soils, to more xerophytic communities in the outer part (Fig. 31).

Altitude and topography together produce another kind of vegetation gradient. In the upper course of the Canela River (in the Interior Hill Range) the dominant communities are *Colliguaya odorifera* and *Trevoa quinquinervis*; one also finds *Fluorensia thurifera* and *Trichocereus chilensis* on northern aspects, together with isolated specimens of *Schinus polygamus* (Fig. 31, no. 7, and Fig. 33).

In the valleys and ravines of the Interior Plain (Fig. 31, no. 6, to Fig. 35) communities of *Schinus polygamus* often appear, intermingled with more developed microphanerophytes. Where the valley is wider and slopes are gentler, the soils become

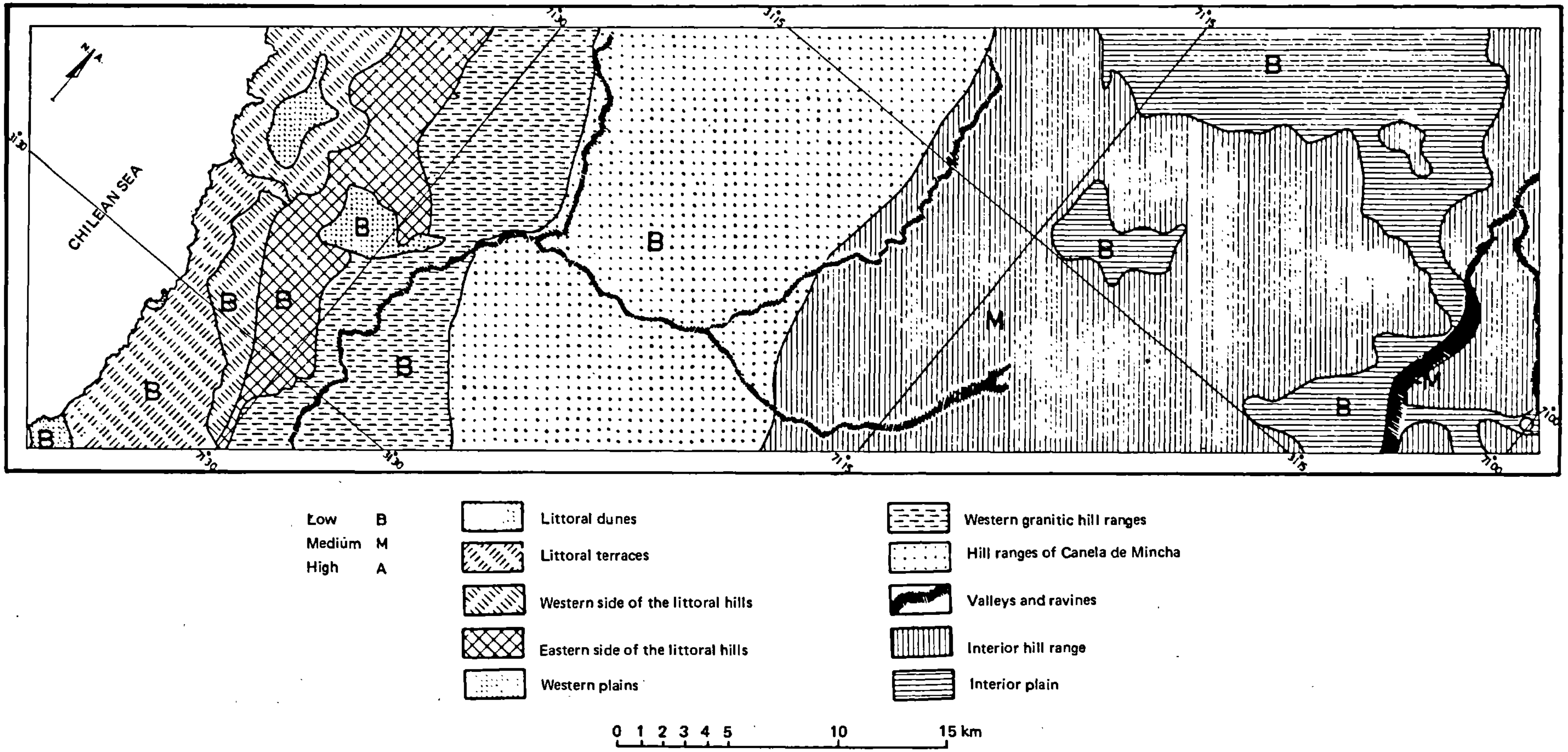


FIG. 29. Map of sensitivity of present vegetation to overgrazing, District of Combarbala

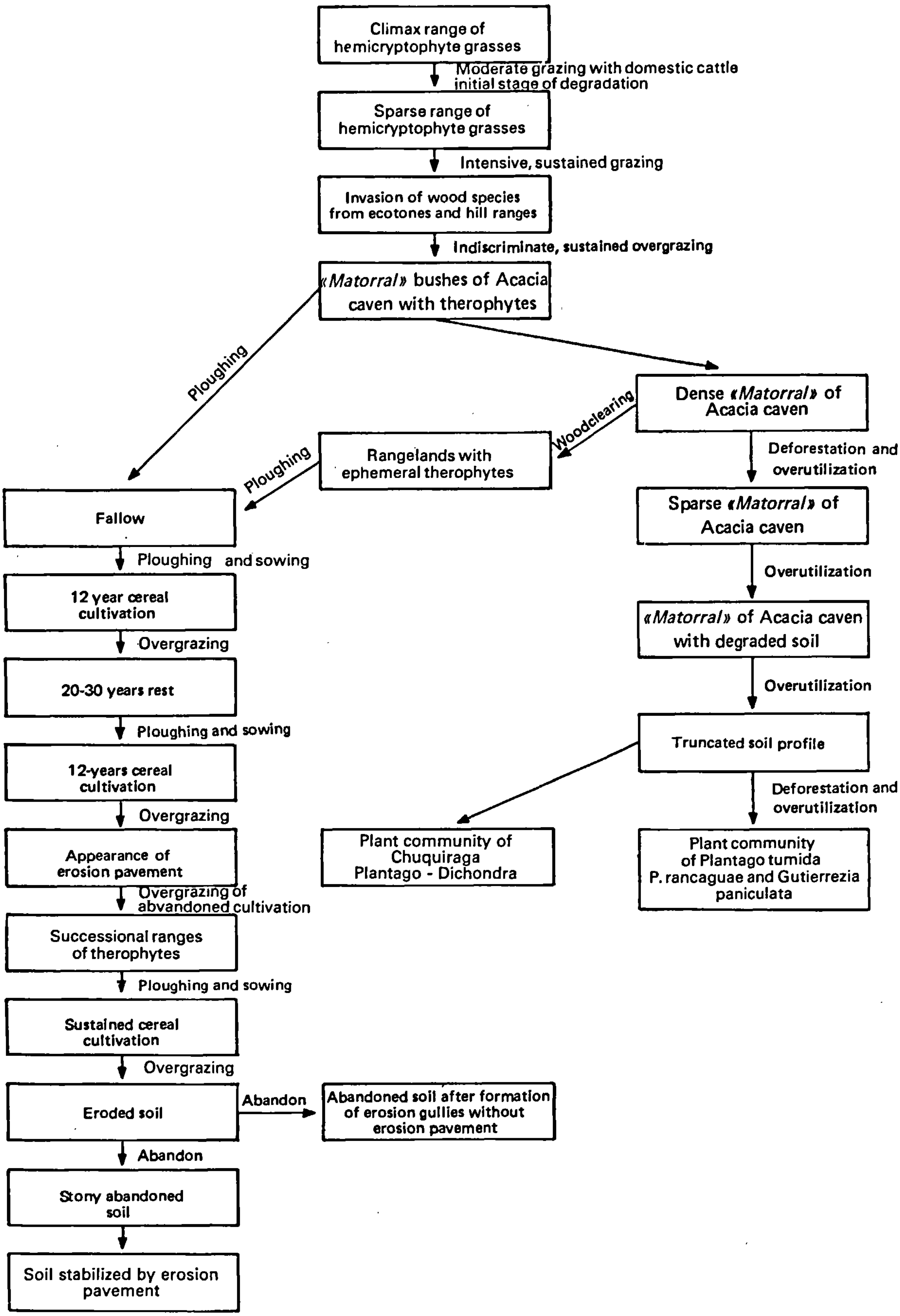


FIG. 30. Scheme diagram of the retrogression of ecosystems in the Interior Plain

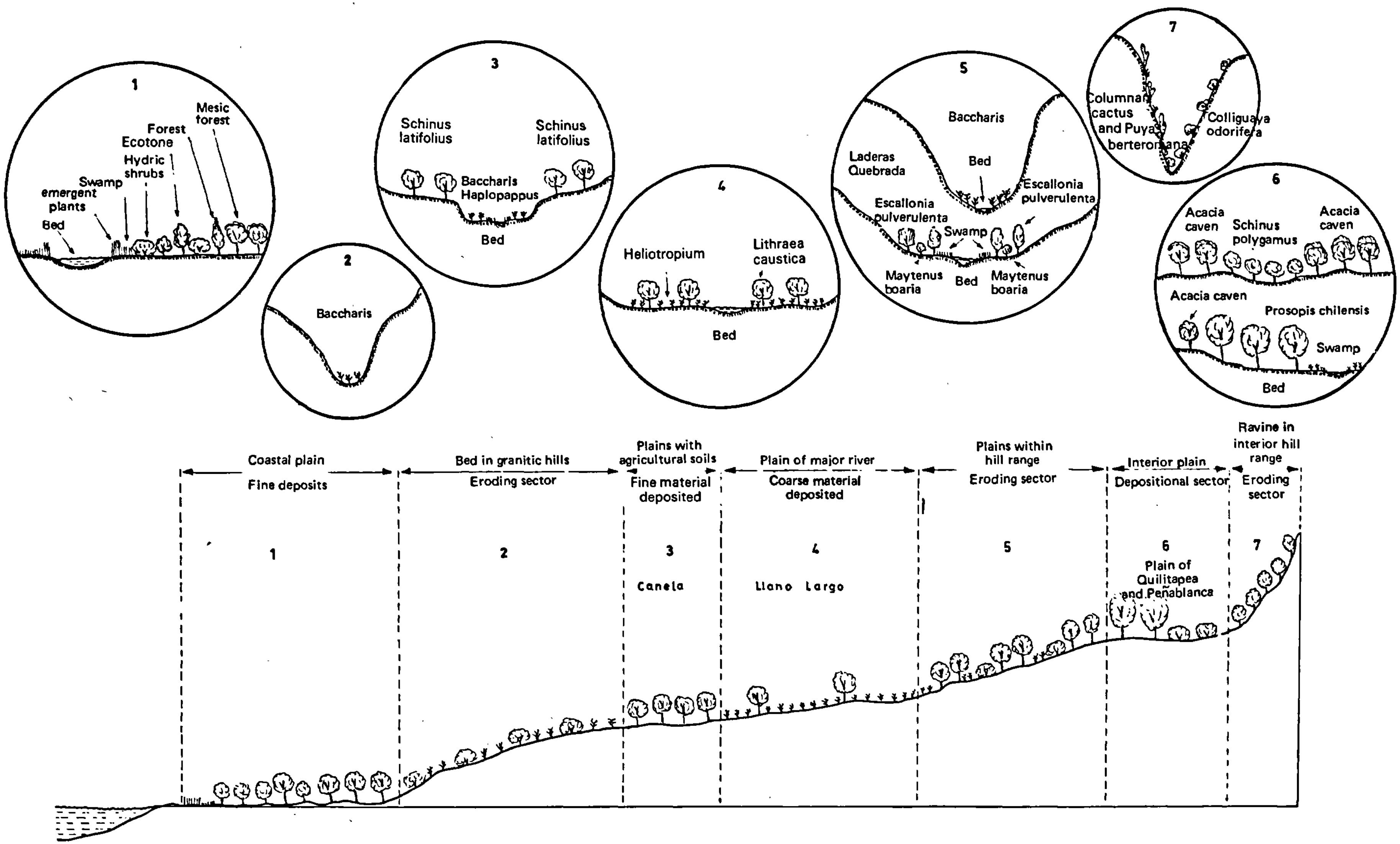


FIG. 31. General profile of valleys and ravines

seasonally hydromorphic owing to shallow flooding, or have a high water-table. There are also permanent stream channels, such as the Pama River. These sectors provide areas for cultivation and for orchards of introduced fruit trees.

The riparian or swampy ecosystem is not very extensive, but it supplies useful forage in critical periods. Toward the outer margins one finds communities dominated by various species of *Baccharis*, of limited interest to man because they supply neither forage nor fuel. The stoniness of the soils, and the saturation of the soil profile, render this ecosystem unsuitable for cultivation. Going further away from the stream channel, one finds an ecosystem which has great importance for the development of the unit, where *Prosopis chilensis* and *Acacia caven* dominate. The nanophanerophyte layer contains isolated specimens of *Cestrum parqui* and *Schinus polygamus*, while the therophyte layer is dominated by *Erodium cicutarium, Plantago tumida*, and *P. rancaguae*; *Dichondra repens* is conspicuous among the hemicryptophytes. This community is developed on an alluvial layer, with variable proportions of rounded gravels and finer materials including sand, silt and clay. The absence of a tree layer and the presence of stone walls in some parts indicate that such areas were under cultivation in the past. In other places, the presence of fruit trees, especially pear trees and fig trees, and abandoned houses, indicates a higher productivity in the past.

In the intermediate sector (Fig. 31, no. 5, to Fig. 35) we do not find a true valley, but narrow ravines with gullied bottoms with some isolated specimens of *Baccharis*, which demand more water. Some wider or stepped sectors lead to the deposition of finer alluvium, which allows the development of restricted communities of *Baccharis piagrae, B. rosmarinifolia, B. paniculata, Maytenus boaria, Haplopappus glutinosus, Escallonia pulverulenta, Plaeocarpus revolutus*, etc.

Going down towards the Junquillar area (Fig. 31, no. 4, to Fig. 35) a depositional zone begins in which rounded gravels predominate together with sand and other materials. In this plain, which can reach a kilometre in width, *Schinus polygamus, Lithraea caustica, Baccharis paniculata, B. rosmarinifolia, Cestrum parqui, Cassia coquimbensis, Ephedra andina, Adesmia microphylla, Atriplex repanda, Plaeocarpus revolutus, Solanum tomatillo, Acacia caven*, and occasionally *Quillaja saponaria* dominate. The plains have a low productive potential for herbaceous plants, but are suitable for the nano- and microphanerophytes, which at the present time are eaten by goats and donkeys.

The lower sector (Fig. 31, to Fig. 34) is more suitable for cultivation due to the finer sedimentary deposit laid down in earlier geological periods. There still exist some fragmentary remnants of the extensive forest vegetation present before human intervention. In this sector agriculture has been more intensively practised, and there is denser human settlement. The dominant tree species is *Schinus latifolius*, mainly restricted to the edges of enclosures.

The sector that traverses the granitic hill ranges (Fig. 31, no. 2, to Fig. 33) is narrow and gently sloping, and is the least developed.

On the coast (Fig. 31, no. 1) the valleys are wider, flat-floored, of low gradient, and can be intensively used for agriculture where water supply and drainage allow. Here is located the hamlet of Huentelauquen, which is one of the oldest and culturally most significant.

Climax situation. The vegetation climax stage in this zone as a whole approximates to that which now exists in the Interior Hill Range, as well as along incised river channels in the adjoining plains. Grazing pressure is not significant as a factor transforming the vegetation owing to the low pasture value of the climax community. The vulnerability of the soil to cultivation is low, except in densely populated areas. The most noticeable difference between the present vegetation status and that of the climax is the decrease in the tree communities due to indiscriminate felling.

The climax stage of the valley segment within the Interior Plain, which has a more favourable environment, included broad-leaved tree species of higher productivity and better quality, although of lesser stability. *Quillaja saponaria* and *Lithraea caustica*, present now in tiny stands, dominated the forest in the past.

Men directed their activities towards the exploitation of the broad-leaved forest of *Quillaja saponaria* and *Cryptocarya alba* in the sector of fine-textured alluvium (towns of Canela Baja and Canela Alta).

The most vigorous and productive vegetation of the valley occurred in the coastal sector of alluvial deposition which had climaxes varying from riparian swamp to hydric and mesic forest, which have now disappeared.

Retrogressive change. In the valleys of the Interior Plain, indiscriminate felling of woody species, in addition to overgrazing and cultivation, led to the formation of almost pure communities of *Schinus polygamus* in the uppermost sectors. In lower sectors, retrogression led to the development of an open forest dominated by *Prosopis chilensis.* Over-utilization and degradation in the hill ranges and piedmonts led to increased run-off together with decreased water consumption by riparian vegetation, all of which resulted in the spread of *Prosopis chilensis*, originally restricted to limited parts of the broad-leaved forest. This resource was later used intensively for firewood, but was also cleared for cultivation. This led to the present vegetation with isolated individuals of low vigour. The condition of the soils has also deteriorated to the point of being unusable.

With the passage of time, abandoned areas now occupy a large part of the valley of the Interior Plain.

In the zone of fine-textured alluvium, near Canela, the soils are less vulnerable to degradation, which has allowed the development of stable ecosystems of annual cropping, alternating with fallowing. The transformation of the natural forest and its replacement by cultivated ecosystems probably took place before the arrival of the European colonizers.

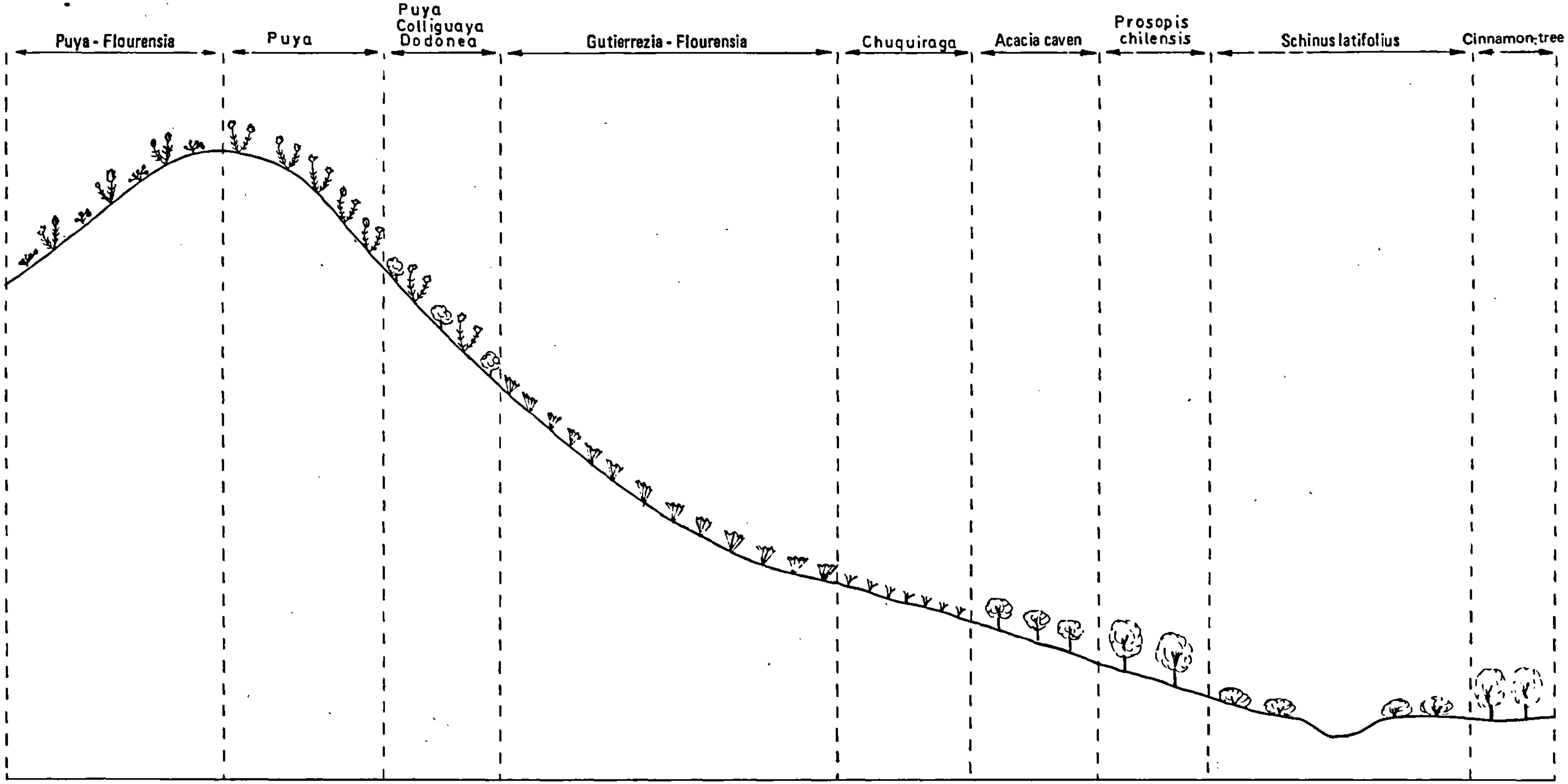


FIG. 32. General sequence of vegetation communities according to altitude in the Interior Hill Range and its valleys

Interior hill range

Present situation. In this unit there is an altitudinal gradient, as well as a slope gradient, which together determine clearly defined plant communities (Fig. 32).

In the rocky upper areas, the characteristic community is dominated by *Colliguaya odorifera* and *Puya bertoroniana.* Over restricted parts a third endemic dominant species appears, *Dodonaea viscosa.* Other abundant species are: *Adesmia microphylla, Gochnatia glutinosa, Plantago tumida, Erodium cicutarium, Sphearalcea* sp., *Medicago hispida, Stipa plumosa, Nassella* sp., *Chorizanthe* sp. Hemicryptophytes protected by bushes attain a good height, although they are sparsely distributed. The slope here is greater than 25 per cent, and rocks and stones are abundant on the soil surface. It is therefore not very suitable for grazing.

The area below the aforementioned community may be dominated by a mono-specific layer of *Dodonaea viscosa,* or by a more or less pure community of *Colliguaya odorifera.* The soil surface is often covered by a pavement of small stones. Therophytes are abundant, dominated mainly by *Plantago tumida* and *P. litorea*; there are also some leguminous forage species such as *Hosachia subpinnata* and *Adesmia tenella.*

The vegetation of the slope immediately below is dominated by low, sparse nanophanerophytes, with *Fluorensia thurifera* and *Gutierrezia paniculata,* and some isolated individuals of *Trichocereus coquimbensis.* Therophytes are abundant, with *Erodium cicutarium, Adesmia tenella, Plantago tumida,* and *P. litorea,* as well as one hemicryptophyte, *Dichondra repens.* The ground layer, which represents a transition towards *espinal* type, is dominated by a low nanophanerophyte, *Chuquiraga acicularis.* This latter layer seems to correspond to a retrogressed successional stage in which there are some fragmentary elements of the climax vegetation.

In more rugged places, with a more arid environment, the vegetation gradient goes from a community of *Gutierrezia paniculata–Fluorensia thurifera* to a community dominated by *Trevoa quinquinervis,* which is found in almost pure communities. During dry years this species constitutes a valuable resource for goats, in spite of its low palatability.

In rocky environments with steeper slopes, the dominant community is made up of columnar cactus of the genera *Trichocereus* and *Eulychnia.*

Climax situation. The climax of the ecosystem, dominated by *Puya berteroniana, Colliguaya odorifera* and *Dodonaea viscosa,* was very little different from the present. The effect of overgrazing, especially by goats, has made itself felt most intensively on the perennial grasses of the genera *Stipa* and *Nassella,* which at present are represented only by isolated specimens in relatively protected environments. As the dominant nanophanerophytes have a low palatibility, they have suffered little from livestock.

The retrogression of the shrub layers left niches free to be occupied by the therophytes, which however do not attain a significant development. Forage productivity is low and is most useful for goats, which have gradually increased in number.

The ecosystem of *Colliguaya odorifera* also displayed a climax like that existing at present. The now subordinate population of low shrubs and hemicryptophytes of forage value were probably both originally present in larger proportion. This is also true in relation to those ecosystems dominated by *Dodonaea viscosa,* of which the climax was similar to that of the present successional stage, with the same retrogressive tendency as the ecosystem of *Colliguaya odorifera.*

In the ecosystem now dominated by *Gutierrezia paniculata* and *Fluorensia thurifera,* the climax was of a different type. The population of *Fluorensia* was originally represented by large, vigorous specimens and the hemicryptophyte layer was of greater importance, giving the aspect of a perennial tussock grassland. The *Gutierrezia* layer, originally absent, took the place of the perennial grasses (Fig. 32).

During the climax stage the lower stratum, now dominated by *Chuquiraga acicularis,* constituted a grassland devoid of woody species, and the therophyte layer was of minor importance. This same process has taken place in other degraded communities of small nanophanerophytes in California and Israel (Naveh, 1967).

Retrogressive change. Overgrazing and to a lesser extent wood-cutting for fuel have been the main causes of retrogression at all stages. Difficulties of access, the geographic position and the rarity of watering points have all prevented excessive utilization, particularly in the most rugged areas. There is no evidence of cultivation. The perennial grasses and the more palatable nanophanerophytes have suffered the most damage, to the point of disappearing.

The marked reduction in productivity of the ecosystems of the middle and lower slopes, where perennial grasses constituted the most important component in the past, is principally due to lower infiltration, as well as to the existence of more open biogeochemical cycles creating a reduction in the availability of mineral nutrients, and to the greater vulnerability of the soil to erosion.

Management and utilization of resources

The present state of the ecosystems described in this report (Fig. 24) is the result of the interaction of their specific characteristics with the intensive, protracted usage to which the ecosystems have been subjected. Land use was moderate at the beginning, but later steadily intensified to levels far higher than the present productive capacity (Fig. 33). A gradual decrease in productivity resulted, which no longer met the needs of the population of the district, leading to permanent emigration. However, the remaining population continues to over-utilize the resources intensively.

The main factor limiting the productivity of ecosystems which have evolved to stages near the climax, is water availability. However, as vegetation, soil and fauna degenerate, this limiting factor becomes less important and gives way to other factors which begin to take priority. The decrease in the

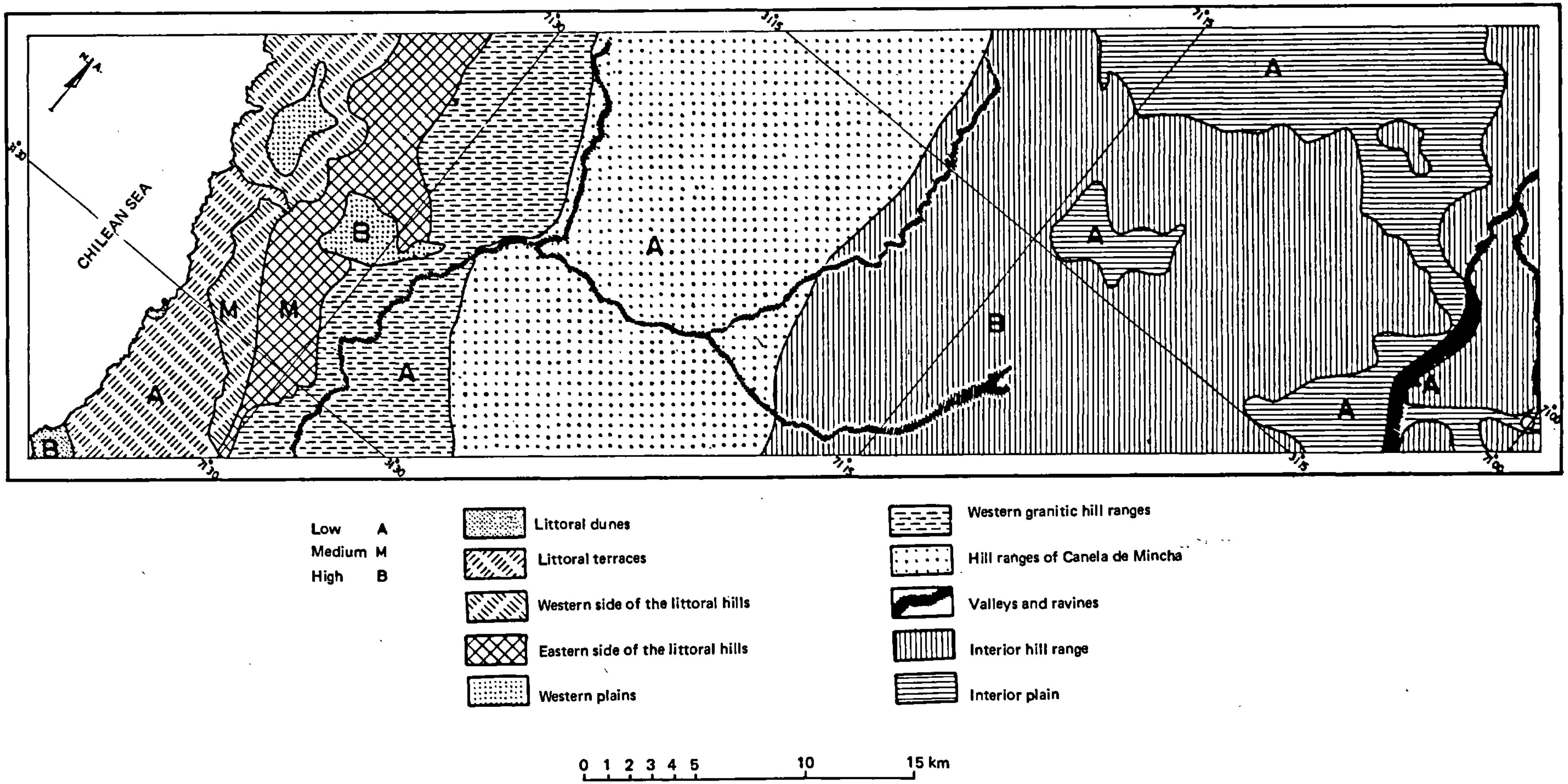


FIG. 33. Map of zones favourable for harvesting the accumulated biomass, District of Combarbalá

productive capacity of the ecosystems of the district is not attributable to climatic variations. Rainfall records from the zone (Oficina Meteorológica de Chile, 1965; Almeyda and Saez, 1958) show that a large variability in annual precipitation is a regular feature of the climate (Pizarro and Rivas, 1965; Gastó, 1966).

A high level of exploitation has been the main mechanism causing the retrogression of the original ecosystems back to their present state, characterized by endemic and invading species of lesser value. Originally, the wild fauna which grazed these natural rangelands were in equilibrium with these ecosystems, over-utilization being avoided through migratory phenomena and auto-regulation of population numbers. The introduction of cattle increased range utilization and meat production for food and the region became more attractive for human settlement. Moreover, a lucrative exploitation of mining resources helped to encourage immigration into this area.

An increased demand for fuel and food grains led to an intensification of cultivation and exploitation for firewood. At the beginning the yields were good, due to the stored fertility and good physical characteristics of the soil (Fig. 34). New areas were cultivated and rotations were shortened to their present level at which productivity decreases every year; moreover the probability of crop failure is increasing even in favourable years (Bull, 1935).

Animal production is becoming more and more unstable, for the increase in forage production in rainy years is not sufficient to carry through the drier years (Fig. 33). Traditionally, the study area included winter pastures, but step by step they became areas of permanent grazing, with limited transhumance into the grasslands of the Andes (Aranda, 1971). Attempts have been made to compensate for the gradual decrease in productivity of local rangeland by successively replacing cattle by sheep, and finally by goats. These latter are able to utilize a greater portion of the plant biomass directly by eating those plants that are less attractive to other species.

Annual cultivation practised without any measures for maintaining productivity finally ended in desertification (Fig. 35). All the systems of agricultural exploitation which exhaust soil fertility and organic matter and destroy soil structure have been short-lived and have led to the degradation of areas where dry farming was practised.

Droughts or low rainfall have been named as the main factor responsible for the failure of the systems used to manage agricultural, forest, and range resources. However, it is likely that the present climatic conditions are similar to those found by the Spanish colonizers four centuries ago. A small decrease in average annual precipitation should have had only a very small impact on overall productivity.

Goats are efficient utilizers of natural resources of environments such as those described in the present study. But neither goats nor grain cultivation are the real causes of the process of desertification, for they may constitute the basis of profitable livestock-breeding or agriculture. Man alone is responsible, through his misuse of natural resources. It is necessary to control man's activities and develop attitudes consistent with conservational management of natural resources; otherwise man's very survival is in peril. It is only a matter of time.

Fauna

Terrestrial fauna

The wild fauna of the district is typical of the fauna of the Chilean mediterranean zone. Most of the species live in all the environments, and their distribution does not coincide exactly with the landscape units already described.

The climax situation of the fauna is characterized by a smaller number of Chilean species than in other homoclimatic zones, which explains why one species is present throughout a broad area and makes a description of its preferred habitat very difficult. In general, birds lay a smaller number of eggs than do similar species in other homoclimatic regions.

The biomass of the vertebrate fauna is high in comparison to other regions of Chile. The mammal biomass can be higher than 20 kg/ha, the bird biomass between 1 to 3 kg/ha, and in some districts the reptile biomass can be higher than that of the other vertebrates.

Changes brought about by man that have resulted in the decrease of species or populations include:

- subsistence hunting of edible species;
- commercial hunting of fur-bearing species;
- domestic cattle-breeding (extermination of predators, decrease in primary production and destruction of dens, species replacement, etc.); at present, 50 per cent of the mammal biomass is composed of domestic animals;
- effects produced by agriculture, mining, and other activities which decrease both primary and secondary production, and reduce the number of nest sites;
- riverside felling of trees and general soil erosion, accompanied by the drying up of watering points and springs;
- introduction of exotic wild species of great adaptability: *Lepus europaeus, Oryctolagus cuniculus, Rattus rattus, Rattus norvegicus, Mus musculus, Lophortyx californicus, Passer domesticus.* At present, 60 per cent of the biomass of wild mammals consist of exotic animals;
- introduction of diseases and parasites: smallpox, foot-and-mouth disease, *Bacillus antraci, Metastrongilus, Distoma, Taenia, Echinococcus, Eimeria*, etc.;
- introduction of cultivated plants and weeds.

Man-made changes resulting in the increase of species or populations include the following:

- decrease in vegetation, which has broadened the distribution of species adapted to arid zones;
- human dwellings and mine tunnels have provided suitable refuges for certain species;
- irrigation of agricultural areas;
- the introduction of domestic animals to the benefit of certain predators.

In general, the entire fauna of the district is decreasing, and some species are now very highly dispersed. The present biomass is unknown, although it is

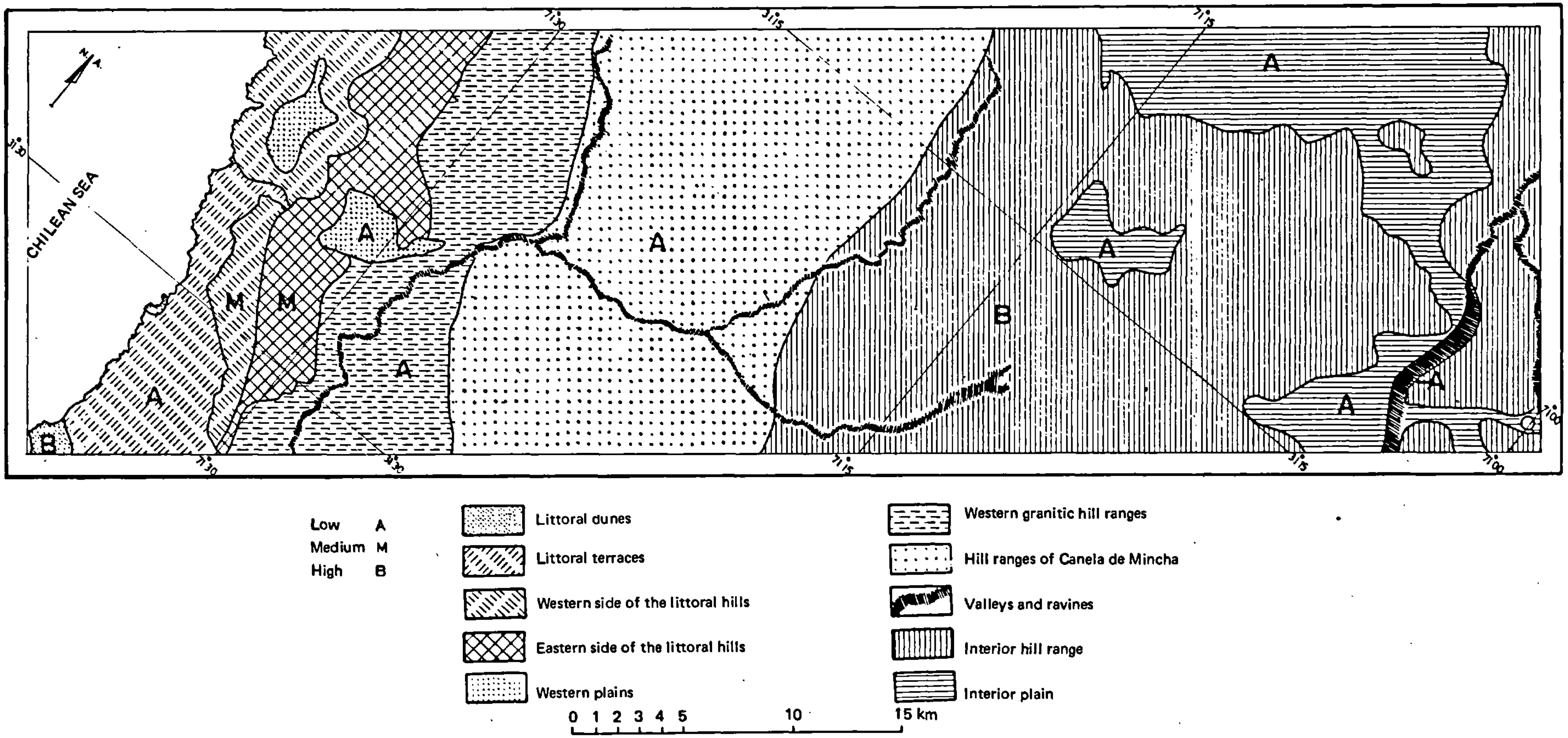


FIG. 34. Map of zones favourable for cultivation, District of Combarbalá

estimated that the wild mammals represent 0·25 kg/ha, and the birds 0·5 kg/ha. With respect to birds, it is estimated that approximately 50 per cent of the species are decreasing owing to the reduction in plant cover; the other 50 per cent have decreased after a reduction in the primary production of food (seeds, insects, reptiles and mammals).

Many pertinent questions must be asked, for example:

- Is the qualitative and quantitative decrease reversible?
- What are the modifications brought about by the introduced flora and fauna?
- What is the degree of dependence between the various plants, or association of plants, and animals?
- What species are best adapted to the new conditions created by man?
- What animals are occupying the empty niches after the extinction of certain species?
- What is the importance of introduced diseases?
- How to quantify decrease in the numbers of species, their density, biomass, and secondary production?
- What is the present situation of the reptiles?

Taking into consideration the abundant fauna of the zone, although several species have decreased or disappeared and the present systems of exploitation are unable to sustain the human population, it would seem necessary for these people to search for a new means of livelihood in which the wild fauna could play an important role. Ecologically oriented management of the fauna could lead to production which would be continuous enough to be of benefit to part of the population (fur, wool, meat, hunting for sport, etc.).

Those species which should become useful to man in the future are: chinchilla, guanaco, partridge, quail, hare, and rabbit. The recovery of wild fauna to a level at which it can be profitably exploited takes less time than the recovery of vegetation, soil or water resources.

Marine fauna

The coastal part of the district is characterized by a rugged rocky shore, with very limited areas of sand. The coast is poorly sheltered, except in the mouths of the ravines. In two of these mouths there are small coves, Caleta Oscuro and Caleta Manso, which provide a seasonal refuge to fishermen engaged in the exploitation of marine resources with the aid of small hand-made vessels. These vessels are 8–10 m in length from stem to stern and are propelled by motors of 20–30 h.p. (Archimedes, Chrysler or Evinrude). The fishing products are sold at the cove to merchants who transport them to consumer centres.

The fishermen have temporary dwellings at Caleta Oscuro and tents at Caleta Manso. Other sandy shores where there is fresh water are occupied in the summer by tourists and fishermen.

Both non-commercial and commercial fishing are influenced by the surface subantarctic water driven north by the Chilean-Peruvian current system, or Humboldt current. Deep-water fishing is influenced by the subequatorial subsurface water driven south by the Chilean–Peruvian countercurrent, or Gunther current. There are also zones of upwelling where marine productivity is higher owing to the greater concentration of nutrients.

The experience of fishermen indicates that ground water reaching the sea could have an important effect on catches; in those years when the rivers have a higher discharge, the underground water is also more abundant and local fishing is more productive. Moreover, some fishermen have observed a parallel between colder currents and a decrease in rainy periods; thus, they have empirically established a relationship between the ocean and the atmosphere.

The main catches made by divers are composed of gasteropods (*locos* (*Concholepas concholepas*) and *lapas* (*Fisurella* sp.)), which are relatively abundant and large in size. As the gasteropods decrease, the fishermen dive deeper or move further north, further from the consumer centres. The harvest of sea urchins has significantly decreased during the last years, although occasional large-sized specimens are found at depths of 15 m or more.

The catching of fish by diving has been, until now, a very important activity of non-commercial fishing. This activity is now steadily decreasing, with only a few remaining boats devoted to it. The fishermen use net traps for capturing sea bass, mackerel, and king-fish, and fishing-lines for the conger-eels, *cojinobas* (*Seriola porosa*), etc. Occasionally, large sharks like the *pejezorros* (*Alopias vulpinas*), or large fish like the *pejeperro* (*Pimelotopon maculatus*), *viejas* (*Graus nigra*), *bilagay* (*Chielodactylus variegatus*), *jerguilla* (*Aplodactylus punctatus*), and *rollizo* (*Mugiloides chilensis*) are caught by harpoon.

Since all fishery products are sold fresh, there are problems of preserving them in ponds or in the rock pools of the low-tide zone. Fish quickly go bad, and there is a need for the establishment of a refrigerated system of transport to the trading centres, as well as the creation of small processing plants to clean and cool fish, and to freeze fillets in periods when fish is plentiful or when demand is lower. Only a small quantity of fish is partly treated in the form of dried or salted products.

In the study area, non-commercial fishing needs urgently to be diversified, for it is based mainly on the exploitation of *locos* (whelks). It would seem helpful to introduce modern methods to locate and catch fish, to improve the trading infrastructure, and to study the possibility of developing the growing of molluscs and other invertebrates in the area.

The species exploited by non-commercial fishing have not received much attention from a scientific point of view. There is a constant and sometimes irreversible decrease as a result of lack of understanding of the life cycles and reproduction rates of the various species. If basic information were available, suitable programmes of technical and financial assistance could be drawn up, based on the real potential of the resources.

Commercial fishing in the area does not have a direct effect on the economy of the district because the catch is brought ashore at ports situated to the north (Coquimbo) or to the south (Quintero). The majority of catches are made on the narrow,

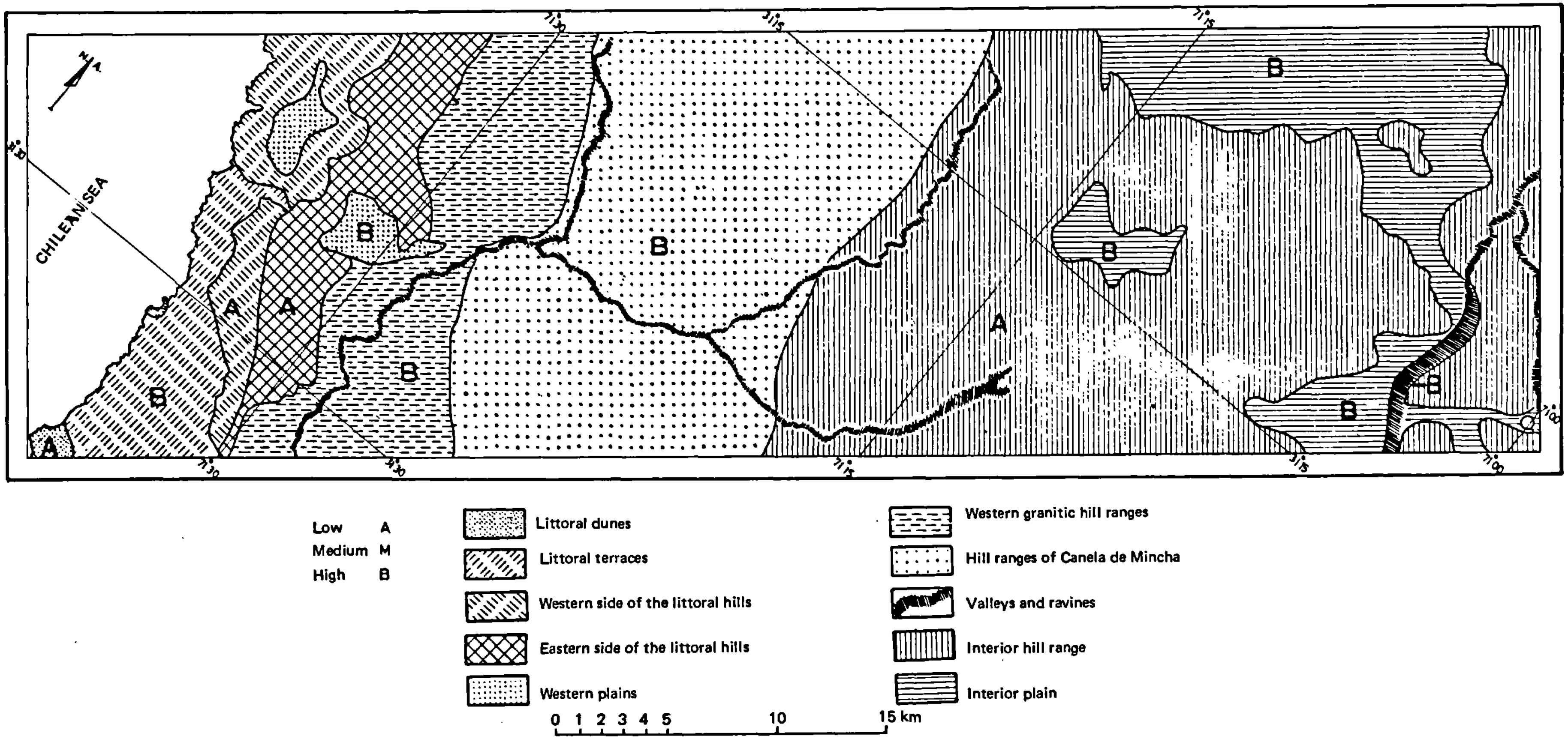


FIG. 35. Map of the sensitivity of present vegetation to cultivation, District of Combarbalá

TABLE 5. Inhabitants of the area of Combarbalá and Mincha (1875–1970) (after Instituto Nacional de Estadística, 1875–1970)

Commune	1875	1885	1895	1907	1920	1930	1940	1952	1960	1970
Combarbalá	14002	15158	13463	16246	15032	16565	19527	17046	17966	17369
Mincha	7728	9826	9907	10420	7672	9969	11371	12070	13567	11347
TOTAL	21730	24984	23370	26666	22704	26534	30898	29143	31533	28692

sometimes non-existent, continental shelf. The deep fishing grounds or 'wells' are few and small in area, are intensively exploited, and as a result the fish population is decreasing. Some regional estimates indicate that increased fishing activity would not be followed by a significant increase over the present level of catches in the Coquimbo–Quintero area.

Exploitation of the fish *lobo de un pelo* (*Otaria flavescens*) is just beginning and this could constitute an important resource of the zone. A suitable programme for managing this species could bring about a successful industry.

The indiscriminate exploitation of some resources potentially endangers the equilibrium of marine ecosystems. For example, *locos* are predators of *picorocos* (*Megabalanus psittacus*), and prawns are the basic food of several kinds of fish. Knowledge about the structure and function of marine ecosystems of the district is urgently needed for predicting the changes which could result as a consequence of fishing activities. Mining activities and their future development also need to be watched, in order to avoid water contamination.

Human population

Demographic aspects

Increase in population

At the time the Spanish conquerors arrived, the region of Coquimbo was occupied by the Diaguitas. The chroniclers on the era estimated that in 1535 there were 25000 Indians in the region included between the Copiapo and Choapa Rivers. A great many died fighting against the conquerors or were forced to work in the farms of the northern and central parts of the country. As a result, by 1545 the Indian population was reduced to 10900. Forced displacement of entire groups was practised throughout the entire period of Spanish domination, altering the number and composition of the indigenous population (Hidalgo, 1972).

At the beginning of the nineteenth century (beginning of Chilean Independence) the Norte Chico (Minor North) constituted a region of great attraction to the rest of the Chilean population. The massive exploitation of gold and copper mines brought about the establishment of rural hamlets and mining towns in the zones situated between the main rivers of the region. These human settlements increased the need for water, food and firewood, and intensified the utilization of the natural resources.

Variations in the populations of the communes of Combarbalá and Mincha, included in part in the present study, are indicated in Table 5. The decrease in population during 1885–95 corresponds to the emigration of the Combarbalá commune inhabitants towards the desert of the Norte Grande (Greater North) in search of wealth from the mines. Between 1907 and 1920, a period during which the exploitation of nitrates of the Norte Grande was at its height, the total population of the district decreased by 15 per cent, this time mainly through the emigration of the inhabitants of Mincha. Between 1940 and 1952, the population decreased in Combarbalá, and between 1960 and 1970 there was a significant diminution all over the district. This phenomenon was due in part to droughts starting in 1968, although there was also a decrease in birth rate during the same period (Fig. 36).

High birth rates were observed during the period 1949–65. In 1952, it was at 38·8 per thousand, in 1960 at 37·7 per thousand, but in 1970 it fell to 26 per thousand. This diminution occurs simultaneously with the introduction of birth-control methods, but it could also well be a response of the population to the catastrophic effects of drought.

On the other hand, the mortality rate clearly decreased during the period 1949–71. In 1952 it corresponded to 17·7 per thousand, in 1960, 15·3 per thousand and in 1970 it was 11·1 per thousand, which is nevertheless higher than the mean of 8·5 per thousand for the whole country during the same year. It is worth pointing out that the mortality rate did not increase in 1970, the severest year of the drought.

TABLE 6. Percentage of children and old persons in the population of the area of Combarbalá and Mincha[1] (after Instituto Nacional de Estadística, 1875–1970)

Communes	1930		1952		1970	
	Children	Old persons	Children	Old persons	Children	Old persons
Combarbalá	43·8	6·0	46·7	7·9	46·5	9·7
Mincha	43·8	6·7	46·5	7·2	49·9	9·3
Average	43·6	6·4	46·6	7·6	48·2	9·5

1. Children: younger than 15 years old. Old persons: older than 60 years.

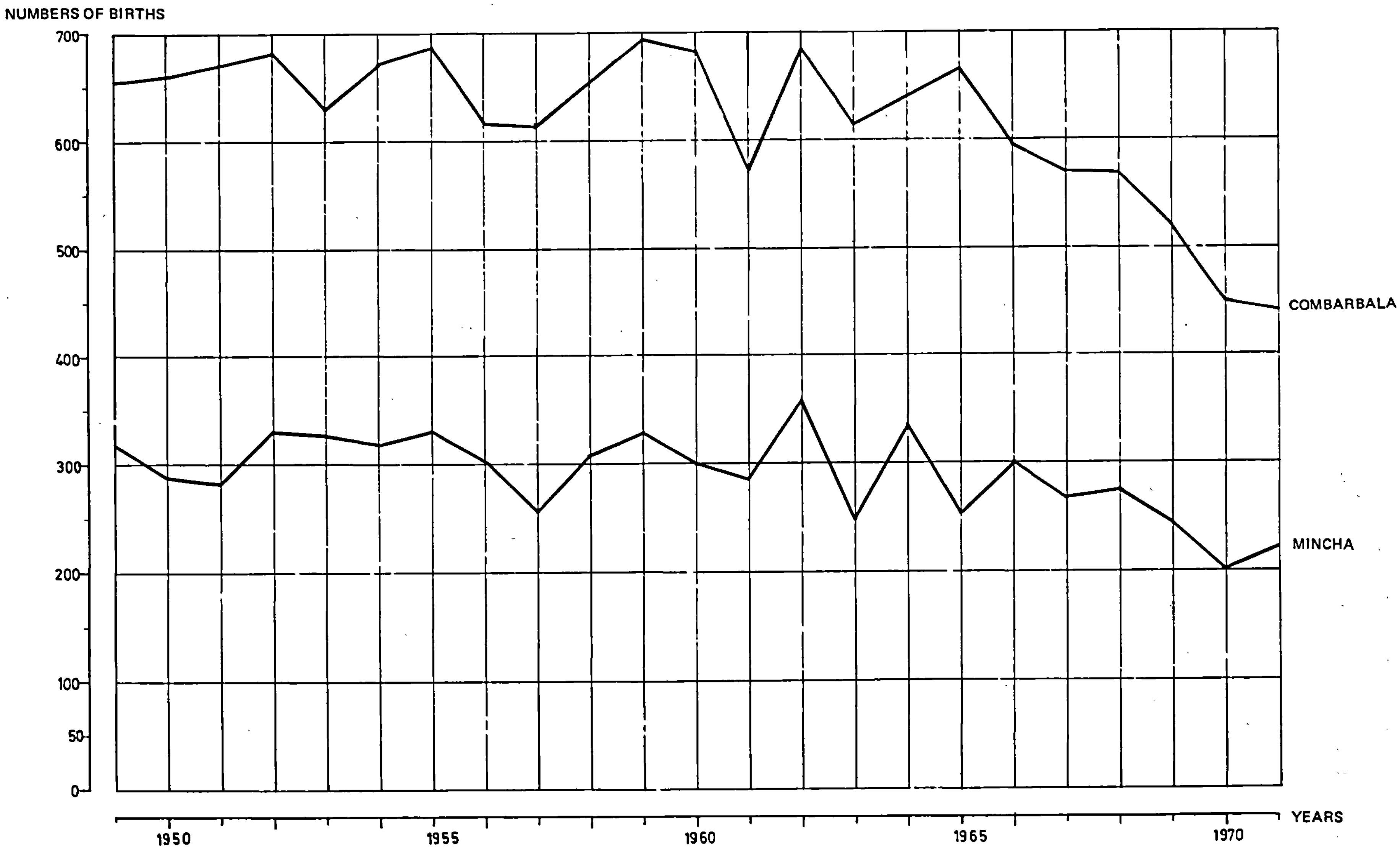


FIG. 36. Number of children born in the area of Combarbalá and Mincha between 1949 and 1971

This could be attributed to the positive effect of assistance measures undertaken by the government and international organizations during this emergency period.

As a result of the phenomena mentioned above, there has been a lower rate of population increase in the district in comparison with the average rate for the rest of the country during the last few years. In 1960 the rate of increase was 22 per thousand compared with 25 per thousand for the whole country, and in 1971 it was 15 per thousand (19 per thousand for the rest of the country).

Composition of the population

In this district there is a predominance of children and old persons in relation to the economically productive population (Table 6). This fact has had repercussions on family relationships and structures, and it also influences economic activities. This tendency has been present throughout the twentieth century, and has been accentuated during the period 1930–70 owing to the emigration of the active population and the high birth rates before 1970. During 1970, records show that 48 per cent of the people were younger than 15 years old, a percentage significantly higher than the national mean value of 39·6 per cent recorded during the same year. The percentage of old persons has regularly increased over the last forty years, owing both to emigration of the active population and to increased life span.

The sex ratio showed a clear predominance of the female population until 1920 (54·4 per cent), but this percentage later decreased to 51·3 per cent in 1970 (Fig. 37). It seems that there has been an increase in the emigration of women during the last decade.

Migration and its consequences

At the time that the Spanish conquerors displaced the Diaguita people, they brought in other Indians as labourers, particularly the Araucanians from the central part of the country, as well as minor groups from Argentina, Peru, and the north of Chile. Black slaves brought in from Guinea during the seventeenth century disappeared as a result of a high mortality rate (Iribarren, 1970).

The exploitation of copper mines was intensified during the seventeenth century and some silver mines were discovered and exploited (Agua, Amarga, Argueros, Chanarcillo). This attracted many immigrant workers, merchants, technicians and businessmen from several areas of the country.

During the second half of the nineteenth century the migration followed an opposite direction, because of the great work opportunities developing in the Norte Grande (Provinces of Tarapaca, Antofagasta and Atacama). At first there was the exploitation of nitrates, which culminated during the first decades of the twentieth century. The exploitation of the large copper mines (Chuquicamata, Potrerillos, El Salvador) began when synthetic nitrate entered the world market. Migration has persisted at varying rates up to the present time: it was very high between 1900 and 1920 and from 1960 to the present.

The people who emigrate from the rural Coquimbo region are mainly males (62 per cent of the total), as opposed to the general tendency in the rest of the country (Zemelmann, 1971; Zuñiga, 1972; Hernández and Thomas, 1975). The average age of these emigrants is 24 years, but there is a clear tendency for women to emigrate younger. Single emigrants represent 82·6 per cent of the total, although they get married (50 per cent) soon after arriving at their new homes (Zuñiga, 1972). About 43·8 per cent of emigrants go towards the north (mostly men), while 14·7 per cent and 6 per cent go to Santiago and Valparaíso respectively (mostly women who work mainly as house servants) (Zuñiga, 1972; Hernández, 1975).

The destination of the emigrants is remarkably stable, owing to the permanent contacts which they maintain with relatives back home. The emigrants themselves periodically set up arrangements to assist new emigrants to move to the great mining centres of the north, where they can live with their relatives. This constitutes an effective mechanism of integration into a different social environment.

Agricultural workers predominate among the emigrants, followed by housewives, students and miners. Their new work is mainly as miners, and to a lesser extent as domestic servants or in other types of jobs.

The predominance of emigrants whose ages range from 20 to 45 years has distorted the population composition of the district. Women, children and old persons have come to fill the role of the family nucleus in the absence of the active male population. It is increasingly frequent moreover that the grandparents bring up their grandchildren in the absence of their fathers.

Owing to the increasing deterioration of resources and the lack of regional development policies intended to improve living conditions, emigration has become the sole alternative for a large part of the population. This response varies roughly with the climate, in that it increases during droughts. This sustained emigration has not only kept the pressure of human population in the district at a constant level (Table 7), but has also brought about several forms of assistance to the inhabitants.

The emigrants very frequently send back money, food and clothes to their relatives. This external aid has been evaluated in the valley of the Hurtado River (north of the district under study), where it constitutes 25 per cent of family incomes (Pascal, 1968). Sometimes this aid is addressed to the whole resident

TABLE 7. Population density in the area of Combarbalá and Mincha (inhabitants/km^2) (after Instituto Nacional de Estadística, 1907–70)

Communes	Census						
	1907	1920	1930	1940	1952	1960	1970
Combarbalá	6·4	5·9	6·5	7·7	6·7	7·1	6·8
Mincha	4·4	3·3	4·2	4·8	5·1	5·8	4·8
Average	5·4	4·6	5·4	6·3	5·9	6·5	5·8

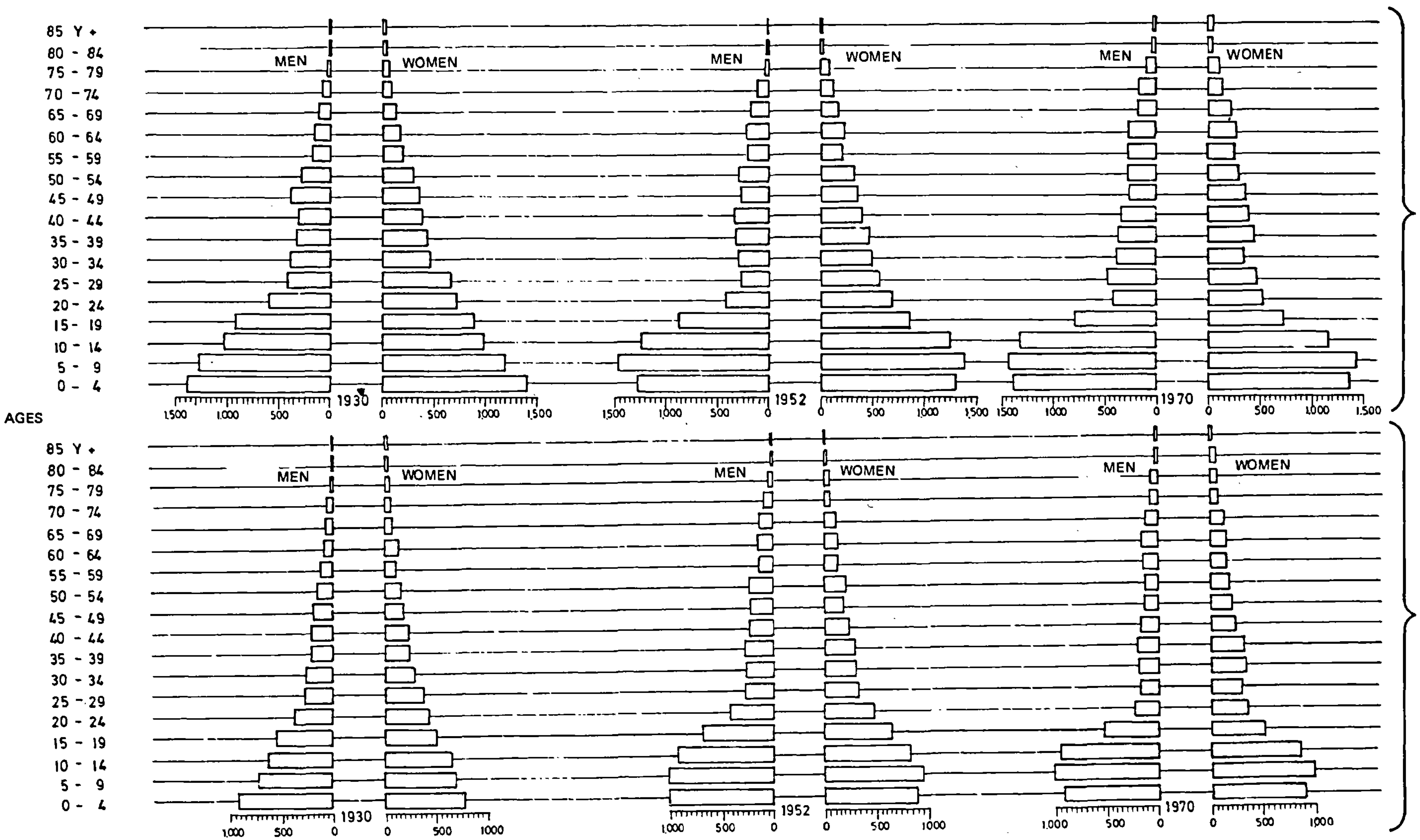


FIG. 37. Sex and age distribution (number of inhabitants) of the population of the area of Combarbalá and Mincha

community, such as the donation of a building to serve as a health clinic in the town of Canela Baja, by former residents now working in the copper mine of Chuquicamata.

One can predict a likely increase in emigration during the coming years, given the difficult subsistence conditions of the district. The accelerating process of urbanization will also strongly affect the work aspirations of the young, which cannot be satisfied within the district. The recent introduction of television into the rural areas is an efficient way of introducing urban cultural elements. At the same time, the content of school programmes and the attitude of country teachers contribute to making the young people want to break with their environment. A survey made in August 1976 among approximately 150 schoolchildren of 12 to 13 years old in rural schools of Quilitapia and Canela Baja showed that only 8·4 per cent of the children wish to work in agro-pastoral, mining or business activities of the zone. In fact, 22 per cent of the male students would prefer to become mechanics, 13·5 to follow military careers and 10·2 per cent become teachers. Among the girls 43·4 per cent would like to be teachers, 22·6 per cent nursing assistants or social workers and 7·5 per cent dressmakers. The aversion from the traditional jobs of the rural social setting is evident.

Social and cultural aspects

Land-ownership and social systems

Two agrarian units, which represent two different systems of land-ownership, coexist in the region of Coquimbo, namely: the large *hacienda* and the agricultural community (Fig. 38). Both came into being during the sixteenth and seventeenth centuries, at a time when the Spanish Crown was giving the Conquistadores large expanses of land.

The hacienda. In the case of the *hacienda*, the lands received from the Crown have been transmitted through inheritance and maintained undivided in the hands of a single owner. Some *haciendas* even increased in area through purchase, or through the occupation of adjacent lands belonging mainly to *comuneros* (members of agricultural communities). During the eighteenth and nineteenth centuries, the *haciendas* reached the height of their development when they specialized in supplying the mining settlements of the region.

Three social classes were connected with the *haciendas*: the seasonal agricultural labourer (*peon*), the tenant, and the permanent labourer (*inquilino*). The *inquilino* provided his own work and not infrequently that of another bound labourer (*peon*). He received a portion of land to cultivate for himself, although this portion was not always large enough to sustain his family (Barros Arana, 1886). The tenant, who paid for the use of the land in kind or in services, in the majority of cases eventually became an *inquilino* (Pascal, 1968). This labour structure involved differences of social and economic status. Skilled workers (carpenter and smith), horsemen (cowboy and foreman), and the supervising personnel (overseer and steward), were of higher status than the agricultural labourers. During the twentieth century this social stratification evolved in two directions: towards a one-man enterprise in which the agricultural labourer gained in importance, receiving payment for his work in money; and towards a larger enterprise which embraced numerous subsidiary family enterprises (share-farmers, tenants, cattle-feeders) from which the present small farmer originated.

The agricultural community. This is a form of land-ownership that was typical in the Norte Chico, and originated during the colonial period. It constitutes a social organization of small farmers, united by bonds of relationship or friendship, living on communal property which is basically an undivided expanse of dry-farming land.

The community itself is the real owner of all the arable lands, rangelands and places where firewood is collected, but all members of the community (*comuneros*) are also individual owners of small irrigated areas called *hijuela*, alongside the ravines. The highest authority in this organization is the General Assembly of *comuneros*, which takes decisions on important matters such as the right to utilize part of the arable lands (called *llovias*) or to grant land for building a house (*piso*). The Assembly elects an administrator of the community, who is vested with authority for administration and for settling conflicts within the community.

Earlier, *comuneros* inherited their membership, and this gave the community a closed structure. During recent years, some outsiders have become *comuneros* by authorization from the assembly to buy a small irrigated plot and rights to the use of common lands from another *comunero*. This situation has modified the traditional closed system.

Comuneros are the poorest people of the region. Their farms are small and barely profitable because they are located in the most degraded areas. Intense human pressure on the land and poor management of natural resources have both brought about this deterioration. Figure 39 shows the population density by district (administrative division), and it shows clearly that, apart from the town of Combarbalá, the highest population densities are found in the areas occupied by the agricultural communities.

In general, only members of the family work on the farm of the *comunero*. The few males remaining after emigration devote their time to cultivating the land and they also take charge of trading; the mother and daughters take care of the cattle, milk the goats and make cheese, which in many cases constitutes the only family income; the children look after the flocks, which usually have no more than thirty goats, some sheep and very rarely a few cattle. The agricultural production is basically made up of wheat, vegetables (tomatoes, corn, beans), and dried fruits coming from some communities of the commune of Mincha.

Present condition of the comuneros. The *comuneros* constitute the majority of the rural population of the region of Coquimbo. In the commune of Mincha, they make up more than 80 per cent of the population. They proudly claim descent from the Spanish

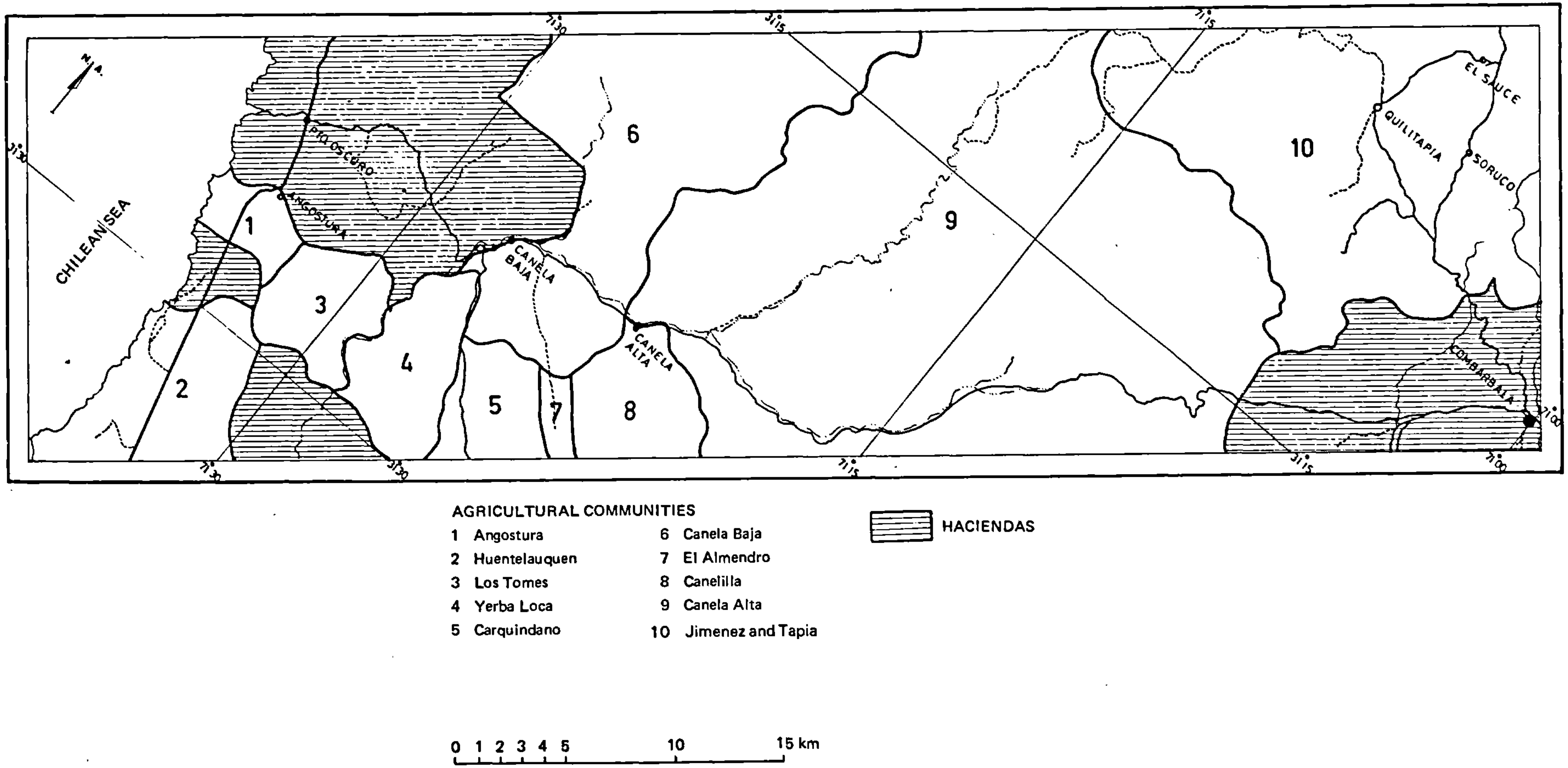


FIG. 38. Land-ownership systems, District of Combarbalá

Conquistadores, in spite of the fact that their present economic situation places them at the bottom of the social scale of the region. An average goat flock in 1965–66 had only twenty-two animals, and the irrigated lands are now generally reduced to a small fraction of a hectare (Cañon, 1966; Pascal, 1968; Hernández, 1975).

The size of the agricultural communities is variable; in the commune of Combarbalá, there is only one—the Jiménez and Tapia Agricultural Community—with almost 50000 ha for 1200 men and their families. Much subdivision into smaller communities has taken place in the commune of Mincha, mainly as a result of land parcelling through inheritance, and secondarily through land sales.

The exact number of agricultural communities is not known because many of them are not duly legalized, even though the registration of property claims began at the same time as the promulgation of the Civil Laws (1847) and the ordinance regulating Real Estate in 1857 (González del Río, 1970). Uncertainty concerning boundaries causes continual conflict between neighbouring communities. Traditionally, 120 has been the estimated number of communities in the region of Coquimbo (González del Río, 1970). However, a much higher number was found after a programme regulating boundaries was put into effect.

Recent studies for a programme for eradicating extreme poverty in Chile, included in the economic and social plan of the government, indicate that the region of Coquimbo has the highest percentage of poor people in the country (29·9 per cent). The communes included in the present study have the highest percentage of poor people of the region (Mincha 42·9 per cent, and Combarbalá 39·7 per cent) (Oficina de Planificación Nacional, Instituto de Economía de la Universidad Católica de Chile, 1975).

Conflicting relationships and power structures

The mining boom which occurred during the nineteenth century aroused the interest of *hacienda* owners in breeding of mules, cattle, and goats using transhumance (Baraona, 1961). In the summer, the livestock moved to the high mountain meadows of the Andes (*veranados*) and in winter to the central and coastal areas (*invernados*). These movements made the dry-farming lands more attractive; serious legal conflicts ensued, with occasional violent and illegal occupation of the lands (Cañon, 1966).

Power structures have changed with time. In the beginning, the lordly power of the land-owner gave him the authority and means of repression. This was facilited by the fact that the landlord was the sole link between the rural areas and the urban centres, where the national authorities were located. With the twentieth century, changes took place as urbanization spread out to rural localities. The networks of national administrative offices were established and new hopes of social development arose among the rural population. To realize these expectations, the inhabitants of rural areas tried to organize themselves into communities and appealed to local people having better educations and bureaucratic connections to intervene and link them with the metropolitan centres of power. These intermediaries were recruited from the middle class (merchants, public officials, local politicians, etc.) and they concentrated the power originally held by the landlords. The biggest centre in the district of Combarbalá is Combarbalá City, the town of Quilitapia being of less importance. The towns of Canela Baja and Canela Alta are situated in the district of Mincha.

Social structures and social upbringing of children

The emigration of fathers has obliged mothers to assume the responsibilities of the head of the household and from early childhood children are expected to take care of flocks, bring water, gather firewood and so on.

A high percentage of unmarried mothers and the accompanying high percentage of illegitimate children are typical of the region of Coquimbo. In 1966 in the province of Coquimbo, 29·5 per cent of the children were illegitimate, and in the commune of Combarbalá, 34·8 per cent. However, the situation of unmarried mothers is accepted as a social fact among the rural inhabitants, without any form of rejection or social sanction. The unmarried mother and her children generally live with the maternal grandparents.

The social upbringing of the child, generally in the charge of the mother and the grandparents, is basically oriented towards preparing it to play its part in the subsistence of the family group. However, the education provided by schools plays an important part in breaking the link between the child and its rural surroundings. The subjects included in the school curricula are exactly the same as those given for the entire nation, and contain cultural elements coming from the urban society which are unadapted to the reality of difficult conditions of life in the countryside. Hence, there is an evident confrontation between the home-acquired social training and the educational lines pursued at school. Most of the teachers come from urban zones (60 per cent in Combarbalá), and unconsciously contribute to awakening and developing the children's expectations in the distant urban centres.

Diet and malnutrition

Typically, the popular diet contains an excess of carbohydrates: wheat, in its various forms, potatoes, rice, pasta, etc. In smaller quantity it contains vegetables (beans, lentils), animal products (meat, milk, cheese), and also a small but inadequate amount of green salads. According to an inquiry made in the commune of Mincha, 44 per cent of the families have meat less than once a month, and 30 per cent once or twice a month. The consumption of goat milk is widespread among children only during the goats' lactation period, and the insufficient amounts of greens are consumed only in summer (Cañon, 1966).

The infant population (younger than 6 years old) of the district is evidently undernourished (defined by the age–body weight ratio). Regular surveys made

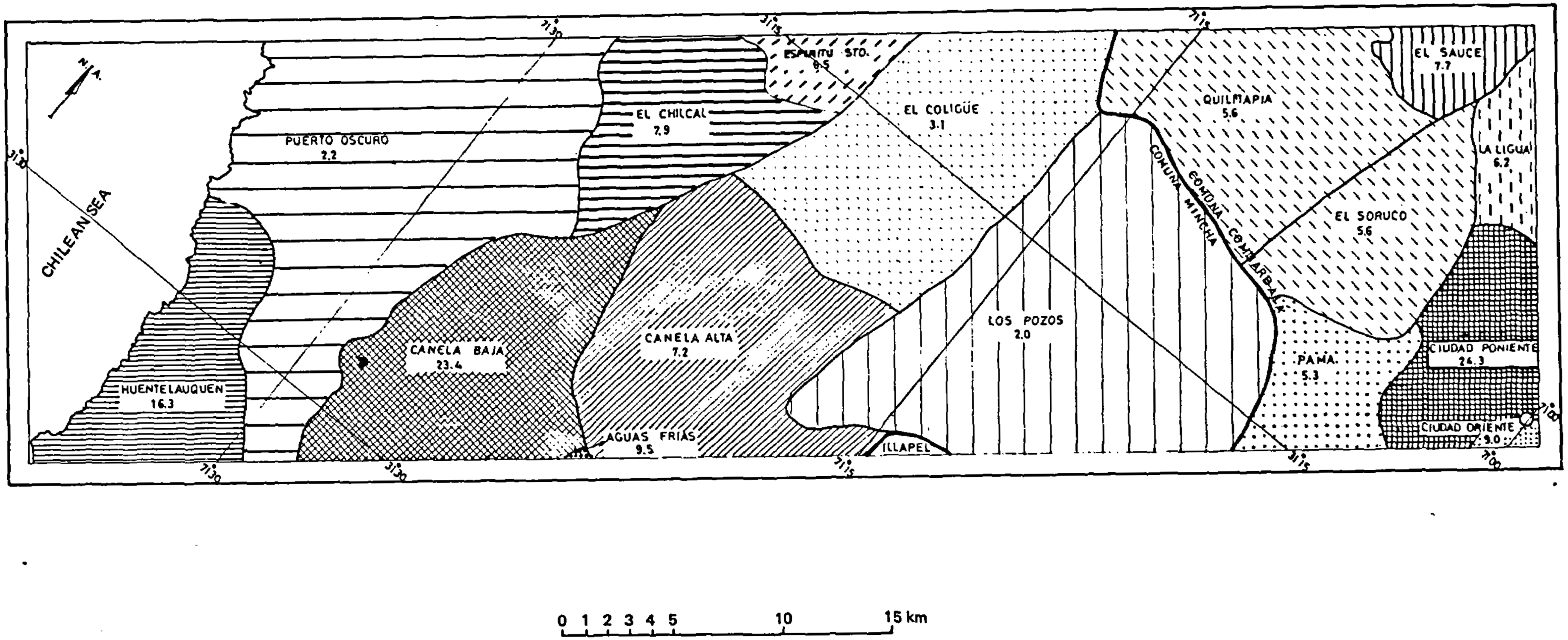


FIG. 39. Population density by district (inhabitants/km^2) in the area of Combarbalá and Mincha, District of Combarbalá, 1976

in the district of Combarbalá show that the percentage of undernourished children was 25 per cent, 28 per cent and 26·8 per cent for 1974, 1975 and the first half of 1976 respectively. This problem is even more acute in some localities, such as the hamlet of Soruco, where 41·3 per cent, 48·1 per cent and 42 per cent were recorded for the same periods. In 1975, 24·4 per cent was recorded in the commune of Mincha.

Fifty per cent of childhood malnutrition appears in children aged between 3 and 5 years; 2-year-olds account for 30 per cent, and 5 per cent is attributed to babies aged 6 months or less. The official programmes of powdered-milk distribution, maintained by both national and international organizations, as well as a breakfast and lunch programme at school, have all prevented even greater undernourished percentages in the child population. These programmes, together with food assistance, were greatly intensified during the drought which began in 1968. On the other hand, the free powdered-milk programmes have caused the mothers to shorten the duration of breast-feeding, with consequences for the health of the child.

In general, very few studies have been done on feeding habits, their nutritional aspects, and on the beliefs and values that determine them in the region. Such studies are indispensable for setting up policies for solving the food problem.

Population health

In the city of Combarbalá there is one hospital staffed with two doctors, two nurses and one midwife, which provides for the minimum requirements of the population. In addition, there are two permanent rural medical posts working with paramedical personnel in the towns of Quilitapia and Canela Baja. The rest of the area is periodically visited by doctors on tour.

Data collected from these medical posts show that bad colds and influenza predominate (33·7 per cent of reported medical cases). The incidence of these diseases is higher in the district of Canela Baja (39·5 per cent) than in the district of Quilitapia (29·1 per cent). Moreover, in the Canela district they are present throughout the year, while in Quilitapia they appear mainly in winter. These differences could be related to the cloudy humid weather of Canela Baja, which is located near the coast. Gastro-intestinal troubles are second in frequency and comprise 31·5 per cent of the medical cases in Quilitapia. Children account for 81 per cent of these cases, mainly in summer, probably due to the seasonal consumption of greens.

Because of the poor hygienic conditions, cases of scabies caused by the mite *Sarcoptes scabiei* are frequent, particularly among children; according to popular opinion the disease is transmitted by sheep and goats, which are generally heavily infested. However, the mite which infests these animals is *Psoreptes equi* var. *ovis,* and is not transmissible to man (Servicio Agrícola y Ganadero, 1976).

Early social and technical development

Prehispanic period

Chronicles of this period point out that dry-farming cultivation began only south of the Río Maule (35° S). The Diaguitas of the Norte Chico cultivated only in the irrigated valleys. Their main crop and basic food was maize. They also cultivated beans, potatoes, quiñoa, and pumpkin. Three kinds of beans are known to have been cultivated by the Diaguitas: black globular, black long, and yellow globular (Iribarren, 1970; Hidalgo, 1972; Cornely, 1956). Near Ovalle, in the district of the Río Hurtado, their technique of hand-sowing is still in practice, and is known under the name of *cultivo a piton* (Iribarren, 1970). The Diaguitas included some fruits from trees and from wild shrubs in their diets. Near their dwellings were silos or granaries used to store food for use between harvests, for critical periods, or for payment of taxes (Hidalgo, 1972). Their agricultural and livestock-breeding activities went on without major problems, amid abundant natural resources. De Bibar (1558) describes the Combarbalá and Choapa Rivers as 'rivers carrying too much water';

TABLE 8. Livestock population and percentage of various species in the area of Combarbalá and Mincha (1906–75) (after Instituto Nacional de Estadística, 1906–75)

	1906		1930		1936		1955		1965		1975	
	Number	(%)	Number	(%)	Number	(%)	Number	(%)	Number	(%)	Number	(%)
Combarbalá												
Goats	15400	(48·1)	57797	(83·1)	50619	(73·2)	81495	(78·3)	56156	(83·8)	66122	(83·1)
Sheep	6781	(21·2)	6415	(9·2)	12434	(18·0)	17098	(16·4)	8468	(12·6)	12035	(15·1)
Cattle	9848	(30·7)	5333	(7·7)	6100	(8·8)	5475	(5·3)	2435	(3·6)	1413	(1·8)
TOTAL	32029		69545		69153		104068		67059		79570	
Mincha												
Goats	6165	(33·3)	40304	(41·2)	27492	(45·7)	42393	(41·6)	28192	(42·7)	48094	(64·9)
Sheep	6830	(36·9)	49175	(50·3)	23653	(39·3)	55140	(54·2)	34501	(52·3)	22497	(30·4)
Cattle	5507	(29·8)	8308	(8·5)	9077	(15·0)	4241	(4·2)	3306	(5·0)	3517	(4·7)
TOTAL	18502		97787		60222		101774		65999		74108	
TOTAL IN THE DISTRICT	50531		167332		129375		205842		133058		153678	

he also tells us that 'in several places of this land there are creeks carrying good water'. The Diaguitas owned many 'sheep of the land' (*Auquenidae*), which they used as beasts of burden; consumed the meat (mainly in a dried form called *charqui*); and utilized the wool for cloth-making. As miners, they worked the copper and bronze mines.

The arrival of the Incas (late fifteenth century), introduced new production methods in agriculture, breeding, and mining. The Incas exploited the gold and silver mines to pay tribute to the Empire. They set up small copper foundries, *huairos*, on hilltops in order to get stronger draught of air and hence a higher melting temperature. The ore was crushed with the aid of the *maray*, a huge block of stone balanced on a rock. Shells of edible molluscs found in the interior indicate that the Incas undoubtedly had commercial relations with the coastal Diaguitas, who lived by fishing.

Spanish period

The Spanish conquerors introduced new species and techniques for cultivation, which intensified the utilization of natural resources. During the first decades of the seventeenth century, the region of Coquimbo had a mixed economy with livestock-breeding and mining. The main exports were tallow, cordovan leather and grease; second in importance was the exportation of copper, in both the raw and refined state. Exports increased so quickly at the beginning of the seventeenth century that a farmer of Mincha (Don Pedro Cortés Monroy), bought several ships of large tonnage to transport his products to Peru (Carmagnani, 1963).

During the second half of the seventeenth century, the economy changed to agriculture and mining and the cultivation of wheat and vineyards became very important. Stock-raising shifted to poorer lands, which led to the virtual disappearance of cattle while goats increased in number.

The importance of the region as an exporter of wheat to Peru began to decline in 1720. From this date on, mining production gained in relative importance and the population increased swiftly. The forests and the *matorral* brush had to be cleared to maintain wheat production (Sayago, 1874). This process of vegetation clearance was accentuated from 1730 onwards between Copiapo and Petorca, but the importance of wheat was definitively on the decline and the region started to export semi-finished products (wines, spirits, and dried fruits).

Mining was the principal economic activity of the region towards the end of the eighteenth century. Between 1750 and 1830, a large number of small foundries worked the copper oxides by using charcoal, particularly coming from the *espino* and the *guayacan* tree, whose wood was also used as supports in mine tunnels.

Recent development and existing economic activities

Agricultural activities

During the nineteenth century, Chile was the foremost producer of copper in the world. Several mines were exploited in the region of Coquimbo and large copper foundries were set up in Tongoy, Los Vilos, Guayacan, La Serena, Chagres, Chanaral and Caldera. Roads and railways were opened and several mining hamlets were established for lodging the incoming population. All this stimulated agricultural activities, but insufficient production and an increasing population made the pressure on natural resources rise to intolerable proportions.

At the end of the nineteenth century, a portion of the population of Coquimbo emigrated when exploitation of the nitrates started in the provinces of Tarapaca and Antofagasta.

The value and importance of dry-farming lands, as well as those serving as summer pastures in the mountains, increased enormously during the mining boom. This was due to the fact that the *haciendas* developed a livestock production based on transhumance. Table 8 shows the numbers and percentages of different species in the livestock population of the district under study. During the present century, there has been a marked predominance of goats. Cattle, relatively important at the beginning of the century, now constitute a very small proportion. Sheep were predominant in the commune of Mincha, but have decreased by half during the last twenty years.

A system of transhumance to the pastures of the Cordillera de los Andes during the summer (extending in part on the Argentinian side), between November and April, allows the *haciendas* to maintain a profitable livestock industry while the *comuneros* have a simple subsistence agriculture. The high mountain pastures are privately owned and are rented in lots having a carrying capacity (determined beforehand) for 500 to 5000 head of small livestock. These areas are termed *posturas*. The *hacienda* proprietor who does not own mountain pastures rents grazing lots on a ten-year basis; *comuneros* and other small land-owners rent them for one year, combining their flocks to get the benefit of the maximum stocking rate (Aranda, 1971). The driving and care of the animals is carried out by a member of the community, who takes in exchange the milk production of that period. Milk is utilized exclusively for making cheese. Three tonnes of goat cheese are traded per week during a normal year in the commune of Combarbalá. Industrial development of goat leather and wool would probably provide better incomes to the small- and medium-sized livestock-breeders.

In the majority of cases, the local agricultural production provides only enough for consumption by the local population. During the period 1930–75, there was a tendency for a decrease in wheat cultivation, together with an increase in the production of vegetables from irrigated plots. The surplus, particularly of tomatoes, is sold in Santiago as early crops. Moreover, in the district of Mincha, the cultivation of cumin seeds has become very important. The commercial production of dried fruits, particularly sun-dried peaches and figs, is still important.

The system of storing and distributing water to irrigate the small gardens illustrates the social system of the *comuneros* and small farmers. The surface water belongs to the entire community and is distributed in turns according to rules fixed by the community. In some communities there exists a 'water-judge' nominated by the *comuneros* and chosen from among its most respected members. In other cases, as in the hamlet of Soruco, nobody is responsible for supervising that people comply with the system of sharing water, since everybody respects what has been traditionally established.

On the other hand, irrigation using underground water is carried out on an individual basis. The most traditional extraction method is manual; a bucket is tied to the end of a rope, and raised up or lowered into the well by a winch with a crank handle. In some districts, like El Sauce and Quilitapia, where there are more or less permanent breezes, windmill-driven pumps are common, with motor pumps being a very recent innovation.

Programmes of socio-technical assistance

The *comuneros* are generally individualistic and competitive. The community deals with the cleaning of drains and irrigation canals, moving livestock, eliminating toxic plants from grazing lands, building social centres, etc. Each farmer manages his agricultural enterprise in an individualistic way. This aspect explains the failure of some co-operative systems introduced since 1960. These rural co-operatives did not improve the organizational structures to the level required to meet the hard living conditions of the region; contrary to expectations, they generated conflicts by superimposing new organizations on existing traditional practices.

A better knowledge of the social dynamics of the groups on which the co-operative programmes were to be imposed, and an ability to profit from their traditional organization in constructing a new one, adapted to real conditions would have given a greater possibility of success (Hernández, 1975).

Technical assistance to the *comuneros* has in general been rare, ill-planned and sporadic. Previous experience has not been taken into account, and an educational phase has not preceded the actual change. However, the mind of the *comunero* is open to technological innovations. It was not difficult to introduce, with success from the outset, the use of small motor pumps to tap underground water. However, most of the farmers have had inadequate means to meet the purchase debt and then the fuel costs. The few who have ventured to buy a tractor have found themselves in a similar situation.

There are several examples of programmes conceived in the great hope that they would permanently solve existing problems, but which very soon failed. The planting of olive trees has already been mentioned; in spite of good development, the yield was not adequate owing to the aridity of the area. A few years ago, the production of roasting chickens was introduced on a large scale because there were temporarily advantageous conditions on the national market. Unfortunately, these units soon went out of business and today dozens of them are to be found in the communities lying in a state of abandonment and dilapidation. None of the supplies necessary for the undertaking was locally produced, everything came from other areas of the country and even from abroad (imported grains). Another example of a temporary solution is the development of the production of cumin seeds, particularly in the areas of Canela Baja and Canela Alta, without taking any accompanying measures to conserve natural resources. This has provided a living and even enriched some producers and merchants, but has resulted in considerable damage to the soil.

Commerce in agricultural products

A network of commercial relationships has been established through marketing of agricultural surplus. It has brought the producers in touch with the merchants of the hamlets, villages and towns, who buy all kinds of products. This network is linked with more important centres, where there are more specialized merchants, and finally with the big urban centres (Santiago, Valparaíso and the mining centres of the Norte Grande).

In the district of Combarbalá, the villages of El Sauce and Quilitapia are important in addition to the town of Combarbalá itself, which is the main exchange centre and also the commercial and administrative centre of the commune. All the services and bureaux of the public administration are located here, as well as the bus terminus, the hospital, secondary schools, courts, police station and a number of shopping centres. The villages of Canela Alta and Canela Baja are the main centres of the district of Mincha.

The merchants from these centres travel through the countryside, generally in their own vehicles, buying and selling consumer goods. This leads to the dependency which is certainly disadvantageous to the small producers, and is a major factor in their impoverishment. It is evident that an arrangement affording the producers a more favourable means of selling their produce and purchasing their requirements is needed.

Mining activities

While agricultural activities have been reduced to critical levels during this century, mining has become an important complement to the economy of the local inhabitants. According to their scale, these activities are classed as either small- or medium-sized mines.

In the region of Coquimbo and Atacama the typical form of mine-working uses traditional methods. A small mine is independently worked by an individual (*pirquinero*), who has generally discovered and developed a mine on land belonging to someone else. The miner makes an informal agreement with the land-owner, promising to pay to him a portion of the minerals extracted. The *pirquen* is the mine-renting contract according to mining traditions in the Norte Chico. There are both privately and nationally owned medium-sized mines, operated by mining companies which have a large infrastructure and a considerable number of workers.

During the periods of extreme drought many inhabitants of the region devote themselves to washing out gold in the ravines as an alternative means of livelihood. The placers of metallic gold have an alluvial origin and are generally exploited by two skilled workers. Exploitation of these placers is possible only where water is close at hand.

The marketing of copper and gold production is done through the National Mining Enterprise (ENAMI), which is an organization of the State.

Fishing

The marine resources of the coast of the district under study could well be exploited by the population living near the coast. However, this activity is in the hands of fishermen from other regions, who cover large stretches of the coast seeking seasonal shelter in the coves of the district. Only a few members of the community of Angostura are sporadically engaged in fishing.

The fishermen operating in the district are exclusively involved in collecting seafood, particularly the whelk called *loco*, which is widely consumed within the country, and is now also exported. These seafood collectors, or *mariscadores*, are conveyed from cove to cove by merchants coming from the urban centres who, besides buying the catch, provide them with supplies and with tents for camping. The arrangement between the merchants and fishermen is not economically advantageous for the latter, for in August 1976 they were paid less than 25 per cent of the price received in the large consumer centres; moreover the fishermen were forced to pay excessive prices for their provisions by the merchants.

A very typical social structure has developed among the workers on the motorized vessels, which reflects the cultural customs of the fishermen. In general, three men work in the vessel, but the top man is the diver, who is the best paid, and at the bottom of the scale is the oarsman. The working conditions of divers are generally difficult, since they are dependent on petrol-driven compressors, and have no regular medical check-up. They frequently get broncho-pulmonary diseases, become prematurely deaf, and are unable to pursue their work beyond the age of 35 years.

Response to drought

The small farmers face droughts passively, fatalistically, and in complete submission to the forces of the climate. They do not respond by seeking either technological innovations or new forms of organization which allow them to reduce the effects of the climatic variations. If drought has already set in at the beginning of the season, the fields are not sown; if the sowing has already been done, the crop is considered irreparably lost. Flocks are greatly reduced through death by starvation or sold at a poor price. The sacrifice of 500 000 goats in the provinces of Limari and Coapa was announced at the beginning of 1976 as an emergency measure in the face of the impending drought. Moreover, the government was asked to reduce transport costs, and to provide other means of evacuating animals to the regions not affected by the drought (*El Mercurio* newspaper, 3 September 1976).

The sole visible response to these difficulties is a notable increase in mining activities, while stock-rearing and agricultural activities are partially or

TABLE 9. Percentage distribution of the population in relation to the economic activities in the area of Combarbalá and Mincha (1952–70) (after Instituto Nacional de Estadística, 1952, 1960, 1970)

Activity	Combarbalá			Mincha		
	1952	1960	1970	1952	1960	1970
Agriculture	52·0	54·4	27·6	75·1	81·2	53·6
Mining	9·1	10·4	24·0	2·7	1·4	4·1
Industry	9·8	5·9	3·1	4·6	3·4	1·5
Building	1·5	2·4	7·8	8·7	2·7	10·8
Trade	5·9	5·6	4·2	2·2	1·9	2·3
Transport	2·9	2·9	4·3	0·4	1·9	2·0
Services	12·1	11·4	11·6	5·9	4·8	7·5
Not specified	6·7	7·0	17·4	0·4	2·7	18·2
	100·0	100·0	100·0	100·0	100·0	100·0

totally given up. This phenomenon is more evident in the commune of Combarbalá than in that of Mincha, where mining has less importance. It seems a matter of the utmost urgency to stimulate and to develop small- and medium-sized mines, as a permanent alternative for the population. The digging and washing out of gold, of poor yield, is not a real alternative but a complementary activity in critical periods (Hernández, 1975).

The population distribution by economic activity in Combarbalá and Mincha shows a clear-cut decrease of agriculture as a source of employment from 1952 to 1960 and 1970. This phenomenon is particularly accentuated in the commune of Combarbalá, where a decrease of 50 per cent took place in twenty years (Table 9). On the other hand, mining activities increased in the two communes, although the increase was greater in Combarbalá. Industrial activities, craftsmanship included, have undergone a constant decrease all over the district. In this connection, an increase in the working of semi-precious stones and other forms of exploitation of regional resources should open up possibilities of more permanent employment.

Conclusions and recommendations

Conclusions

Throughout the region described in the present study, which has an arid-mediterranean climate, the main factor limiting agriculture and stock-raising activities is water availability. The water deficit is becoming increasingly critical. Run-off losses are accentuated by a rugged topography and by over-exploitation of the vegetation cover. Available records show a decrease in rainfall in the present century, but this does not allow one to conclude that there is a secular trend towards a more arid climate. Some partial observations would indicate a possible cyclic pattern of rainfall of very long duration, so this decrease in rainfall could well be a part of a long phase with precipitation below the average.

The present vegetation of the district has been seriously disturbed, and in several places not even fragments of the climax state remain. This degradation has led progressively to the establishment of invasive communities together with the persistence of some native species, both being less productive. This loss in ecosystem productivity cannot be attributed to variations in annual precipitation, since these show a regularity of climate in the region. On the contrary, it can well be ascribed to the over-utilization of natural resources, the consequence of yearly cultivation and overgrazing. Man alone is responsible for this situation.

At present, the wild fauna is also far from its climax state. Several species of the area are in danger of extinction or are already extinct, although they still survive in more favourable environments elsewhere. Those species particularly adapted to more arid zones are the only ones on the increase.

The majority of soils display generalized erosion, those areas located near human settlements being the most affected. The predominance of steep slopes, medium- to light-textured soils, in association with the damage to the plant cover, have favoured surface run-off, causing severe sheet erosion and occasional gullying. Rapid mineralization of the scanty organic matter and compaction of soils through treading by livestock have helped to destroy the structure of the topsoils.

The prevailing system of land-ownership, known as agricultural communities, as well as a fluctuating mining activity, in the region, have resulted in over-population of the rural sector in relation to the agricultural, pastoral and industrial potentialities of the district. In spite of a more-or-less constant emigration of the active population, it is evident that there still exists an excessive human pressure on the natural resources, and that the resident rural population is subject to further impoverishment.

Apart from work done to stabilize the coastal dunes and to regenerate the overgrazed rangelands with well-adapted forage shrubs, there is a complete absence of comprehensive programmes of rehabilitation. Such programmes are ecologically possible, but they are economically impracticable on an extensive scale, given the present condition of the country.

Recommendations

In the light of the present study, it is recommended that a more profound interdisciplinary study be made of the same area. It is the general opinion of the specialists contributing to the present study that they were correct in choosing this area, since it represents a wide variety of conditions and problems common to all non-irrigated parts of the whole region. Lack of time and the complex nature of the study prevented a thorough study of particular topics and concepts judged to be important. Moreover, it also would seem to be more appropriate to make an integrated and more detailed study of a circumscribed area of the district. The catchment basin of Canela Creek, including two villages with some urban elements, displays all the socio-economic activities and problems typical of the region; this catchment basin could provide an adequate model for establishing the basis of any future development programme.

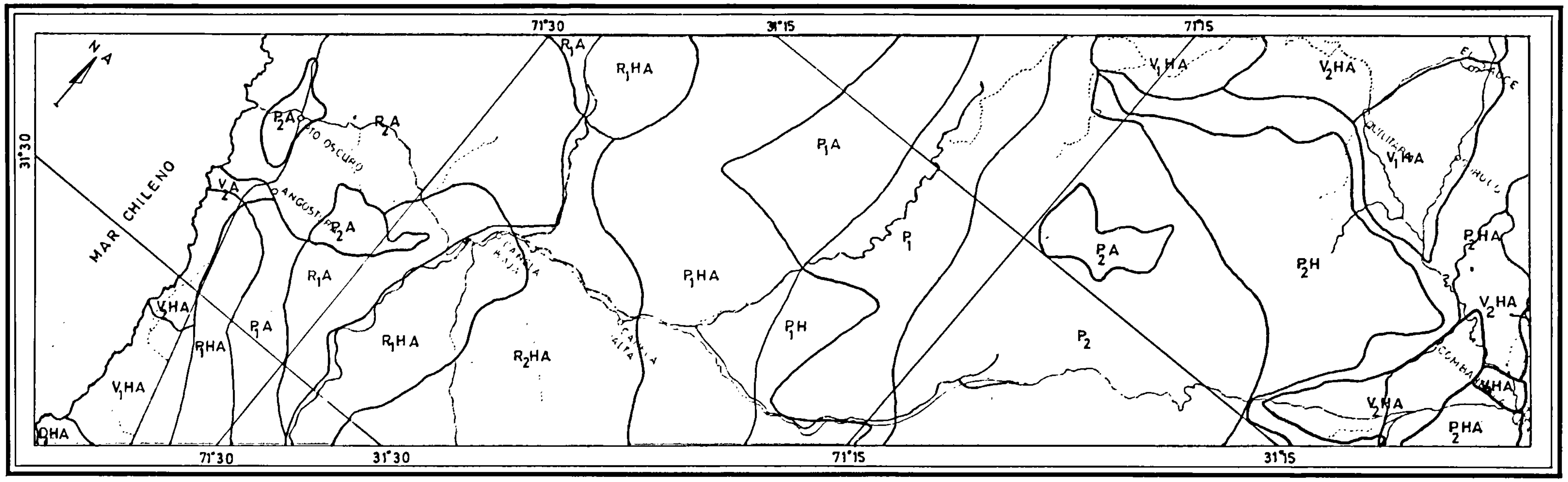
From this, as well as from other studies made in the region, it is possible to make some general recommendations for rectifying the tendency towards a greater disequilibrium between the population and natural resources. It is extremely urgent that action should be taken to improve in the short term the living conditions of the rural population. This action must be included in social development programmes capable of producing immediate results; this short-term action should not be mistaken for long-term aims which seek the return to an ecological equilibrium.

Among the short-term measures, the following proposals can be considered:

- to develop and diversify regional mining, thus furnishing stable employment to a larger proportion of the active population;
- to develop intensive agriculture in small irrigated valleys and ravines, producing fruit and vegetables for sale as first-fruits;
- to support adequate levels of agricultural research and exchange of agricultural technology. At present there exists a good supportive framework in the Regional Programme for Arid Zones (UNDP, World Bank, Israel);
- to develop secondary and craft industries for local products. The concentration of people in the communities will facilitate training schemes for manufacturing such products;
- to furnish opportunities for young people to realize their aspirations to do work other than that connected with agriculture and stock-raising.

Among the long-term aims the following must be considered:

- reorganization of the land-ownership system, eliminating the excessive subdivision of land by regrouping small family holdings into larger units;
- regeneration of ecosystems, by banning cultivation and grazing in the most vulnerable and eroded areas over a prolonged period;
- controlled grazing of rangeland, with low stocking rates and long resting periods, to allow for the preservation and improvement of vegetation;
- consideration of the preservation and improvement of the natural vegetation as of utmost priority. The regeneration of grasslands is to be recommended. Under present conditions, it is impossible to increase livestock and crop production in the short term to economically profitable levels;
- every programme or strategy selected for resolving the problems of this region must have an integrated approach, differentiating clearly between the social, economic and political problems of the population and those related to production efficiency.



Legend

DEGREE OF DESERTIFICATION HAZARDS
(In zones likely to be affected by desertification)

very high

high

medium

VULNERABILITY OF LAND TO DESERTIFICATION PROCESSES

	Severe to medium	Medium to slight
Surface subject to:		
Formation of dunes, shifting sand, hummock, sandy cover by wind erosion	D_1	D_2
Enlargement of areas of rock outcrops or indurated horizon by erosion	R_1	R_2
Enlargement of bare areas by sealing of soil surface, increasing runoff, decreasing available water, poor germination of seed	P_1	P_2
Areas likely to be affected by water erosion	V_1	V_2

HUMAN AND ANIMAL PRESSURE

Human pressure	H
Animal pressure	A

BIOCLIMATIC ZONE

Arid

FIG. 40. Synoptic map of desertification hazards in the Combarbalá region

Bibliography

ALBRECHT, W. A. 1956. Physical chemical and biological changes in the soil community. In: W. L. Thomas (ed.), *Man's role in changing the face of the earth*, p. 648–73. Chicago, University of Chicago.

ALMEYDA, E.; SAEZ, F. 1958. *Recopilación de datos climáticos de Chile y mapas sinópticos respectivos*. Santiago, Ministerio de Agricultura.

ANTONIOLETTI, R. R.; SCHNEIDER, H.S.; BONCOSQUE, J. L. D.; ZARATE, E.C. 1972. *Características climáticas del Norte Chico*. Santiago, Instituto de Investigación de Recursos Naturales (IREN), Artes Gráficas CEPCO. 102 p + maps.

ARANDA, X. 1971. *La transhumancia. Un tipo de ganadería tradicional en el Norte Chico*. Santiago, Universidad de Chile, Centro Demostrativo Corral de Julio y Departamento de Geografía. 195 p.

ARMIJO, T; NAVA, C. R.; GASTÓ, J. 1976. *Fundamentos de transformación de ecosistemas*. Saltillo (Mexico), Universidad Autónoma Agraria Antonio Narro. (Monografía técnico-científica 2.)

ASCHMANN, H. 1973. Distribution and peculiarity of mediterranean ecosystems. In: F. di Castri and H. A. Mooney (eds.), *Mediterranean type ecosystems. Origin and structure*, p. 11–19. Berlin, Heidelberg, New York, Springer Verlag. (Ecological studies 7.)

BAIER, W. 1971. Evaluation of latent evaporation estimates and their conversion to potential evaporation. *Can. J. Plant Sci.*, vol. 51, p. 255–66.

BARAONA *et al.* 1961. *Valles de Putaendo. Estudio de estructura agraria*. Santiago, Universidad de Chile.

BARROS ARANA, D. 1886. *Historia general de Chile*. Santiago de Chile.

BIBAR, G. de. 1558. *Crónica y relación copiosa y verdadera de los Reinos de Chile*. Santiago.

BLANEY, H. F.; CRIDDLE, W. D. 1950. *Determining water requirements in irrigated areas from climatological data*. Washington, United States Department of Agriculture, Soil Conservation Service. (Tech. Publ. 96.)

BORGEL, O. R. 1965*a*. *Las dunas litorales de Chile*. Santiago, Universidad de Chile, Facultad de Filosofía y Educación, Instituto Geografía. 38 p.

——. 1965*b*. *La Carretera Panamericana Norte. Descripción física y cultural del marco regional entre cuesta El Melón y cuesta Guayacán*. Santiago, Universidad de Chile, Facultad de Filosofía y Educación, Instituto Geografía. 52 p.

BULL, M. 1935. Antes llovía más en Coquimbo. *Bol. Soc. Agríc. del Norte*. Febrero. 29 p.

CAÑAS, R.; GASTO, J. 1974. Costo de cosecha y eficiencia de producción de ecosistemas ganaderos. *Cienc. e Invest. Agr.* (Santiago), vol. 1, no. 4, p. 177–85.

CAÑON, P. 1966. *Las comunidades agrícolas de la provincia de Coquimbo frente a una reforma agraria. El casa de Mincha*. Santiago, Ministerio de Agricultura, Consejo Superior de Fomento Agropecuario.

CARMAGNANI, M. 1963. *El salariado minero en Chile colonial*. Universidad de Chile, Centro de Historia Colonial.

CASTRI, F. di. 1968. Esquisse écologique du Chili. In: C. Delamare-Deboutteville and E. Rapoport (eds.), *Biologie de l'Amérique Australe*, t. IV, p. 7–52. Paris, CNRS.

——. 1973. Climatographical comparisons between Chile and the western coast of North America. In: F. di Castri and H. A. Mooney (eds.), *Mediterranean type ecosystems. Origin and structure*, p. 21–36. Berlin, Heidelberg, New York, Springer Verlag. (Ecological studies 7.)

——; HAJEK, E. R. 1961. Índices pluviotérmicos como base para una clasificación del país en zonas bioclimáticas. *Bol. IV. Conv. Méd. Vet. Santiago*, p. 19–23.

——; ——. 1976. *Bioclimatología de Chile*. Santiago, Universidad Católica. 129 p.

——; ——; ASTUDILLO, V. 1962. Importancia pecuaria de los ambientes desfavorables chilenos. *Bol. Prod. Anim. (Chile), no. 1, p. 7.*

CHANG, J. H. 1968. *Climate and agriculture. An ecological survey*. Chicago, Aldine.

CORNELY, F. L. 1956. *Cultura Diaguita chilena y cultura de El Molle*. Santiago, Editorial del Pacífico.

CORREA, V. L. 1938. *Agricultura chilena*. Santiago, Editorial Nascimento. 410 p.

DOBOSI, Z.; ULRIKSEN, P. 1970. Distribution of global radiation over Chile. *Int. Solar Energy Soc. Conf.* Melbourne, International Solar Energy Society, Australian and New Zealand Section. (Paper 3/106.)

ELIZALDE, M. R. 1970. *La sobrevivencia de Chile*. Santiago, Ministerio de Agrícola, Servicio Agrícola Ganadero. 493 p.

EMBERGER, L. 1955. Afrique du Nord-Ouest. In: *Plant ecology: reviews of research/Ecologie végétale: compte rendu de recherches*, p. 219–49. Paris, Unesco. (Arid Zone Research/Recherches sur la Zone Aride 6.)

ENCINA, F. A. 1940–52. *Historia de Chile*. Santiago, Editorial Nascimento.

GASTÓ, J. 1966. Variación de las precipitaciones anuales en Chile. *Univ. Chile. Fac. Agron. Bol. Tecn.*, no. 24, p. 4–20.

——. 1976. *Ecología silvoagropecuaria*. (Mimeo.)

GONZÁLEZ DEL RÍO, F. 1970. Algunas consideraciones sobre las comunidades agrícolas de la provincia de Coquimbo. In: *El hombre en la zona árida del Norte Chileno*. Santiago, Plandes. (Boletín especial.)

GUTHRIE, D. A. 1971. Primitive man's relationship to nature. *Bioscience*, vol. 21, p. 721–3.

HAJEK, E. R.; CASTRI, F. di. 1975. *Bioclimatografía de Chile*. Santiago, Universidad Católica, Vice Rectoría Académica. 230 p.

——; PACHECO, M.; PASSALACQUA, A. 1972. *Análisis bioclimático de la sequía en la zona de tendencia mediterránea en Chile*. Santiago, Universidad Católica, Instituto Geografía. (Estudio 45.)

HELBAECK, N. 1959. Domestication of food plants in the old world. *Sci.*, vol. 130, p. 365–72.

HERNÁNDEZ, R. 1975. *Mecanismos de adaptación de las comunidades rurales del Departamento de Combarbalá ante los cambios ecológicos culturales*. Santiago, Universidad de Chile, Departmento de Ciencias Antropológicas y Arqueológicas.

——; THOMAS, C. 1975. *Diagnóstico de la migración en Chile*. Santiago, Universidad de Chile, Departamento de Ciencias Antropológicas y Arqueológicas.

HIDALGO, J. 1972. *Culturas protohistóricas del Norte de Chile*. Santiago, Editorial Universitaria.

HILLS, G. A. 1961. *The ecological basis for land use planning*. Maple, Ontario Department of Lands and Forests, Research Branch. 204 p. (Research Report 46.)

HOLMES, R. M.; ROBERTSON, G. W. 1957. Conversion of latent evaporation to potential evapotranspiration. *Can. J. Plant Sci.*, vol. 38, p. 164–72.

HUBER, A. 1975. Beitrag zur Klimatologie und Klimaökologie von Chile. Universität von München. (Thesis.)

HUMPHREY, R. R. 1958. The desert grassland. *Univ. Arizona Agric. Expt. St. Bull.*, no. 299. 62 p.

INSTITUTO DE INVESTIGACIONES GEOLÓGICAS (Chile). 1968. *Mapa geológica de Chile*.

INSTITUTO NACIONAL DE ESTADÍSTICA (INE). 1875, 1885, 1895, 1907, 1920, 1930, 1940, 1952, 1960, 1970. *Censos de población*. Santiago, INE.

——. 1930, 1936, 1955, 1965, 1975. *Censos agropecuarios*. Santiago, INE.

IRIBARREN, J. 1970. *Valle del río Hurtado. Arqueología y antecedentes históricos*. Edición del Museo Arqueológico de La Serena.

JILES, P. C. 1963. *La flora con valor económico de la provincia de Coquimbo*. Comisión Coordinadora Zona Norte (CONORTE). (Mimeo.)

KARTZOV, G. R.; LAILHACAR, R. 1965. Ensayos sobre establecimiento de *Atriplex semibaccata* en la zona costera de la provincia de Coquimbo. Universidad de Chile, Facultad de Agronomía. 123 p. (Thesis.)

KUMMEROW, J. 1966. Aporte al conocimiento de las condiciones climáticas del bosque de Fray Jorge. *Univ. Chile. Fac. Agron. Est. Exp. Agronómica. Bol. Tecn.*, no. 24, p. 21.

LAILHACAR, K. S. 1962. Adaptación de especies forrajeras en el sector norte del secano de la costa (Departamento de Illapel). Universidad de Chile, Facultad de Agronomía. 200 p. (Tesis Ing. Agr.)

——. 1966. *Programa de forrajeras de secano.* Convenio Comisión Coordinadora Zona Norte y Facultad de Agronomía, Universidad de Chile. (Mimeo.)

MATHER, J. R. 1965. Average climatic water balance data for the continents. Pt VIII. South America. *Publ. Clim.*, vol. 17, no. 2, p. 297.

MATTE, H. 1968. Consideraciones forestales sobre las zonas áridas. *Bol. Univ. Chile,* vol. 87–8, p. 34.

MILLER, P. C.; BRADBURY, D.; HAJEK, E. R.; THROWER, N.; LA MARCHE, V. 1977. Macroenvironment. In: H. A. Mooney (ed.), *Synthesis volume IBP Mediterranean scrub ecosystems,* p. 27–72. Pennsylvania, Dowden, Hutchinson & Ross.

NAVEH, Z. 1967. Mediterranean ecosystems and vegetation types in California and Israel. *Ecology*, vol. 48, p. 345–59.

NAZAR, J. 1969. Analogías bioclimáticas entre Chile y California. *Zooiatria*, vol. 9–10, p. 62–84.

——; HAJEK, E. R.; CASTRI, F. di. 1966. Determinación para Chile de algunas analogías bioclimáticas mundiales. *Bol. Prod. Anim. (Chile),* vol. 4, p. 103–73.

OFICINA DE PLANIFICACIÓN NACIONAL (ODEPLAN); INSTITUTO DE ECONOMÍA DE LA UNIVERSIDAD CATÓLICA DE CHILE. 1975. *Mapa de extrema pobreza.* Santiago, Tallares Gráficos Instituto de Capacitación e Investigación en Reforma Agraria (ICIRA).

OFICINA METEOROLÓGICA DE CHILE (OMCH). 1964. *Climatología de Chile.* Fasc. II. Santiago, Oficina Meteorológica de Chile.

——. 1965. *Pluviometría en Chile.* Santiago, Oficina Meteorológica de Chile. 268 p.

OLIVARES, E. A.; GASTÓ, J. 1971. Comunidades de terófitas en subseres postaradura y en exclusión en la estepa de *Acacia caven* (Mol.) Hook, et Arn. *Univ. Chile. Fac. Agron. Est. Exp. Bol. Tecn.*, no. 34.

ORTIZ, G. J. 1969. *Plantas silvestre chilenas de frutos comestibles por el hombre.* Museo La Serena. 28 p. (Contribuciones Arqueológicas 8.)

PASCAL, A. 1968. *Relaciones de poder en una localidad rural.* Santiago, Instituto de Capacitación e Investigación en Reforma Agraria (ICIRA).

PASKOFF, R. 1970. *Recherches géomorphologiques dans le Chili semi-aride.* Bordeaux, Biscaye Fréres. 420 p.

PIZARRO, H.; RIVAS, R. 1965. Algunas consideraciones sobre la irregularidad de las precipitaciones en el Norte Chico. Santiago, Oficina Meteorológica de Chile. 23 p. (Mimeo.)

RODRÍGUEZ, Z. M. 1959–60. Regiones naturales de Chile y su capacidad de uso. *Agr. Téc. Chile*, vol. 19, p. 307.

SAYAGO, C. M. 1874. *Historia de Copiapó.* Copiapó, Imprenta El Atacama.

SCHNEIDER, H. 1969. *El clima del Norte Chico.* Santiago, Universidad de Chile, Departamento de Geografía. 131 p.

SERVICIO AGRÍCOLA Y GANADERO. 1976. *Elimine la sarna de sus ovejas.* Ministerio de Agricultura (Chile). (Boletín Divulgativo 12.)

THORNTHWAITE, C. W.; MATHER, J. R. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. *Publ. Clim.*, vol. 10, no. 3, p. 185.

TRICART, J. 1967. *Reconocimiento geomorfológico en la cuenca del río Maule.* Santiago, Universidad de Chile, Departamento de Geografía.

VICUÑA MACKENNA, B. 1970. *El clima de Chile.* 2nd ed. Buenos Aires, Francisco de Aguirre. 399 p.

WORKMAN, J. P.; HOOPER, J. F. 1968. Grazing vs. wheat production on marginal Utah croplands. *Utah Sci.*, vol. 29.

ZEMELMANN, H. 1971. *El migrante rural.* Santiago, Instituto de Capacitación e Investigación en Reforma Agraria (ICIRA).

ZUÑIGA, J. 1972. *La emigración rural en la provincia de Coquimbo (Chile).* Santiago, Instituto Latinoamericano de Investigaciones Sociales (ILDIS).

3

Desertification in the Eghazer and Azawak region

Case study presented by the Government of Niger

Acknowledgements

Unesco would like to express its thanks to the Institut de Recherches en Sciences Humaines (IRSH) of the University of Niamey (Niger), which helped in the preparation of this case study, and to the author E. Bernus of the Office de la Recherche Scientifique et Technique d'Outre-Mer (ORSTOM) in Paris.

Assistance was provided by the following institutions in Niger: Ministère de l'Économie Rurale; Direction de l'Élevage; Service des Eaux et Forêts; Institut Forestier; Laboratoire d'Élevage; Office des Eaux et du Sous-sol; and the Institut de Recherche Agronomique Nigérien.

Unesco also wishes to thank M. Mainguet and L. C. Canon-Cossus of the Laboratoire de Géographie Physique Zonale, Université de Reims, for their valuable contribution towards the map work.

UNDP, FAO and WMO also collaborated in this study.

Introduction

Niger was chosen, as a country located in an arid and semi-arid summer-rainfall zone, as one of the six case studies included in the Programme for International Co-operation in the Struggle against Desertification.

Niger, located between the 13th and 23rd parallels, is roughly included within the Saharan, Sahelian and north Sudan zones. It is a continental country, situated

> within the rainfall gradient crossing West Africa, from desert to dense forest, which results from the alternating and antagonistic relationship of two main air-masses. One is the continental tradewind, dry and cool to begin with and then becoming warm, which travels north to south then north-east to south-west. The other is the monsoon, humid and cooler, originating in the Atlantic and moving from south-west to north-east. In summer the edge of the oceanic air stream slips under the tradewind and pushes it back towards the north. As this Intertropical Front (ITF) sweeps across the Sudan, the Sahel and even the extreme south of the Sahara each summer, the conflict generated by the two air flows causes torrential rains (*tornados*), the intensity of which naturally decreases from south to north. (Monod, 1975.)[1]

The Saharan zone begins north of the 100 mm isohyet, but it is difficult to speak of an average rainfall in most of the zone since it does not rain every year. Here there are mobile sand dunes, which either are totally devoid of vegetation or have a sparse cover of non-woody species. The zone is characterized by

> great spaces between the perennial grass or woody plants found there, a remarkable reproduction rate of the annuals and pronounced xerophytic morphology in general. In addition, annual plants grow irregularly, only on the small areas which receive random rainfall. (Peyre de Fabrègues and Lebrun, 1976.)

The Sahel zone, which covers the middle section of Niger, is situated beetween the 100 mm and 500 mm isohyets. It is

> a steppe zone changing from a cover of scattered shrubs in the north to a wooded steppe in the south . . . The woody layer can be quite low or almost non-existent in certain unfavourable stations, or it can be composed of dense shrubs and even trees in some areas mainly to the south. The grass layer varies in density and height, is dominated by annual species, and always reflects very accurately the year's rainfall. (Peyre de Fabrègues and Lebrun, 1976.)

The Sahel zone itself can be subdivided into two parts, each with a different potential. The north Sahel or nomadic zone is located between the 100 and 350 isohyets and the south Sahel or sedentary zone between the 350 and 550 mm isohyets. In the north Sahel zone, dry farming of millet is so uncertain that, with the exception of very limited irrigated farming,

1. T. Monod, 1975, La zone sahélienne nord-équatoriale (unpublished manuscript communicated to author).

this zone is almost exclusively reserved for pastoral use. In the southern or sedentary zone, there is enough rain to allow cultivation of cereals (millet and sorghum), while pastoralism is still practised. These two areas are complementary: pastoralists in the nomadic zone live largely from the cereals of the sedentary zone, and the agriculturists of the south send their herds to the north during the rainy season.

The Sudan zone, south of the 550 mm isohyet, is characterized by savanna vegetation with a thicker tree cover and a continuous grass layer.

The area chosen for the project: advantages and disadvantages

In the UNDP document of 14 October 1975, entitled 'Project of the Niger Government', the Agadez area was chosen for study, but no precise boundaries were given. The Niger Government requested that the Azawak region[1] be included in this proposal, since no boundaries were specified in the Agadez area. The Azawak is roughly the Tchin Tabaraden district, and its addition to the project allowed more precise boundaries to be drawn. If Azawak were included in the study, the Agadez region could then refer only to the Eghazer wan Agadez, a pastoral area to which nomads from the south migrate in summer. Thus a coherent area was obtained by joining two complementary regions which could not easily be considered separately.

This area falls between the 15th and 18th parallels, i.e. entirely within the north Sahel nomadic zone suitable for pastoral use (between the 350 mm and 100–150 mm isohyets), with an area of a little over 100 000 km^2. The region thus covers a vast area, comprising almost 10 per cent of Niger's total territory, but containing a much smaller proportion, roughly estimated at 2 or 3 per cent, of the total population. The population density is always less than one inhabitant/km^2, but this figure has little meaning in a country where nomadic populations move about and migrate in the rainy season. Thus the arrival each year of a varying number of strangers to the region must be taken into account, and populations recorded in one district very often also migrate into another for years on end. The notion of pastoral carrying capacity, one of the conditions of survival for the pastoralists, is of greater importance.

The choice of such a study area presents a certain number of problems: first, the size of the area requires that the study be approached on a scale different from other case studies foreseen in the UNEP programme. Secondly, by choosing the Azawak, i.e. the nomadic section of the Tchin Tabaraden district, a part of the population registered at the subprefecture, but living on the southern borders, is excluded from the study. This makes it difficult to obtain clear demographic data and to distinguish between groups which live on either side of a very uncertain border. This problem is inherent in all studies of nomadic populations.

1. Azawak or Azawagh is a fossil valley which forms the upstream section of the Dallol Bosso. The name however has come to include the entire surrounding pastoral zone both in Niger and in Mali. In this study Azawak refers to the Niger portion of the area.

This choice is justified, however, by certain advantages. This area has always been among the first to benefit from land planning and management for pastoral use, for example the introduction of pumping stations, wells, etc. Studies, already of long standing, on the human factors involved have been carried out by researchers interested in the Foulani (Dupire, 1962) or the Tuareg (Nicolas, 1950; Bernus, 1974*b*). Surveys of nomads have more often concentrated on this area than on areas further to the east. Recent surveys include those on demography and the economy (INSEE, 1966), on animal husbandry from the point of view of agrostology (Rippstein and Peyre de Fabrègues, 1972) as well as from that of pastoral economy (Coulomb, 1972; SEDES, 1972–73), on water resources (Greigert, 1968; Greigert and Sauvel, 1970) and on pastoralists' reactions to the water development policy (Commissariat Général au Développement, 1972). Synoptic studies made within the framework of modernizing the pastoral zone (SEDES, 1972–73) and those relating to the Development Project of Eghazer wan Agadez (Le Houérou, 1972) complete the mass of material which has been accumulated over the past dozen years and which facilitated the preparation of this monograph. Some of the information is at times out of date as a result of the recent drought in the Sahel zone from 1969 to 1973, but it is invaluable as reference material.

Problems of desertification in the area

The area chosen was severely hit by the drought of 1969–73. The plant cover was temporarily or permanently diminished, as happened generally throughout the Sahel. However, the study area did have some special characteristics. Since 1960 the Republic of Niger has applied a concerted policy to develop the Sahel pastoral zone, as is expressed in the 1959–60 report of the Direction de l'Élevage (Animal Husbandry Service). Animal husbandry was to be promoted and developed through a policy of water management at a time when the Sahel zone was passing through a period of normal to heavy rainfall. This policy was accompanied by legislation designed to safeguard the rights of pastoralists against the agriculturists who were moving north and occupying grazing lands. It was an attempt to develop, modernize and thereby to intensify animal husbandry in a region which was to be dedicated to pastoral use. The first activities were mainly in the Tchin Tabaraden district and later in the Agadez district. The study area was therefore privileged in many respects.

The Azawak, within the boundaries of one administrative district, is inhabited by a largely Tuareg population, whose traditional political organization coincides with the present-day administrative organization. Hydrogeological conditions are such that deep ground water can be exploited within the framework of a relatively coherent social system. Finally, the plain surrounding the Aïr has more recently been chosen for irrigated farming on heavy clay soils, which could benefit from run-off water from surrounding hills and from local artesian ground water.

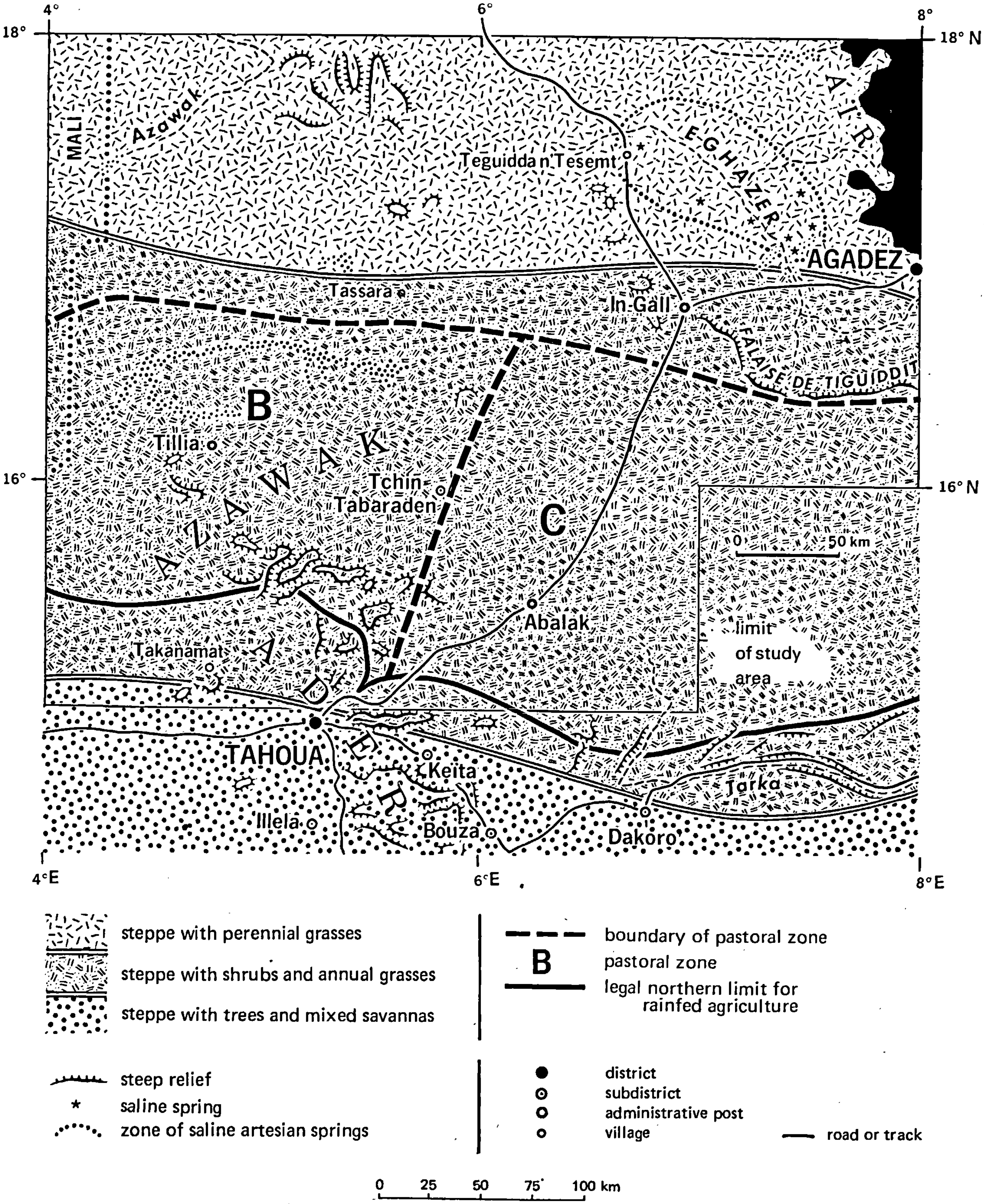


FIG. 1. Eghazer and Azawak region of Niger

These few general examples show that the recent drought occurred as development projects were in progress. These activities contributed to desertification wherever they increased pressure on the area and caused changes in the vegetation around the sites of the projects.

Desertification processes in the area can be studied at two levels: generally, by considering the consequences of the general lack of rainfall over five years; more specifically by reviewing the results of local actions to intensify pastoralism and/or agriculture and to create permanent fixed settlements, actions which almost always increased human and animal pressure on the land. The two processes always work together, and neither should be ignored in an area which has often been chosen for agricultural and pastoral innovations.

The position of the area on the FAO desertification map (1/25 000 000)

On the desertification maps being drawn up by FAO for UNDP an aridity index is used:

$$\frac{\text{Rainfall (in mm)}}{\text{Penman's potential evapotranspiration}} \quad \frac{P}{ETP}$$

Four bioclimatic zones are thus delimited:

- the hyper-arid, with an index of less than 0·06.
- the arid zone, from 0·06 to 0·20.
- the semi-arid zone, from 0·20 to 0·50.
- the subhumid zone, above 0·70–0·75.

If this index is calculated for Agadez in the northern part of the study area and for Tahoua, which is situated beyond its southern limit but is the only reference point possible, the results are:

- Agadez: 0·06.
- Tahoua: 0·16.

On the general desertification map, the study area is therefore located in the northern part of the arid zone, on the edge of the desert.

General description of the area

Climate

The study area, located roughly between the 100–150 and 350 mm isohyets, is completely contained within the north Sahel zone at the southern edge of the Sahara, and each year receives summer monsoon rains. This rainy season occurs every year but diminishes from south to north in length as well as in the quantity of rain received. Nevertheless, the year is organized around this vital season, throughout the area.

The annual cycle of seasons

The inhabitants of the area divide the year into four main seasons: the rainy season, in the heart of the summer; the post-rainy season, which is hotter and more difficult to bear because the air is still humid, although the rains have stopped; the cooler, dry season; and finally the hot season preceding the rains, when temperatures rise without being tempered by rain and the first threat of storms. Thus to the simple division of the year into two seasons—one wet, the other dry—the inhabitants have added two transitional seasons, both characterized by the humidity of the air and by a rise in temperature. The relative lengths of the seasons vary from south to north: the rainy season begins at the end of May or early June in the south, but not until July in the north. Similarly, the last rainfall comes at the end of September or early October in the south, while in the north the last storms occur before the 15th of September.

These different seasons, well known and understood by the inhabitants, illustrate the inherent climatic mechanism. The onset of the rains corresponds to the arrival of the Intertropical Front (ITF). This front is the line of contact between dry, stable continental air and humid air originating at sea. Turbulence develops at this unstable junction and turns into violent convective storms which most often break at the end of the day following diurnal convection. The rain is preceded by violent sandstorms and does not always reach the ground. As the ITF moves north, the 'monsoon' arrives, with humid winds from the south-west. The retreat of the ITF toward the south is accompanied by the arrival of the harmattan, a dry north-east wind. Rain is therefore linked with the advance of the Intertropical Front, which is very unstable and moves erratically. An early advance of the ITF, a temporary retreat and late return, often cause the rainfall to be badly distributed and detrimental to the vegetation.

The intermediate seasons, corresponding to the warm periods of May and June and the end of September and beginning of October, indicate the passage of the ITF as it advances north and retreats towards the south, a time when the two air masses are not yet definitely established in their patterns.

For the pastoralist, the seasonal cycle dictates a calendar of activity quite different from that of the southerner, who is involved in rain-fed cultivation. The rainy season means abundance to the pastoralist: pastures grow, animals give milk and the herdsmen are freed from watering them at wells. During the following seasons, in autumn and the beginning of the cold season, surface-water pools can be used and the pastures are at times still sufficient. However, by the end of the cold season and beginning of the hot period in March or April, the animals can find nothing more to feed on than dry straw, and must be watered at deep wells or boreholes. Food for people becomes dangerously scarce as the milk production dwindles, while watering and guarding the animals become increasingly burdensome. The food gap to be bridged occurs in the hot season before the return of the rains. The farmers, on the other hand, have their abundant period after the rains are over and harvesting is in progress. Their period of seasonal shortage comes with the rainy season, when weeding is often done with granaries already empty.

Climatic elements

Two meteorological stations serve as reference points in the study: Tahoua in the south and Agadez in the north. The town of Tahoua is located slightly beyond the southern boundary of the area, but is the only

TABLE 1. Mean monthly and annual temperatures

Month	Mean monthly and annual temperatures (°C)	
	Agadez, 1926–54	Tahoua, 1939–54
January	20·0	24·1
February	22·8	25·7
March	27·4	29·4
April	31·1	32·6
May	33·9	33·6
June	33·5	32·4
July	32·2	29·3
August	30·7	27·5
September	31·3	29·2
October	29·7	29·9
November	25·0	27·5
December	21·3	24·2
Annual mean	28·2	28·8
Maximum monthly temperature	48·5 (May 1940)	46·6 (May 1940)
Minimum monthly temperature	1·5 (January 1944)	4·2 (January 1941)

station which can be used in comparison with Agadez because of the long series of records available (forty-seven years). All the new stations[1] have been set up too recently for 'normals' to have any significance.

Temperature

Table 1 gives mean monthly and annual temperatures and the extreme temperatures of the periods under consideration (Rippstein and Peyre de Fabrègues, 1972).

It can be seen that the mean annual temperature increases from north to south, but not by very much. In contrast the annual temperature range increases from south to north. Both the maximum and minimum monthly temperatures become more extreme in the north, but the minimum temperature changes more rapidly than the maximum.

Evaporation

Evaporation plays a very important role in north Sahel life because it desiccates plants and dries up pools. Evaporation rates are highest during the hot dry months from March to May, decrease in the following months, and increase again from November (Table 2).

Evaporation varies according to wind and temperature. Temperature seems to play the predominant role, since the three or four hottest months (March to June) have the greatest evaporation rate, but the dry north-east harmattan wind also contributes to increased evaporation. Generally, evaporation increases as rainfall decreases; in other words evaporation rates inversely follow the isohyets. This explains why the first rainfall, especially where there is little or no plant cover, evaporates without penetrating the ground, and why a considerable amount of water is necessary to wet the soil and allow vegetation to start growing. Moreover, the combination of great heat and maximum evaporation is hard on men and animals, who often have particularly heavy work to do at this time.

1. In particular In Gall and Tchin Tabaraden.

Rainfall

Rainfall is the chief climatic factor in arid countries because it determines the state of vegetation and surface water as well as shallow ground water. The rainy season becomes shorter from south to north in the study area. At Tahoua it lasts from 15 May to 1 October, while in Agadez it lasts only from 15 July to 15 September (Table 3).

Rainfall variability

Rainfall in the Sahel zone can best be characterized by its irregularity.

Irregular rainfall in the Sahel zone is due to variations in the northerly advance of the Intertropical Front, with its trailing heterogeneous air mass, as it follows a certain distance behind the sun in its swing around the equator. When the Front goes far to the north, rainfall is heavy and the rainy season is longer than average. If on the other hand its northward movement is limited, rainfall is inadequate, the rainy season is shorter and evaporation increases so that the soil, already insufficiently moist, dries up more rapidly.

Rainfall is irregular both in space and in time.

Spatial variations. These are easily discernible in the field from the uneven distribution of the plant cover, but are at times difficult to verify from climatic data owing to the great distances between meteorological stations. Studies by hydrologists at ORSTOM have given an idea of rainfall variations within the limits of a small drainage basin. For example, three rain gauges were placed a few kilometres apart (less than ten kilometres between the extreme points) in the drainage basin of Tchirozerine, 30 km north of Agadez. From these three rain gauges and the one at Agadez 30 km away, the results shown in Table 4 were obtained during 1973.

There is a considerable difference in the month of August between P2 and P3, situated less than 5 km apart. The lower the average rainfall the greater the possible difference between two neighbouring points, since a single storm at one station can significantly alter its total. That is what happened in this case, when on 14 August 1973 the western part of the

TABLE 2. 'Piche' evaporation (mm/month) at Agadez (1953–64)

January	February	March	April	May	June	July	August	September	October	November	December	Total
284	304	370	413	415	346	247	170	267	342	315	289	3762

TABLE 3. Mean rainfall and number of rainy days[1] (1921–54)

Month	Mean, 1921–54			
	Tahoua		Agadez	
	Rainfall (mm)	Number of rainy days	Rainfall (mm)	Number of rainy days
January	—	—	0·1	0·1
February	—	—	—	—
March	0·2	0·2	—	0·1
April	2·8	0·5	1·2	0·1
May	17·4	2·8	6·1	1·5
June	48·0	6·0	7·3	2·3
July	110·1	9·5	43·1	6·2
August	140·2	11·6	90·3	9·7
September	53·3	8·2	15·7	2·5
October	12·7	1·2	0·3	0·1
November–December				
TOTAL	384·7	40	164·1	22·6

1. Days with > mm rainfall.

basin was locally affected by a storm which deposited 50·4 and 49·2 mm of rain at P1 and P3 respectively, while P2 received only 24 mm. Stations P1 and P3 received two-thirds of their total monthly rainfall and more than a fourth of their total annual rainfall in a single storm.

These spatial irregularities occur during dry years as well as during wet years, and their consequences for the distribution of pastures within a single year can well be imagined. It can be seen that the mean isohyets which appear as roughly parallel lines on maps of the Sahel zone are not an accurate image of reality.

Variations in time. These are easier to check where rainfall readings over a sufficient number of years are available. Rainfall irregularities occur at two levels: on the one hand rainfall is unevenly distributed within one annual cycle, and on the other hand rainfall totals vary considerably from one year to another.

Irregular rainfall distribution over time can mean that large annual totals, even above average, may often not be beneficial to vegetation. Here the idea of 'useful rain' should be introduced, i.e. the portion of rainfall that has a direct effect on the development of the plant cover. In the Sudan zone, rain that comes too early with too long an interval between each shower often obliges the farmers to sow their crops several times. The same is true of the natural Sahel vegetation. Rain which comes too early in the season induces the vegetation to germinate and grow, but it cannot survive if it is not followed shortly by more rain. If the rains return a month later, vegetation recovery can only come from those species with sufficient reserves, and from the germination of a second stock of seeds whose dormancy had not been broken by the earlier rain. In any case, the vegetation is thereby weakened, stunted and thinned out. 'Such abnormal timing of rainfall, if it happens for the first time in several years, can wipe out a large number of annual species while the perennial plants become relatively more predominant; if such irregularity repeats itself, even perennial plants use up their reserves and decrease' (Peyre de Fabrègues, 1971).

Useful rainfall can be defined as the first rains that enable the soil to retain enough water to allow plants to develop to maturity without a break. J. Gallais (1967) judges that in a more southerly zone[1] than the study area, useful rainfall means 'more than 3 mm of rainfall followed by at least the same amount of rain within a maximum period of one week'. According to Peyre de Fabrègues (1971) in the south Tamesna region (included in the study area) 'the water needs of the vegetation are satisfactorily met if, during 70 or 80 days of the rainy season, rainfall comes at regular enough intervals to prevent the soil's water balance from dropping below the wilting point (at least for too long a time depending on the plant) and if total rainfall reached about 320 mm in the south and 150 mm in the north'.

The useful rainy season is relatively short. In the same zone, the dates of this period can change from one year to the next, but in the study area it generally lasts from 15 July to 31 August and often extends to 15 September. The concept of useful rainfall helps to explain why there were many droughts which caused serious loss of livestock due to lack of pasture, at a time when total rainfall was normal, or even above average. This was the case in 1967 and 1968 throughout the study area, from Tahoua to Agadez. At the latter station, the total rainfall was 155·3 mm in 1967 and 165·1 mm in 1968 (the mean from 1921 to 1954 was 164·2 mm). The year 1967 was a good one, while 1968 was a drought year when a great many animals died. In 1967 the rainfall came at regular intervals. In 1968, although total rainfall was higher, the portion of useful rainfall was very low: 50·2 mm of rain fell at the end of April in only six days. In the following month, only 0·5 mm fell, and this in one day. In other words, the 50·2 mm of rainfall in April started the vegetation's growing cycle too early and it could not reach maturity at a normal rate because of the lack of rain in May (Bernus, 1974*a*). In some cases drought is due to a deficiency in useful rainfall so that the vegetation cannot develop normally.

Rainfall irregularity between years is emphasized to show that annual averages poorly represent a complex situation.

The variation in the annual extremes at Agadez goes from 25 per cent (1970) to 182 per cent (1958)

1. The interior delta of the Niger, i.e. the Macina in Mali.

TABLE 4. Local spatial variations in rainfall (mm) during 1973 (Carré, 1973)

Stations	May	June	July	August	September	Total, 1973
P1	—	0·5	32·5	80·4	—	113·4
P2	—	4·2	31·2	45·8	0·2	81·4
P3	—	2·3	25·0	91·5	—	118·8
Agadez	—	10·8	39·4	17·9	0·1	76·1[1]

1. Including 8·1 mm in April.

TABLE 5. Variation in monthly rainfall extremes during the period 1966–70 in relation to the corresponding monthly mean, calculated over a period of fifty-three years (Peyre de Fabrègues, 1971)

Agadez	Tahoua
In April: from 0 to 4180% of the mean (1968)	In April: from 0 to 1850% (1968)
In May: from 0 to 350% of the mean (1966)	In May: from 5% (1967) to 371% (1966)
In June: from 0 (1970) to 270% of the mean (1968)	In June: from 71% (1966) to 264% (1968)
In July: from 20% (1969) to 140% of the mean (1968)	In July: from 66% (1966) to 157% (1967)
In August:[1] from 15% (1970) to 75% of the mean (1967)	In August:[1] from 30% (1968) to 128% (1966)
In September: from 19% (1969) to 160% of the mean (1967)	In September: from 56% (1969) to 231% (1967)

1. Note that during the period observed, the August rainfall never equalled nor exceeded the mean.

with respect to the mean calculated over a period of fifty-three years. At Tahoua, over a period of fifty-one years, the variation ranges from 53 per cent (1942) to 154 per cent (1936). Variation increases to the north, as rainfall decreases.

This interannual irregularity can often produce rainfall shortages over a series of successive years, as was the case from 1969 to 1972. The cumulative effects of these years cause droughts of catastrophic proportions (Tables 5 and 6).

Statistical analysis shows that there is one chance in two that rainfall will total between 120 and 196 mm during any given year. There are two chances out of three that the total will fall between 101 and 215 mm, and nineteen chances out of twenty that the figure will be between 44 and 272 mm. There is only one chance in 100 that total rainfall will be below 10 mm or above 300 mm during the course of any one year.

TABLE 6. Rainfall at Agadez, as an example of rainfall variability (Le Houérou, 1972): annual recorded rainfall from 1922 to 1972 (in mm)

1922	170·2	1939	139·0	1956	162·2
1923	155·2	1940	184·0	1957	118·9
1924	119·5	1941	139·5	1958	288·3
1925	107·3	1942	—	1959	234·3
1926	88·3	1943	210·3	1960	147·0
1927	144·9	1944	107·2	1961	216·0
1928	106·0	1945	224·9	1962	150·9
1929	148·3	1946	139·6	1963	175·0
1930	154·0	1947	270·4	1964	128·7
1931	203·0	1948	54·8	1965	149·7
1932	219·8	1949	118·2	1966	104·0
1933	157·2	1950	261·8	1967	155·3
1934	157·3	1951	108·2	1968	163·2
1935	180·0	1952	210·1	1969	80·7
1936	229·6	1953	287·6	1970	39·7
1937	132·0	1954	230·2	1971	92.6
1938	139·0	1955	158·0	1972	73·9

Annual mean over 50 years ($\bar{P}$) = 158·7 mm.
Mean annual days of rain (P > 0·1 mm) = 22·6.
Variance (V) = 162858/50 = 3257.
Standard deviation (σ) = $\sqrt{3257}$ = 57·1.
Mean deviation $|\bar{e}|$ = 2208/50 = 44.
Coefficient of variability = ($\sigma/\bar{P}$) = 0·36.
Median (M) = 152·5.
Probable deviation (ep) = 0·6745 σ = 38·5.

TABLE 7. Frequency distribution of annual rainfall at Agadez (1922–72)

Class (mm)	Number	Percentage	Class (mm)	Number	Percentage
0–50	1	2	150–200	13	26
51–100	6	12	201–250	9	18
101–150	17	34	251–300	4	8

Table 7 shows that the probability of obtaining less than 100 mm during any one year is about 14 per cent, i.e. one chance in seven. The theoretical probability of having four consecutive years of less than 100 mm each, as has been the case since 1969, is, according to binomial law, $(1/7)^4 = 1/2400$. This demonstrates very simply how exceptional is the present disastrous drought. In contrast, the probability of having more than 200 mm during any one year is about 26 per cent, or roughly speaking one chance in four.

The 1969–73 drought and earlier droughts

Drought periods seem to occur rather regularly, but in the study area rainfall readings are still much too recent to give a precise idea of how often to expect them; in Tahoua as in Agadez the first observations date from 1921.

The Tuareg, who have lived in the area a long time, have kept alive memories of past droughts by giving each year a name commemorating an outstanding event during the year. The elders can still today give the name of each year as far back as the beginning of the century. It is thus possible to obtain an idea of the frequency of past droughts, not just in one region because of irregularly distributed rainfall, but throughout the zone as a whole, with the help of this oral tradition, collected by numerous authors, as well as by using the rainfall readings which already exist in other Sahel countries.

The drought of 1910–15 appears to have been a deficit period throughout the Sahelian zone. The year 1915 was named *Awetay wan Mayatta* by the Aïr Tuareg, meaning the year of Mayatta, in reference to the Mayatta well near Dakoro, 300 km to the south of their normal nomadic zone. Drought and lack of pasture had temporarily forced them to a refuge far to the south. Rainfall statistics from other Sahel stations (Boudet, 1972) confirm this oral tradition. At that time the Tuareg suffered heavy livestock losses.

The period 1930–32, described as a time of famine (Fuglestad, 1974; Salifou, 1975), does not seem to have been deficient in rainfall. The cause was the destruction of millet harvests by locusts. Both farmers and pastoralists in the study area were severely affected by this food shortage.

From 1940 to 1943 a new drought affected the Sahel zone as a whole, but it was less severe than in 1910–15.

Climatic fluctuations are not discernible in the rainfall means calculated over fifty-four years, nor in the isohyets. A period of several years' drought, like the one from 1969 to 1973, is reflected in the advance of the Sahara and a corresponding retreat of the Sahel region. If a wet period should follow, the edge of the Sahara will move back towards the north. In the study area, the 100 mm isohyet moved 200 km to the south between 1969 and 1973, and the 350 mm isohyet, which marks the southern boundary of the area, moved 150 km to the south.

The recent drought is not a new phenomenon; it is part of the irregularity of rainfall that is characteristic of a marginal zone, with rainfall variability increasing as total rainfall decreases. However, these deficit periods do not appear in a regular fashion and it is impossible to speak of cycles which might permit more or less long-term forecasts to be made. Hence, making all the reservations necessary when analysing bad periods in relation to a limited set of data, one can only resort to statistical probability. Using this approach, droughts like those of 1913 and 1972 appear as phenomena occurring every fifty years and the 1943 drought as a thirty-year occurrence, with the thirty-year and fifty-year phases expressing frequency not periodicity. In addition, just because the droughts of the same intensity occurred in 1913 and 1972, it cannot be claimed that the worst conditions have been reached; it is not possible to exclude the eventuality of even more disastrous drought periods whose probable frequency cannot *a fortiori* be predicted.

In conclusion, it should be emphasized that although opinions differ on long-term climatic change there has been no decisive proof to show that total rainfall is diminishing at the present time. One can here cite hydrologists to the effect that 'at present there is no general trend toward the drying up of the Sahel and tropical zones' (Carré, 1973). Only the irregularity of rainfall, i.e. the irregular succession of dry years, remains an uncontested feature of the Sahel climate.

Landform and soils

Relief

A vast sedimentary basin, the Ioullemmeden Basin, takes up the entire western part of the Niger Republic and overlaps to a great extent into neighbouring states, particuarly Mali. This huge depression rests on a four-cornered base: Adrar of the Ifoghas and the Aïr to the north, the Gourma country and northern Nigeria to the south. The study area is contained within the north-east section of the basin and is bordered on the north by the first foothills of the Aïr mountains.

The basin is dominated by broad plateaux and plains. It lies at an altitude of 600 m in the south at the edge of the Ader mountains and continues at around 400 or 500 m all the way to the margin of the Aïr. The basin is made up of continental and marine sedimentary rocks which form classic *cuestas*, with scarps generally facing towards the north-east, in the direction of the Aïr. Several distinct regions can be identified from their landscape and relief, each taking the form of an arc following the strike of the *cuestas*.

In the far south, the last foothills of the Ader form a cliff which is broken and indented by deep valleys with vertical walls of more than 150 m.

At the foot of the Ader begins the region of fossil dunes which cover the underlying sedimentary formations and form large sandhills. These are held in place by the vegetation and rarely show a parallel alignment.

Next to the north come monotonous sandstone plateaux, interrupted only by small rock barriers and broad valley depressions. These are the Tegama plateaux, ending in the north-east at the Tiguiddit escarpment which, in its central part, forms a continuous and regular arc.

Between this sheer massif, which disintegrates into isolated hills in the north, and the first foothills of the Aïr, there is a broad plain of deep impermeable clays which forms a peripheral depression on the margin of the ancient massif. The plain is known as Eghazer wan Agadez, meaning 'the plain, the one of Agadez', and is completely flat, interrupted only by a few sandstone buttes forming islands in the valley plain. This plain gathers a cluster of *wadis* from the Aïr and the Tiguiddit scarp into one main drainage channel which flows north-west before turning south and cutting across the various sedimentary arcs under a succession of names, such as Azawak, Dallol Bosso and Boboye. After crossing Malian territory, this dry valley reaches the valley of the Niger, well beyond the study area.

The various sections of the area are connected by the main valleys which, from east to west, make their way toward the north–south axis of the Azawak. These dry valleys form broad depressions in the sandstone plateaux and are also evident among the tangle of dunes of the ancient erg. At two points only have the dunes covered the valleys of the Azawak and of the Azar in the south; everywhere else their outline remains clearly visible as a noticeable depression. The valleys also cut into the various escarpments that they cross.

It must be remembered, however, that these dry valleys are linear depressions which very rarely carry water, except in short sectors after a violent rainstorm, and in the plain west of Agadez, where the Eghazer is fed by larger *wadis* and, in some years, is filled with turbulent waters flowing north–west and disappearing in the In Abangarit region.[1] The valleys are thus large furrows sunk into the sandstone and traceable through the dunes, marked by dense woody vegetation and, in the rainy season, by a series of stagnant pools which flood the depressions.

The *cuestas*, with more or less unbroken scarps, are at times reduced in size to small hills. The resistant strata are of sandstone, or more rarely of limestone, and form the topographic framework of the sedimentary basin.

Soils

The soils of the area according to the soil map of Africa (Hoore, 1964) and pedological studies by ORSTOM (Boulet, 1964, 1966; Gavaud, 1965) can be divided into the following five groups.

Raw mineral soils. These are present especially at the northern limits of the area, while in the south

1. We personally observed such flows in August 1962 and in August 1965.

they are more often associated with other soils. Types to be distinguished are:

- rocks and rock debris, indurated material in places reduced to coarse debris by weathering;
- regs (gravel plains) mantled with coarse debris derived from rock weathering;
- sands or dune fields.

Weakly evolved soils. These show little differentiation of their horizons. They are common in the area but are almost always associated with other types of soils. Undifferentiated desert soils, very low in organic material, are characteristic.

Brown and chestnut soils of arid and subtropical regions. The colour of these soils is due to the presence of organic material in small amounts well-distributed throughout the profile. They include brown soils and reddish-brown soils.

Halomorphic soils. These are characterized by soluble salts in the profile.

Hydromorphic soils. These are characterized by temporary or permanent water-logging as a result of their location in the lowest-lying parts.

From this brief and rather theoretical description of soils, it can be seen that only a large-scale map can properly represent the major climatic formations, the variations in the substratum, and the surface relief.

'The most important ecological factor for the pastures is the soil's ability to absorb and retain water. This depends on soil texture and surface relief. Thus, the following soils can be differentiated according to texture: sandy soils, loamy soils and clay soils' (Rippstein and Peyre de Fabrègues, 1972).

Sandy soils can be coarse (0·2–2 mm), fine (0·05–0·2 mm) or very fine (0·02–0·05 mm). 'These soils have a high water-absorption capacity, but low retention. Plants can satisfactorily grow there, but those with a shallow root network dry up with the end of the rains' (Rippstein and Peyre de Fabrègues, 1972). Sandy soils are by far the most extensive in the area, with the coarse-grained variety located primarily on the tops of large dunes, on sandy plateaux and in *wadi* beds. The fine-grained soils make up the low dune terraces in particular.

Loamy soils and clay soils cover very limited areas and are found only in such low zones as inter-dune hollows, valley bottoms, etc. These soils, although often only temporarily waterlogged, have such a large capacity for water retention that plants cannot use it. The soils have bare surfaces or only scattered vegetation (Rippstein and Peyre de Fabrègues, 1972). Vegetation usually develops therefore on the periphery of clay hollows, on the edge of pools where the clay is mixed with sand and has a lower water retention.

In conclusion, it is necessary to remember that a large part of the region 'is covered by a stabilized erg whose soils are largely brown or reddish-brown, of sandy texture and with small amounts of organic matter' (Rippstein and Peyre de Fabrègues, 1972).

Water resources

Water for the pastoralists comes from three main levels: surface water, shallow ground water and deep ground water.

Surface water

During the rainy season, surface water gathers in all depressions in the clay soils. The water collects in pools, none of which are permanent except for one at Tabalak-Kéhéhé in the extreme south of the region. Their persistence and the quality of water they contain vary from year to year, but a few of them, because of their topographical location, are usually large and retain water until February or March in the following year. This is the case of the pools of Chin Ziggaren, Ebrik and Ekawel in the valleys of the Tegama plateau. Most pools, however, dry up in November or December, or more rarely in January. These pools, which are sometimes large but rarely very deep, dry up through the combination of very high evaporation and the dry harmattan wind. The pools play an important role throughout the region in freeing herdsmen from the task of watering for several months.

Water can also be found in rocky areas where a rock barrier allows a basin (*agelmam* or *guelta*) to be formed. Such reserves however, although sometimes quite deep, are small in size and rare in the area. Only a few, short-lived reserves are found in the escarpment north-west of In Gall. They are much more numerous in the Aïr Mountains.

In the Teguidda region, a small area in the central part of the Eghazer (west of Agadez and north of In Gall), there is a series of mineral springs where pastoralists come in great numbers to water their herds during the rainy season.

These surface-water resources complement each other. The pools scattered throughout the region south of the Eghazer (Agadez–In Gall Plain) are only temporary. Permanent springs are used the year round by the relatively few pastoralists who live near by. However, during the rainy season countless herds from the south encroach on the permanent springs and often return there a second time during the dry season.

Shallow ground water

Shallow ground water is available to pastoralists, who dig shallow wells, rarely more than ten metres deep. The mouth of the well is often situated on a small rise and is encased at ground level by several layers of branches. The circular wall of the well is padded with straw to keep it firm and to prevent it caving in. Branches are used if straw is not available for this purpose. As a general rule, each shallow well holds only 30 cm of water, which is rapidly depleted after one or two buckets have been drawn. For this reason, several shallow wells are always sunk in the same place, so that when a herdsman has momentarily depleted one well he can go on to the next. He then returns to the first when it has refilled with a small amount of water.

> The existence of shallow ground water is directly related to pools and to deposits in the valleys and is discontinuous in both space and time. A spatial discontinuity occurs because the Quaternary deposits which fill in the valley floors are not of alluvial origin but are debris of various types, such as dune sands, lacustrine silt and sandy-clay soils. Ground water is thus restricted to certain places known to the nomads. The latter sink shallow wells mainly on the edge of dried-up pools. Such wells are also dug at places where valleys meet.
>
> Shallow ground water is discontinuous in time because it reflects the amount of rainfall received each year: one part of the valley that has had good rains will give full wells, while another, used in previous years, may not have been replenished by the year's rains. Shallow layers of ground water result entirely from the irregular rainfall, and each layer exists independently of the others.
>
> The shallow wells are very often emptied before the end of the dry season. They are fragile and cave in almost every year in the rainy season when the pools fill up. These wells are therefore short-lived and for ever changing position, which means that herdsmen do not gather around any particular well in December and January when the pools dry up. (Bernus, 1974*a*.)

Lastly, in those rare parts of the country which are mountainous enough for the rainy season to cause violent floods in the *wadis*, pastoralists use the underground water flow by digging into the *wadi* bed. These wells are very shallow and frequently collapse: they are often shored up by branches and straw. They are found in the *wadis* which descend the Tiguiddit escarpment. For a long time the sedentary population of In Gall used water from a nearby *wadi*.

Deep ground water

Deep ground water is most often exploited by cement-lined wells or by pumping stations constructed by government departments. In a small number of places deep ground water has been used since ancient times by the inhabitants themselves. It seems that the oldest wells were dug by populations long disappeared, who inhabited the land prior to the peoples there today. One of the most successful examples of these ancient wells is located at In Arraman and is still used. The nomads know the location of these wells and still use them often. Today in the same Tadarest region, in the Tegama sandstone plateau, a great many deep wells are dug by traditional methods. Because of the consistency of the rock, water can be reached at a depth of 40, 50 or even 80 m.

The main deep aquifers in the region, from north-east to south-west include:

- the sub-artesian aquifer in the sandstone of Agadez (0–215 m), with a small artesian zone between Teguidda n Tesemt and Teguidda n Adrar;
- the unconfined aquifer of the Continental Intercalary (15–100 m), which stretches throughout the entire Tegama plateau to the south of the In Gall Plain;
- the confined Continental Intercalary aquifer (250–800 m), under pressure, which is an extension towards the south-west of the unconfined aquifer. Here the water is confined below Cretaceous beds, which must be dug through.

The deep water-table is at present tapped using the following methods:

- traditional deep wells, old or new, almost all dug in the unconfined Continental Intercalary and in the Agadez sandstones;
- cement-lined wells, dug by government departments, also in the Agadez sandstone and the unconfined Continental Intercalary aquifer. There are no such wells in the zone of Cretaceous formations, which have remained unproductive despite numerous attempts at exploitation;
- pumping stations exploiting both the unconfined and confined Continental Intercalary aquifers. In the latter case, drilling must bore through all zones of the Cretaceous in order to reach the confined water-table at very great depths (690 m at Digdiga);
- deep boreholes (without mechanical pumping) exploiting the Agadez sandstone aquifer, particularly in the artesian zone. The first artesian borehole drilled was at In Gitan, but today there are a great many others.

Hydrogeological provinces

From the preceding discussion, it is evident that this region can be broadly divided into several sectors, defined according to the types of water use by pastoralists:

The Tiguiddit escarpment and the In Gall Plain (Eghazer). In this area, ponds are few and ephemeral. The only large and lasting (up to February) surface water is that retained by the Tiguerwit dam, constructed in 1968. The springs of the Teguidda region play a very important and unique role in animal husbandry in Niger. The flow of ground water is tapped in the beds of the principal *wadis*. The artesian conditions allow the deep aquifers to be exploited by means of numerous boreholes, many of which are a result of exploration by research organizations, the Commissariat à l'Énergie Atomique (CEA) in particular.

The Tadarest and the Tegama sandstone region. This region is rich in pools on the floors of the main 'fossil' valleys, and some of these last for several months. In contrast, shallow ground water is rare and there are few shallow wells. There are many traditional deep wells or cement-lined wells in the valleys, as well as several pumping stations. In other words, this area has plentiful deep ground water but limited shallow ground water, and there is no transition between surface waters and the deep aquifer.

The region of fossil dunes and of Middle Cretaceous rocks. Surface water is abundant, and pools are of varying size and duration, depending not only on rainfall but also on their topographic position. The pools at the foot of escarpments which abut against dunes are in favoured positions. Examples include: the pools of Wezzen and Gharo at the foot of the Cenomano-Turanian escarpment; the pools of Segat, Douroum and Kao at the base of the more southerly Senonian and Palaeocene escarpment, and particularly the pool at Tabalak-Kéhéhé, situated in a valley at the foot of sheer cliffs, where torrential run-off from the slopes is collected on impermeable ground below.

The greatest number of pools occur in the numerous interdune hollows, although these are of brief duration.

In this sector, shallow ground water is an important resource; it is found at the edges of all dried-up pools and allows for a greater dispersal of men and livestock during the dry season. In contrast deep wells are rare and pumping stations, which are abundant in the region, are the only means of exploiting the confined Continental Intercalary aquifer at great depths.

In summary, this area has surface water, shallow ground water, and deep ground water, the use of which is restricted by the limited number of pumping stations, which can rarely be replaced by wells.

These three hydrogeological provinces were considered in relation to their potential use by men and their herds, and this leads to a study of the vegetation. This will also be approached through the use made by pastoralists, i.e. in terms of rangeland. This makes up the other half of the water–vegetation relationship that rules the life of pastoralists and their animals.

Vegetation and rangelands

The plants which make up the rangelands, on which all animals entirely depend, can be studied by use of several overlapping criteria. There is a distinction between trees or shrubs and grasses, which form the two browse layers. Vegetation can also be classified according to rainfall zones: north and south of the 200 mm isohyet, for example. Finally, topographic conditions and soil texture can be used: coarse-grained sand, fine loamy sand, sandy clay soils and clay loams. Of course, each of these soils is found in each climatic zone.

Agrostological maps distinguish two main types of rangelands: those usable in the rainy season and those usable in the dry season. The latter can be further subdivided into good, fair and poor rangeland.

Rainy-season rangelands

These rangelands are located in the north of the study area and cover the sandstone plateaux of Tegama to the west, and especially the plains, dunes and plateaux north of 16°30′ N. Grass species dominate these ranges with perennials such as *Panicum turgidum* on the dunes and plateaux and annuals like *Aristida hordeacea* on the plains. Special mention should be made of the clay plains of the Eghazer, which in a good year provide rich pastures containing *Sorghum aethiopicum, Schoenefeldia gracilis, Aristida* spp., *Ipomoea verticillata* and *Psoralea plicata.* For a relatively short time they can support many animals.

However, this entire northern region is very poor in forage trees, and in the dry season can support only a relatively small number of animals. Trees such as *Acacia ehrenbergiana, Salvadora persica* and *Acacia raddiana* are very rare, scattered and normally small.

Dry-season rangelands

Good rangelands

Good grazing is found on the subSaharan rangelands at the northern borders of the study area, which cover vast areas until as late as January and sometimes even into March. These are the extensive rangelands of *alwat* (*Schouwia thebaica*), stands of which are found in the In Abangarit region on flood plains devoid of shrubby vegetation. This forage species is relished by camels and is sought out by all pastoralists.

The great majority of dry-season rangelands are found in the south of the study area on the sandstone Tegama plateaux, where *Commiphora africana* is dominant on the stable dunes of the Abalak region, which offers good-quality rangelands, and in the central 'fossil' valleys.

Medium-quality rangelands

Also found in the south, these rangelands cover immense areas of dunes in the west with *Aristida mutabilis* and *Aristida funiculata,* and also valleys of the Tegama plateaux.

Poor pasture

These develop near rock outcrops, with *Aristida funiculate* in the ground layer and *Acacia seyal* in the tree layer.

Complementarity of rangelands

Except for the subSaharan zone of *alwat*, used exclusively by subSaharan camel pastoralists, the study area has two contrasting zones. The northern one has grass rangelands which vary a great deal depending on the rainfall but which, in the clay plains, can have an extremely high production value of about 2000 kg of dry matter per hectare. This means that one hectare will feed one to two TLU[1] during the short rainy season. In other words, these plains offer very good grazing for a short period, but have exclusively grass forage species without a shrub or tree layer.

The rangelands of the southern zone never reach the forage value of those on the clay plains to the north, but can be used in all seasons. Agrostologists calculate that a surface of ten hectares is required to maintain one TLU. These rangelands however have both a grass and a shrub/tree layer. The latter includes *Maerua crassifolia, Balanites aegyptiaca, Acacia raddiana, Acacia nilotica, Zizyphus mauritania,* and has excellent forage value not subject to the seasonal variations of the grass layer. The shrubs are available when grass has dried to straw and lost its nutritive value. This explains the contrast between

1. TLU: Tropical Livestock Unit, a reference unit adapted to African breeds; i.e. one animal at 250 kg liveweight. One camel = one TLU; one bovine = 0·75 TLU; one sheep or goat = 0·10 TLU.

the two zones and the mechanics of a land use which varies both in time and space.

Spring water carrying mineral salts; wells and artesian boreholes; different forage species; saline soils eaten from the ground—all combine to meet the needs of the animals, to purge them and free them from intestinal parasites. Pastoralists thus benefit from the complementarity of two quite different zones, by means of the wet-season movement, commonly called a 'salt cure'.

Population

Sources of information

Available information on the population of the area comes from administrative censuses of the Agadez and Tchin Tabaraden subprefectures. Data drawn from these censuses should always be used with caution, and it is necessary briefly to point out the difficulties involved in their interpretation.

The censuses are carried out by 'group', each group being made up of a certain number of 'tribes', as in the case of the canton of an agricultural zone made up of several villages. The census of each group and of each tribe is taken in succession, according to a plan drawn up by the administrative authorities. This means that there is no picture of the population at a given moment, but rather a series of censuses taken over several years. From time to time census records are more or less brought up to date by noting the deaths and births. Names are crossed out and written in but there is no question of a complete registration. Errors are often greater in the nomadic zone than in the sedentary zone because it is difficult for the census-taker actually to contact all members of a dispersed tribe. He must often be content with the answers of a third party, the head of the tribe or family.

It must not be forgotten that these censuses serve a fiscal purpose, and in the records there is always a distinction between 'tax-payers' and 'non-tax-payers', the latter including children under 14 years, old people and the disabled. 'Non-tax-payers' are often recorded with less precision.

The censuses are recorded in 'notebooks' which group together one tribe, or if it is too big, one clan of a tribe. This group of people, which uses the name of a single person, often a common ancestor, is almost always scattered over a very large area and rarely occupies an exclusive territory unshared by numerous other tribes. Moreover, tribes coming into the Tchin Tabaraden or Agadez districts often continue to be listed by their old district. Inversely, tribes which have migrated remain administratively attached to Tchin Tabaraden and Agadez. Census-taking tends to be conservative, and departures and arrivals are not known and brought up to date for several years. Thus the Foulani tribes which have lived in the district for more than thirty years were only attached to Tchin Tabaraden, as the ninth nomadic group, in 1974.

In summary, administrative censuses, often the only source of documentation, must be interpreted with caution, and verified and cross-checked as often as possible.

For the district of Tchin Tabaraden, information can also be found in the results of the Enquête Economique en Milieu Nomade (Economic survey in the nomadic area), carried out in 1962–63 by sample surveys, with the help of statisticians from the Institut National de la Statistique et des Études Économiques (INSEE) and the Société d'Études et de Développement Économique et Social (SEDES) (INSEE Coopération and SEDES, 1966). The survey provides more accurate demographic data on the natural evolution of the population in that period. Even if it does not cover the entire study area, since the populations of In Gall and Adadez are not included, it nevertheless furnishes basic data on the demography of nomadic populations.

Population of the area

In the study area the majority of the population is of Tuareg origin. 'Tuareg' however does not mean a homogeneous human group in the biological sense, but a very mixed population joined by a traditional political framework, the unity of which is principally cultural. When populations called 'Tuareg' wish to define themselves in relation to other groups, they call themselves 'Kel Tamasheq', meaning those who speak the Tamasheq language, and they are fully aware that their unity is mainly cultural. Before the colonial period, the entire area was under the exclusive control of Tuareg chieftains. The other peoples in the area are 'nomadic Arabs' who settled here at the end of the nineteenth century with the agreement of the Tuareg chiefs.

Newcomers, the Foulani, have been arriving over the past thirty years and are dispersed throughout the area. If census figures are used as reference, the data for the Tchin Tabaraden district give:

Kel Tamasheq	*Arabs*	*Foulani*	*Total*
75634	8365	6782	90781

An estimate of the relevant population for the northern part of the area, the Agadez district, is less readily obtained.

All populations recorded at the administrative office at In Gall live in the area:

Kel Tamasheq	*Arabs*	*Foulani*	*Townspeople**	*Total*
8144	1260	815	2327	12546

*In Gall and Teguidda n Tesemt.

There remains only the populations recorded at the Agadez subprefecture, a large part of whom live in the Aïr mountains or in the Aderbissinat region in the south, both out of the study area:
12

*Kel Tamasheq**	*Townspeople†*	*Total*
3300	6694	9994

*Belonging to the Kel Ferwan—a very approximate estimate.

†Agadez town.

In all, the total for the region is:

Kel Tamasheq	*Arabs*	*Foulani*	*Townspeople*	*Overall total*
87078	9625	7597	9021	113321

Among these populations it must be noted that, besides the townspeople of Agadez and In Gall, there are in the southern Tchin Tabaraden district some groups which have settled in villages and around fields and which have lost their pastoral mobility; some are located on the southern limits of the study area, others further to the south, and it is difficult to separate them. Lastly, the inhabitants of Tchin Tabaraden or Abalak do not appear on the records because most of them are counted in their tribe of origin.

The mobility of populations and herds

For the populations whose estimated numbers have just been cited, the district in which they are recorded is based on residence during the dry season, i.e. for nine or ten months of the year.

The regional complementarity, described in the section above on rangelands, explains population mobility. The groups which live in the dry season on the northern plains, where there is high grazing potential during the rainy season, move very little during the course of the year. Groups occupying southern rangelands (largely those originating in the Tchin Tabaraden district) migrate north in the rainy season and concentrate on the clay plains of Eghazer during the short time that these plains can maintain a very large number of animals. This summer movement, generally lasting from the beginning of August to the end of September, leads nomads from all the wells of the Azawak to converge on the northern plains. Although the destination is the same, the departure point varies for each camp as its members move during the dry season in a valley which changes very little from one year to the next. The routes towards the north always remain the same; however, participation in the 'salt cure' varies from one year to another, depending on the rainfall and on the state of the pools and of the rangelands. For two months the south is relatively deserted, as people concentrate in the Eghazer to the north.

In addition, during the rainy season, the area is invaded by outside populations, i.e. people counted in the southern districts. There are Foulani herds, men with large herds of cattle, and sometimes sheep, from Dakora, Tahoua, Birni n Konni, Madaoua and even from northern Nigeria. Kel Gress Tuareg come from the same regions with large herds of camels and also cattle, sheep and goats. Almost always it is a matter of a few families which accompany most of the village or tribal herds. Grazing pressure on the area increases tenfold, and other herds occupy regions abandoned by the Tchin Tabaraden pastoralists. These few facts show the difficulty in estimating human and animal pressure on the land, because it varies so much in time and space.

Demographic data

The administrative censuses that have been used as overall estimates provide information that is often difficult to interpret for natural trends or growth of the population. The results are very deceptive, as is shown by a report by the Ministère du Plan (Planning Ministry) on Agadez province (Albenque, 1974–75), which attempted to measure changes in the population of the province between 1963, 1972 and 1975. The variations recorded in the Agadez district (− 2·2 per cent in 1964–72, + 10·4 per cent in 1964–75, − 12·9 per cent in 1972–75) seem to be the result of census methods rather than of actual population trends. This hypothesis is confirmed by the abnormally small number recorded of children under 14 years of age (24 per cent of the total population and 14 per cent and 18 per cent for Foulani and Tuareg nomads respectively). 'In conclusion,' says the report, 'it does not seem to be useful or possible to seek demographic data in the census documents and one must be content with overall estimates.' These remarks are also applicable to the Tchin Tabaraden district and confirm the criticism of information sources made at the beginning of this chapter. Until the next general census of Niger, now in preparation, there is only the demographic survey of 1962–63 (INSEE-Coopération and SEDES, 1966), which is already quite old and covers only Tchin Tabaraden, but was carried out by more precise sampling methods within a single year. This survey gives information on the nomad demographic situation at that time and can be used as a reference for the neighbouring population of Agadez (Table 8).

It should be noted that the survey extended as far south as Tahoua, which includes an area to the south of the present study area. Because of this, the Farfarou Foulani were studied, while the present study area includes only the Wodaabe Foulani, commonly called the Bororo, who today are registered at Tchin Tabaraden. The demographic survey thus included the entire area north of Tahoua and studied the following groups:

Tuareg and Arabs: 82000 *Foulani:* 18000

with the following composition:

	%		%
Tuareg:	17	*Bororo:*	8
Arabs:	12	*Farfarou:*	10
Bouzou (ex-servants):	53		—
	—		
Total Tuareg population:	82	*Total Foulani population:*	18

It should be remembered that if the Tuareg and Arabs are those counted in the censuses, the Foulani are more numerous in this inquiry since they include the Farfarou, who are as much farmers as pastoralists. They differ in this respect from the Bororo, who were the only Foulani for whom census data were given above, because of their more northerly position.

TABLE 8. Age composition of population[1]

Population group	Total population (%)		Niger: sedentary rural population (%)
	Foulani	Tuareg	
Children (under 15 years)	47	36	43
Adults (15–59 years)	50	59	52
Old people (60 years and over)	3	5	5
	100	100	100

1. Based on demographic survey of Tchin Tabaraden district, 1962–63 (INSEE Coopération and SEDES, 1966).

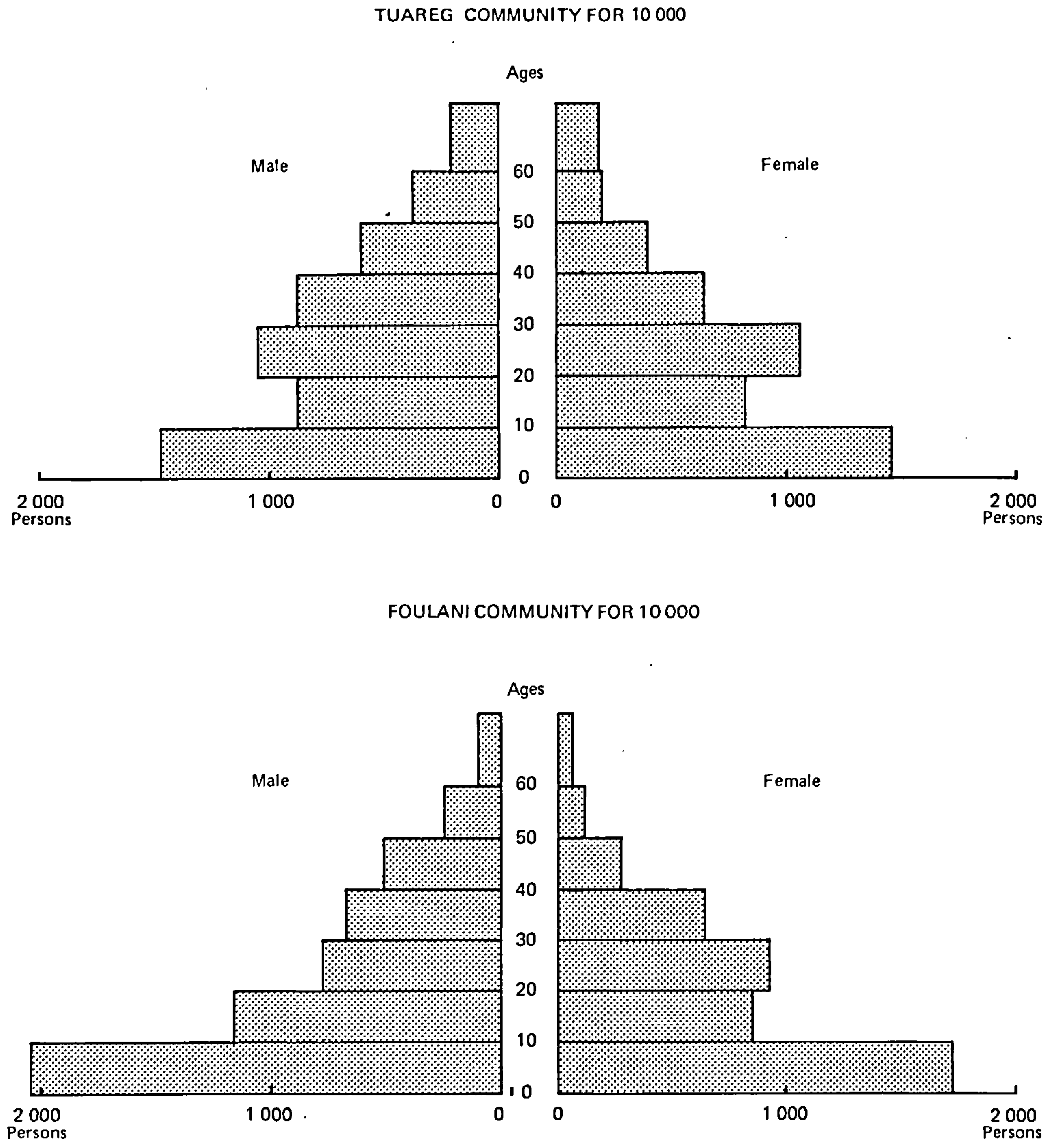


FIG. 2. Age-class pyramids based on 10000 people in each ethnic community

The natural population trends, based on the demographic survey are:

Foulani population	Birth rate: 41 per thousand Death rate: 22 per thousand
Tuareg population	Birth rate: 52 per thousand Death rate: 27 per thousand

This gives a growth rate of 19 per thousand for the Foulani and 25 per thousand for the Tuareg.

In all groups there is a particularly high ratio of males. This is difficult to explain and may come from a systematic survey error (Bernus, 1974*b*): 116 males per 100 females in the Tuareg population and 123

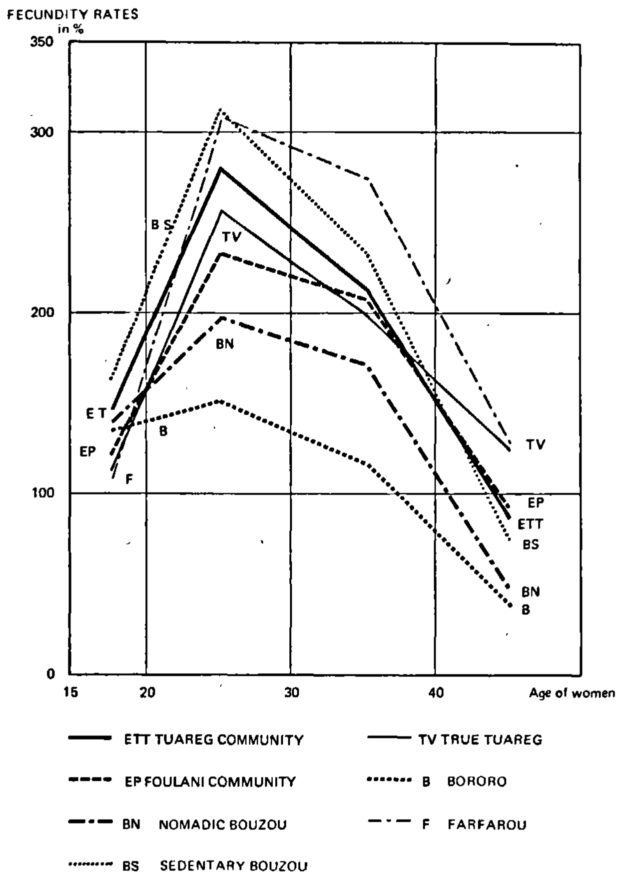


FIG. 3. Fecundity rates by age and ethnic group

per 100 among the Foulani. The main age groups appear to differ very little from those observed in surveys of sedentary societies.

The annual growth rates observed, 19 per thousand for the Foulani and 25 per thousand for the Tuareg, are comparable to those in other African countries. They are the sign of a rather rapid expansion which 'would lead to a doubling of the population in less than thirty years, assuming that birth and death rates remain the same as those of the survey'. However, within each of these two main groups, there are differences: the growth rate of the nomadic pastoralists (Tuareg, nomadic Bouzou and Bororo) is lower than that of the sedentary groups engaged predominantly in agriculture (sedentary Bouzou and Farfarou) (Fig. 3). The annual population growth rates (per thousand) of subgroups are as follows:

	‰		‰
Bororo:	11	*Farfarou:*†	24
True Tuareg:	12	*Sedentary Bouzou:*	35
*Nomadic Bouzou:**	23		

*The Bouzou are the former servants of the Tuareg.

†Among the Foulani, the Farfarou are farmers, differing from the Bororo in this respect; they live mainly to the south of the study area.

A reasonable hypothesis would be that the nomadic pastoralists of the Agadez region have a growth rate comparable to that of the non-farming pastoralists of Tchin Tabaraden, i.e. below the average.

In their conclusion, the authors of the demographic survey express the hope that the demographic data be considered only as a general indication 'rather than as precise and definitive figures'.

Pastoralism and society

The area has a pastoral potential and supports herds of camels,[1] cattle, sheep and goats. Only the southern edge has fields of rain-fed agriculture, which can extend to the north of Tchin Tabaraden and Abalak in a wet year. Pastoralism is also dependent on environmental conditions: the north, between the 100 mm and 200 mm isohyets, is the best area for camels; cattle on the other hand are better adapted to the southern zones, between the 200 mm and 400 mm isohyets; while sheep and goats are found everywhere. In spite of the rather difficult environment however, pastoralists often prefer types of animal husbandry based on social factors and their own traditions. For the Tuareg the camel is the prestige animal, whereas for the Bororo Foulani, cows are the wealth and capital which give a man dignity. The Bororo zebu, characterized by lyre-shaped horns, a prominent hump and a plain, dark coat, is totally different from the small Azawak zebu of the Tuareg, which has small horns and a spotted coat. These few differences show that pastoralists do not always respond in the same way to the same environmental constraints.

The diet of the pastoralists living in the area is principally composed of dairy and cereal products, which in fact most often means milk and millet. As the dry season progresses and herds give less milk, millet becomes increasingly important as food. Meat remains a luxury, eaten in large amounts on rare occasions such as religious or family festivals or visits by important guests.

With the exception of gathered food, of which wild-grass seeds are an important supplement, a large part of the area's food resources comes from the southern zone of rain-fed cultivation of millet and sorghum. Pastoralists thus sell surplus animals at southern markets in order to buy cereals and produce not found locally, such as tobacco, tea and sugar, as well as clothing and blankets. The sheep are short-haired animals which do not produce wool, and Tuareg and Foulani societies do not have specialized weavers. Pastoralists sometimes exchange small livestock for millet which farmers bring to them out in the rangelands. These food customs and the need for outside produce render the area's inhabitants dependent on the Sudan agricultural zones as well as on grain prices. A bad millet harvest is as damaging to the pastoralist as a decline in pasture growth.

Evolution of land use

Historical summary

Sources

Sources for the history of the area are few but diverse, and further knowledge is continually being added, even today.

1. The animal in question here is, in fact, the dromedary, erroneously called 'camel' by all authors.

Archaeology reveals prehistoric human activity in the area. Arrowheads present throughout the area testify to the activities of Neolithic hunters and fishermen. Excavations, which often confirm historical traditions, show there to have been fixed human settlements in places where today there is only nomadic pastoralism. Azelik, in the Teguidda region of the Eghazer, may be the Takedda visited by Ibn Batuta in the fourteenth century. Further west was In Tedoq, occupied according to tradition by populations which today are exclusively nomadic.

Written sources such as the Arab *tarikh* are used today to shed new light on the history of the populations of the area. These sources are the work of religious Arab and Tuareg tribes (*ineslemen*) (Norris, 1975; Ghoubeïd Alojaly, 1975).

Oral traditions are very rich and have for a long time been the source of Tuareg epic history relating warriors' deeds of valour and great battles.

Administrative and technical reports provide a knowledge of policies, the resistance that these policies encountered, and the general evolution of the area in the realm of administrative and technical organization for the period since the colonial era.

Population distribution before the colonial period

Throughout the area, but particularly in the northern plateaux, prehistoric settlement is evident from cave paintings, stone-workshops, flint arrowheads, and stone burial mounds—pre-Islamic tombs—scattered over rocky surfaces.

Centres such as Takedda (probably Azelik), where copper was mined, developed through the distant influences of the various Sudanese empires, Mali, Songhay and Bornu (the last affecting the Aïr region). Agadez, founded in the second half of the fifteenth century, became the residence of the Sultan of Aïr (1405). More to the west, In Tedoq, of which remains still exist and which is still remembered in tradition, became a centre surrounded by satellite villages engaged in animal husbandry, hunting, crafts and agriculture. After In Tedoq was destroyed by war, tribes which had lived in the city emigrated to the Azawak, where they are still found today. These religious tribes, Ayt Awari, Dahusahak and Kel Eghlal, newly settled further south, retained their political power. However, noble warrior tribes, which had separated from their families remaining at Menaka, arrived from the west and took over the chieftaincy.

The important thing to be understood from this brief description is that two population strata occupied the area in succession: the religious tribes from In Tedoq, followed by the warrior tribes with the Kel Nan as their leaders. The latter took over the chieftaincy of the new political grouping thus created; the tribes which had arrived earlier kept only a juridical role linked to their knowledge of Arabic, with the sole exception of a brief episode when one of them took power in the name of Islam (El Jelani from 1809 to *c.* 1816).

Thus, after this short episode, a confederation was created, that of the Ioullemmeden Kel Dinnik, led by an *Amenokal*, chosen from one of the noble tribes (Kel Nan) with, at its summit, noble tribes ruling a hierarchical and pyramidal society. This 'political entity' occupied, broadly speaking, the entire present-day district of Tchin Tabaraden and extended its influence south over the agricultural Ader region, which was a producer of millet. At the very end of the nineteenth century, around 1890, Arab tribes including the Daremshaka group arrived in the Azawak, having left the Adrar of the Ifoghas because of disputes with the Tuaregs of Menaka. They were warmly welcomed, settled down in the northern Azawak, and became the defenders of the northern borders.

The second half of the nineteenth century and the very beginning of the twentieth saw the various neighbouring Tuareg confederations in continuous struggle with one another. The Kel Dinnik Tuareg of the Niger Azawak set themselves against the Kel Ataram Tuareg in the west, the Kel Aïr and Kel Ahaggar in the north, and the Kel Gress in the south. The struggle with the southern group was particularly intense for control of the Ader region, which produced cereals. The principal noble tribes of the Azawak, with their respective dependants, occupied the southern part of the present pastoral zone; the Irrewelen were in the west, the Kel Nan and Tigguirad in the centre, and the Ikherkheren and Tellemidez in the east, thus covering the entire area.

The Agadez region was occupied by successive waves of nomads from the north, the first of which was made up of 'men of religion', the Igdalen. After the destruction of Takedda, the Sultan of Agadez, a sedentary chief, controlled the commercial routes and played the role of arbitrator between the warring nomadic confederations. He ruled the important towns of In Gall and Teguidda n Tesemt.

Before settling in their present area, the Tuareg groups passed successive periods of time in the Aïr mountains. The Kel Fadey left the north-west of the Aïr to occupy the In Gall plains; the Kel Ferwan came down from Iferwan to reach the southern Aïr, the Agadez region and the southern plateaux. The most recent arrivals, the Kel Ahaggar tribes, came to nomadize to the west of the Aïr and in the plains west of Agadez. This never-ending shift of populations testifies to a regular movement towards the south, which the arrival of the colonizer did not halt.

Changes since the colonial era

In 1900 the first military columns occupied Tahoua, but the Kel Dinnik Tuareg did not submit until the end of 1901. The presence of this new authority brought profound changes, not only in society but in its spatial organization. The authorities isolated the pastoralists and confined them to the nomadic zone in order to free the agriculturists from the pastoralists' hold. The nomads were thus deprived of southern markets and cereals which were indispensable to them. Colonization introduced a partitioning of territory which was completely contrary to the ideas of land-ownership held by Tuareg pastoralists.

These constraints, as well as the reduction in the chiefs' power and the creation of new chiefs in order greatly to increase the number of intermediaries, became intolerable to the warriors, who tried to free themselves from this new authority by the great revolt of 1917, which mobilized the entire Tuareg people. Put down with difficulty, this revolt caused the death of numerous warriors and provoked a general impoverishment due to livestock losses.

From then on, the colonial authorities, fearing new revolts, sought to reduce the authority of the chiefs. The tital of *Amenokal* was abolished and the Azawak Tuareg were divided into six groups, each with its own chief. The traditional organization was abolished and tribes were detached from their own nobles to be reattached to others. Geographically these new links caused confusion, since some tribes were attached to a chief more than 100 km away. The threat of reducing and splitting up the tribes was constantly made in order to coerce unco-operative chiefs. Finally, liberation of the slaves was attempted, but without any real success because of the fear of causing an economic and social crisis which would damage production.

Henceforth, the tight network of administration boundaries made acts of war impossible and confined the nomads within their zone. Compulsory taxation required that a census of the population be taken in order to follow their activities and control them better.

Until the colonial conquest, the area inhabited by a homogeneous Kel Tamasheq population was ruled by authoritarian chiefs who controlled incoming tribes seeking to occupy confederation territory. New tribes were admitted, as in the case of the Arab group, only upon recognition of the *Amenokal*'s authority and upon agreement to participate in wars. Under the colonial authority, this control could no longer be practised. Thus, beginning in 1940, small groups of nomadic Wodaabe Foulani, usually called Bororo, started coming into the area. Family after family settled near a well, and after an agreement with the neighbouring Tuareg, remained there. Other families followed the same route, with the result that the number of Foulani and their cattle steadily increased.

Driven from over-populated agricultural zones, where the fields with cash crops such as ground-nuts and cotton were continually expanding, the Foulani were pushed to the north, which had been spared this agricultural colonization. Their infiltration still continues, but for many years they were counted in the census of their original district, and it was not until 1974 that a ninth group was created at Tchin Tabaraden—a late recognition of a very old arrival.

Hausa farmers were clearing fields in the rangelands of the study area at the same time as these pastoralists arrived.

After the flow of Tuareg groups over the centuries from north to south, there is now a colonization movement in the opposite direction. This has brought with it an excessive pressure on land resources caused not only by natural population growth, but also by the arrival of foreign pastoralists or farmers, who furtively settled on the land by means of local agreements but without the authorization of chiefs or even of the administration.

The colonial era brought about a certain number of changes in herd management and in land use. Peace and the end of raids allowed a greater dispersal of men and herds, who no longer sought to cluster around warriors out of fear of surprise attacks. Tuareg society also underwent a slow but irreversible change, caused by the departure of the slaves, who until then were responsible for guarding and watering the herds. Because of this, sheep which require close and constant surveillance suffered from the departure of numerous shepherds. There was thus an increase in large animals and a decrease in small stock.

In the last twenty years, the veterinary services have systematically vaccinated cattle, and the great epizootic diseases—rinderpest and pleuropneumonia—have been wiped out. These vaccination campaigns, linked with the arrival of the Foulani with their cattle herds and with changes in Tuareg society following the desertion of numerous herdsmen, caused a considerable increase in the proportion of cattle in the area. For this reason the government decided in 1960 to apply a pastoral policy for the nomadic zone. The Tchin Tabaraden region had a leading place in this effort.

Pastoral policy and new land use up to the time of the drought (Bernus, 1974*a*)

Principles

Although deep wells had long been drilled by the administration, a turning point in the development of the Sahel pastoral zone was reached in 1960. This policy has been described in two reports which can be considered as the charter for water development (Receveur, 1960*a*, 1960*b*).

Since herds suffer from a permanent water shortage during the dry season, the livestock population must be provided with water that is immediately available. Deep wells dependent on draught animals give an inadequate yield. Thus, it was planned to set up shallow wells (less than 40 m) where the shallow ground water could be reached, and pumping stations which would reach the deep ground water, with a minimum flow of 4 litres per second. These stations were to be equipped with mechanical pumps, with a water-storage device and sufficient drinking-troughs to meet the needs of many animals.

The report refuted the objections raised against such a system:

- economic objections, because of investment costs and especially operating costs. A solution to these difficulties would be found through a financial contribution by the beneficiaries, whose livestock wealth would be increased;
- technical objections, because of the difficulty in operating distant and scattered installations, and especially because of the grazing pressure which would destroy the rangelands.

This last point was the major objection. It was considered important therefore to establish rules for using rangelands. By deciding that the forage area around a pumping station was a circle with an approximate radius of 8 km, and taking into account the fact that this grazing period would not exceed eight dry-season months, a carrying capacity of 5000 cattle units or 10000 units of all species was obtained.

The report concluded that 'it appears to be clear that it is improbable that the saturation point of animals on the land, leading to overgrazing of rangelands, will be reached'. The theoretical solution is to place a network of wells every 7–10 km and of boreholes every 20 km. However, because of the presence of pools and shallow wells at the beginning of the dry season, the boreholes did not need to be put into full service except from February to July, and the distance between boreholes could be increased by 40 or 50 km.

A very strict set of rules would have to be applied for the operation of these boreholes, their opening date, and the number of animals authorized to use them.

Legislative controls

In order to implement this policy, laws were promulgated in 1961 and 1962. The first decree fixed a very precise northern limit to cultivation. Its purpose was to forbid northward movement by farmers who year after year clear new fields at the expense of rangelands. It was thus a matter of protecting a zone with a more pastoral than agricultural potential because of the low and irregular rainfall. The second decree created a zone of pastoral modernization, covering the Sahel region to the north of the legal limit of cultivation.

Subsequent decrees defined the limits of the first four sectors of this zone. They created a department responsible for the pastoral modernization zone and defined conditions for allocating pumping stations and their pastures to certain groups. Decrees were to name the pastoral communities who would benefit from this, taking into account their customary rights. One decree defined the rules for using the pumping stations and the range dependent on them. The periods of operation were to be determined each year by the administrative authority, which would take into consideration the climatic and social conditions of that year. Rangelands located within a 40-km square and having a pumping station at the centre were considered as reserved. When the station was closed, rangelands situated within a 20-km square were forbidden to pastoralists. The maximum stocking rates permitted on the reserved pastures were to be determined each year, but they could not exceed one cow per five hectares per year (or one camel or ten sheep or goats). Provision was made against bush fires and for systematic vaccination of the herds grazing around the pumping stations. The stations were thus to become the focal points of medical, educational and economic programmes. Finally, in 1963, a public office responsible for the exploitation of underground water (Office des Eaux du Sous-sol—OFEDES), was created.

All these decrees were thus part of a coherent policy favouring the nomads, a policy which took into account ecological conditions and economic potential at a national as well as at a regional level.

Installation of pumping stations

The first pumping stations were constructed in the northern part of Tahoua province, in the present district of Tchin Tabaraden. This region is fed by ground water from the Continental Intercalary aquifer in the Tegama Sandstone, one of the richest reserves in the Ioullemmeden Basin. The strike of the strata is generally north-east/south-west, and in the eastern section the water is tapped directly in the Tegama Sandstone, whereas throughout the entire south-western section it can only be reached beneath non-yielding Cretaceous strata. Both unconfined and fossil (confined) ground water is thus obtainable at depths that increase from north-east to south-west.

From 1961, some twenty pumping stations were gradually put into service. Some of them, for various reasons (repeated breakdowns, insufficient flow or damage due to pastoralists' malevolence) were abandoned, and today about fifteen operate normally. The first boreholes (Den Buten, Ibeceten, Abalak, In Waggeur) were equipped with windmills between 1956 and 1960, but these were not followed up because the winds were too weak and too irregular to produce a sufficient and constant flow. It is estimated that a wind of 5 m/s for ten hours a day is necessary, 15 m above the ground. At Tahoua, the wind is less than 3 m/s for at least half the year, 10 m above the ground (COGERAF, 1962).

It was only from 1961 that the stations were supplied with standard equipment: two 30 hp motors under a metal hangar, a pump, a reservoir for the water, galvanized drinking-troughs for animals, and taps for domestic needs. These were progressively installed as follows:

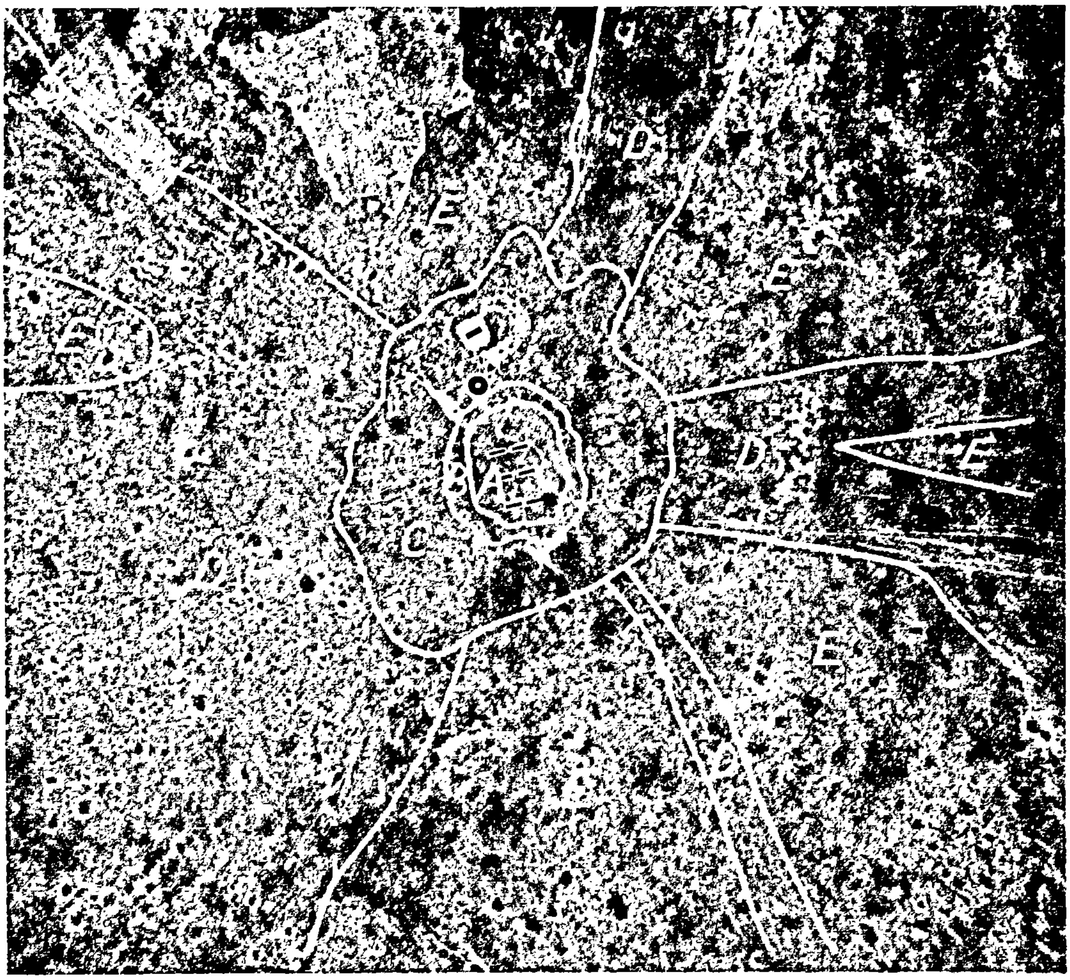
December 1961	Denbuten—Abalak—In Waggeur—Ibeceten
June 1962	N Kao Kao—Tchin Salatin—Tasataqopet
November 1962	Tarasedet
December 1962	Akaranna
January 1963	Illeba
May 1964	Ekinawan
April 1965	Tofamanir—Tamaya—Abouhaya
July 1966	Tchin Tabaraden
April 1967	Tassara
December 1967	Egawen—Tatawasen (or Akebennou)
April 1968	Chiguilal
November 1968	Egarek—Digdiga—Tiguezefen
June 1969	In Tamasgueyt

A few of these stations are located in the Filingué district (Chigilal, Digdiga and Tiguezefen), but are nevertheless managed by Tahoua. Some boreholes were abandoned, such as Ibeceten in 1964, after serious breakdowns (filters choked with sand), or Tasataqopet on 22 April 1967, rendered useless by pastoralists who had thrown stones into the tubing. Of twenty-one stations, not all operated at the same time. Some were temporarily closed because of breakdowns and others for economic reasons, with the result that, by the beginning of 1964, about fifteen stations were regularly in service in rotation.

An initial evaluation

After a ten-year period, it is possible to examine the results of the installation of fifteen deep boreholes from the point of view both of their operation and of their consequences for nomadic pastoralism. It is apparent that the difficulties which the report of the Direction de l'Élevage refuted, by pointing out ways to avoid them, were not always overcome.

The financial problems, particularly the cost of



● = Water tower
= Watering-trough
= Borehole and shelter of the pump

A Central area
B Ist and 2nd rings
C 3rd ring
D Cluster of paths
E Less degraded natural pasture

FIG. 4. Aerial photograph of the pumping station of Ekinawan showing the effects of livestock concentration (from Peyre de Fabrègues, 1971)

the water thus delivered, will not be discussed here. For a while it was intended to ask the pastoralists for a small contribution, but the administration did not dare demand an additional fee, since the pastoralists, who are taxed on their livestock, often feel more heavily taxed than the farmers. The technical difficulties associated with the financial problems will also be passed over.

Overgrazing of rangelands around the boreholes has been the most serious problem and has never been completely controlled. Figure 4 shows the effects of livestock concentration around a pumping station. The planned number of animals to ensure a normal pastoral balance—5000 cattle or 10000 livestock units[1] of all species—has everywhere been exceeded and often more than doubled.

Few counts were carried out around the pumping stations, but the data available all give the same picture. An estimate made in 1961 gives the following figures, which, although unconfirmed, can be taken as a general order of magnitude (Ministère de l'Économie Rurale, 1961).

1. In 1960 the Direction de l'Élevage used the Livestock Unit (LU), corresponding to one camel, one cow or ten sheep or goats. Later this was revised and became a Tropical Livestock Unit (TLU), corresponding to an animal of 250 kg. See footnote page 125.

At the Abalak pumping station, it was estimated that the following numbers of animals came daily to water—7000–8000 cattle, 8000–10000 sheep and goats, and 1500–2000 camels, i.e., an average of 18250 head of livestock, or 10150 LU. However, cattle, sheep and goats are very often watered every other day, and camels every fourth or fifth day, so that the figure of livestock on the surrounding rangeland would be double, namely 37500 head of various livestock or 20300 LU, a total four times that planned.

This estimate calls for some explanation, however. As is said elsewhere in referring to the study of watering problems made by the Niger Nomadic Development Service (Commissariat Général au Développement, 1972), there exists a range of watering intervals. The pastoralists distinguish between daily (*tameswit*) and non-daily (*taghruft*) watering, and during the dry season most animals are not watered daily. In addition, since some pastoralists only water their sheep once every four or five days in the cold season and camels (with the exception of lactating females) once every ten days, the estimate given seems reasonable.

At In Waggeur station the daily estimates for 1961 were—5000–6000 cattle, 6000–7000 sheep and goats, and 1000 camels; or an average of 13000 animals or 7150 LU. If these were being watered every two days, allowing the same adjustment as for Abalak, there would have been 26000 head and 14300 LU dependent on the station. Here the figure is three times that planned.

At Ibeceten, finally, the same daily estimates gave 6000 cattle, 4000 sheep and goats, and 200 camels; that is, 10200 animals and 6600 LU, or with watering every two days, 13200 LU. The planned figure was therefore doubled.

The preceding figures should of course be treated with caution since the counts could not be carried out under the strict conditions desirable. That is why other data must be sought to check this information, for example, the amount of water delivered by the pumping stations. This was done in the year 1968–69 for three stations chosen from among those with the greatest discharge (first, second and fourth greatest discharge),[1] using 40 litres/d as the standard desirable water consumption rate per LU. It was thus calculated that:

- the Ekinawan pump provided water for 9585 LU/d for 244 operational days;
- the Egarek pump provided water for 7300 LU/d for 243 operational days;
- the Abalak pump provided water for 6260 LU/d for 250 operational days.

These theoretical calculations are unsatisfactory. They may be overestimated, since water used for domestic needs is not taken into account, nor are losses caused by evaporation and spilling; or they may be underestimated, since the 40 litres attributed to each LU are an abstract figure, based on daily watering. An animal which goes to water only every two days (cattle) or every four or five days (camels) drinks a much smaller quantity of water.

1. Tchin Tabaraden station, with the second largest flow, is omitted since it provides water largely for the needs of the sub-prefecture inhabitants.

TABLE 9. Water consumption by stock (in TLU) on the Ekarafan ranch (Peyre de Fabrègues, 1971

Period	Average ration (litres) per TLU	Period	Average ration (litres) per TLU
October 1968	*more than* 42	February 1969	*more than* 28
November 1968	*more than* 35	March 1969	*more than* 32
December 1968	*more than* 29	April 1969	*more than* 36
January 1969	*more than* 24	May 1969	*more than* 40

More detailed surveys have been carried out by agrostologists on changes in the rangelands around pumping stations (Peyre de Fabrègues, 1971). Faced with the impossible task of counting the animals, the author of this report also used as the basis of his estimates the water delivery rates of the pumping stations. An earlier survey carried out at the Ekarafan ranch made it possible to calculate variations in the amount of water drunk during different months of the dry season. The results were reduced to the Tropical Livestock Unit (TLU) which, by convention, represents an adult zebu of 250 kg liveweight.

Thus, a theoretical unit is used as a basis for evaluation. 'It is by the volume of water rations consumed that the theoretical stocking rate on the land and its relative variations around the pumping stations are estimated. These are theoretical rates because the estimate is made in TLU, thereby without allowances being made for other breeds of livestock, nor for very young or very heavy animals, nor even for losses (which are negligible).'

Table 9 shows that the water ration varied with temperature and inversely with relative humidity. Figures for the quantity of water provided month by month can thus indicate the number of animals using the pumping stations.

These figures confirm the estimates made from the yearly quantity of water flow but are more reliable because the daily water ration has been apportioned by month (Table 10). It would seem that use of the stations is at its height from December and sometimes

TABLE 10. Numbers of stock (TLU) using selected pumping stations on the basis of water consumed (from Peyre de Fabrègues, 1971)

Period	Numbers of TLU	
	Ekinawan	Egarek
1968–69		
November	10380	5200
December	12100	6380
January	12620	14460
February	17530	15860
March	16900	13400
April	16530	10305
May	14020	10125
1969–70		
December	9965	9760
January	13790	11730
February	12145	12890
March	12060	14400
April	12250	11805
May	7775	7600

January onwards, varying year by year according to when pools and even shallow wells begin to dry up.

All the estimates agree in showing that the animals actually present are two or three times more numerous than foreseen by the planners. 'Thus, for example, the area in which herds coming to drink wait each day has a radius of about 400 m, i.e. an area of 50 ha. If 12 000 TLU are watered, the stocking rate of this area, if each animal waits there two hours per day, is 20 TLU/ha/d. But the potential average annual stocking rate of rangelands in the nomad zone is estimated at one TLU/5 ha/yr, in the best possible case.' (Peyre de Fabrègues, 1971.)

One may wonder how such large concentrations of animals came about when the legislative texts had foreseen this difficulty.

In fact, the decree of 25 July 1961, which aimed at reserving the boreholes and their surrounding rangelands to certain groups of pastoralists with traditional rights in the region and at forbidding free access to all the new pumping stations, could not be put into effect. To give good-quality water to some and refuse it to others has always been an insurmountable obstacle, in principle and in practice. The choice is always difficult, because of the risk of favouring important chiefs and the richest pastoralists who reserve for themselves exclusive use of boreholes near their camps. In the second place, the Foulani who are new to the region cannot be denied water on the pretext that they are not counted in the district census and pay their taxes in the southern districts. Faced with disputes between Foulani and Tuareg, the government thought of reserving the Abalak and In Waggeur boreholes, in the east and north-east part of the Tchin Tabaraden district, for the Tuareg, and leaving the boreholes of Tofamanir, Tamaya and Abouhaya to the Foulani. But in the end this ethnic distribution was never applied. There is free access to all the pumping stations.

If the government never sought to limit the number of users, the reason is perhaps that it did not see how discriminatory regulations could be applied in such a vast area. Neither did it want to run the risk of favouring some groups over others and causing disputes around the boreholes, for water is always the crucial point in rivalries between ethnic groups or between tribes. The government therefore decided to apply time limits only, by regulating the opening and closing dates of the stations; they were opened at different times each year, depending on climatic and social conditions.

Opening was delayed until the surrounding pools had dried up, and the stations were closed as soon as the rain again provided available surface water. Opening dates, between November to January, are generally more flexible than closing dates. Finally, a borehole was occasionally closed for a year so that the surrounding rangeland could be restored (N Kao Kao in 1967–68, In Waggeur in 1970–71, for example). The government preferred to control machines rather than men, and limited itself to regulating the organization and management of the pumping stations from the prefecture.

It was not possible to apply another point of the rules established in 1960. The government did not wish to make pastoralists pay for water, since they were already heavily taxed on their livestock. It had nevertheless been clear from the beginning that pastoralists should be asked to contribute, even symbolically, so that they should participate in this water-development policy. Thus, in addition to the financial problems, payment for water was a necessary part of the attribution of pumping stations to a particular tribe or nomadic group.

To summarize, the opening of public works with free access changed pastoral land use. Self-management of rangelands by the nomads themselves no longer worked, and the obvious increase in well-being produced by abundant water of good quality was offset by a maldistribution of men and herds.

The 1968–73 drought and its consequences

Situation at the beginning of the drought

The recent drought, which has already been compared with the droughts of the first half of the century, occurred after a relatively favourable period of generally normal or above-normal rainfall.

Some authors (Rippstein and Peyre de Fabrègues, 1972) consider that rainfall has been diminishing since 1953. The curves calculated for the 1953–70 period show a rainfall decline of 9·0 mm/yr at Agadez, 17·1 mm at Filingué, 17·0 mm at Tanout and 12·5 mm at Zinder. These rates suggest that there was a decrease in rainfall of from 5 to 10 mm in the zone included between the 300 and 500 mm isohyets. However, these results were obtained because the series of years measured come between two abnormally high rainfall years (1953–54) and two low rainfall years (1969–70). In many stations, the latter two years had the lowest rainfall ever recorded since observations began. On the other hand, a rise in the shallow water-table was noted during the period from 1953 to 1970, and the large pool at Tabalak-Kéhéhé, which previously dried up every year, became permanent from 1953. Since then the *Acacia nilotica* trees have been dying of asphyxiation. The pool forms a huge permanent sheet of water and even the recent drought has not emptied it.

As a result of these favourable conditions, the size of the herds was constantly increasing. Estimates from the Direction de l'Élevage are indicated in Table 11.

According to agrostological studies made before the drought (Rippstein and Peyre de Fabrègues, 1972), the area did not seem to have an excessive stocking rate. In the study cited, Zone B, which concerns the south-west of the study area and Zone C, the south-east of the area (although without exactly the same boundaries) had average stocking rates, depending on the season (Table 12).

TABLE 11. Estimate of livestock population, 1968 (Ministère de l'Economie Rurale, 1969)

Types of livestock	District of Tchin Tabaraden	Province of Agadez
Cattle	300 000	120 000
Sheep	130 000	100 000
Goats	325 000	200 000
Camels	90 000	100 000

TABLE 12. Estimated stocking rates in 1968 (Rippstein and Peyre de Fabrègues, 1972)

Season	Number of ha/TLU	
	Zone B	Zone C
Dry season	16	12
Rainy season	11	8·5

It is evident that these averages cover very diverse potentials.

Estimates of the actual stocking rate, in relation to theoretical possibilities, give the figures shown in Table 13.

Table 13 shows that, before the drought, the study area had not reached its maximum stocking rate, in spite of the very rapid recent increase in herd sizes. However, these figures must be examined carefully: they are of value only where there is balanced use of rangeland with herds distributed equally throughout the region. However, during the few dry-season months, herds are concentrated around wells and pumping stations. This is why pastoral use of the area is discontinuous in time and in space, even in a favourable period like the one which preceded the drought. Although the region as a whole is not overstocked, there are very high concentrations at particular points, as shown by the counts at pumping stations.

Reactions of pastoralists to the drought

The first drought year started during the 1968 rainy season. This was followed by a dry season when pasture was so poor that many animals died. The total rainfall was almost the same everywhere, and even above normal, but the early and abundant rainfall in March and April was followed by an almost completely dry month in May. This sequence, as was already noted in the discussion of climate, prevented the forage species from growing normally.

Subsequent years were almost all highly deficient in rainfall and each year the decline in forage was accentuated (Table 14).

Animals began to die in greater numbers after the poor rainy season of 1972. Although pools lasted for a shorter period, thus reducing the length of time that neighbouring pastures could be used, ground water in the study area did not vary to the extent of depriving animals of water. Of the two essentials necessary for herd survival, only pasture was missing: animals died mainly of hunger. All the pastoralists were affected; faced with catastrophe, they reacted in very diverse ways.

TABLE 13. Comparison of actual and potential stocking levels, 1968 (Rippstein and Peyre de Fabrègues, 1972)

Zone	Season	Estimate of actual stock numbers (TLU)	Potential stocking (TLU)
Zone B	Dry season	192500	213500–309800
	Rainy season	276000	456500–607800
Zone C	Dry season	380000	452600–505800
	Rainy season	550000	685100–688300

TABLE 14. Annual rainfalls during the 1968–73 drought

Year	Agadez (mm)	Tahoua (mm)
1969	80·7	317·0
1970	39·7	421·7
1971	92·6	267·9
1972	73·9	266·2
1973	76·3	244·9
Normal	158·0	395·4

Migration to the south

If organized in time, when animals were still strong enough to move, flight to the south appeared to be the most logical solution. It was a matter of fleeing before the danger and seeking refuge in a more welcoming region which was better watered. This solution was suggested by the government itself and in September 1972, a mission, led by the Ministère des Affaires Nomades et Sahariennes (Minister of Nomadic and Saharan Affairs), proposed to the chief of the third group at Tchin Tabaraden that he send his herds to the Gaya region. This latter region had been spared from the drought, and contacts had officially been made with the inhabitants there. The suggestion was not taken up.

This lack of response seems to be justified in the case of the Tuareg, whose camels and Azawak zebus take badly to such long movements. It seems that the risks of such a migration are higher, for the Tuareg herds, than those of staying and resisting the drought conditions. It is said that some Tuareg herds fared better by staying than those which left for the north of the Sudan zone.

The reactions of the Wodaabe Foulani were very different. More recently arrived in the area, the Foulani are much more mobile than the Tuareg; they can without great difficulty leave an area where they have problems. The absence of a centralized chieftaincy leads to greater adaptability, which is manifested by flight from human or environmental hostility, and this was demonstrated during the drought. Bororo cattle are also much better walkers than those of the Tuareg, and this encourages mobility. The Tuareg are more attached to the area, and to the valley which is their natural setting. Their political and social structure tends to unite groups and tribes and creates a rather precise spatial organization in which everyone has a place. Because of this, they do not leave their country except in final necessity. Thus all the Foulani left the region and in the most striking case, sixty-eight families of the Bikorawa I tribe registered at In Gall went as far as Cameroon. But the Kel Tamasheq did not leave the area. Some families went off, but only a short distance; the area remained occupied for the most part by tribes in their traditional setting, with only a few families missing.

TABLE 15. Estimate of livestock losses in 1969 (Ministère de l'Économie Rurale, 1969)

Zone	Cattle	Sheep and goats
	(%)	(%)
Northern zone (Agadez)	30	27
Middle zone (Maradi, Tahoua, Zinder, Diffa)	13·3	11

Regrouping of the drought victims

Pastoralists who had lost everything were grouped at certain points and received issues of cereals and powdered milk. In the Agadez region, vast camps were set up at Chimounim (near In Gall), Teguidda n Adrar, Arou Margaren etc. The authorities transported by lorry those nomads who had lost their riding animals. The remaining pastoralists survived where they were able to save part of their herds. In general, cattle and sheep died but camels and goats fared better. The nomads used any food that could be gathered by traditional means, but all that was unaffected by the drought were products that were generally despised, such as wild-grass seeds, fruits of *Boscia senegalensis*, leaves from *Maerua crassifolia*, etc.

Search for alternative livelihoods

Some herdsmen, on their own initiative, sought alternative livelihoods within the area. The Arabs of the sixth group often sold their animals before the latter died, and with the profits set up shops in all the centres: Agadez, In Gall, Tofamanir, Abalak, Tchin Tabaraden and even further south, Tahoua, Dakoro or Maradi. Some Tuareg experimented with agriculture, even though they had no tradition of working the land. Others (Kel Ahaggar, Kel Fadey, Igdalen) started cultivating land around the artesian boreholes of the Eghazer (north of In Gall, west of Agadez) by irrigating plots of wheat in winter and millet and sorghum in summer, using seeds from free distributions. In the Tchin Tabaraden region, plots were made on the edge of pools and the beds were watered by digging channels uphill to shallow basins to which water was carried by hand in buckets. These imperfect solutions were often inadequate, at least as far as agriculture was concerned, for satisfying their food requirements. Nevertheless, they show the vitality of the pastoralists who refused to accept the role of public wards.

Livestock losses

There are no precise data on this subject and published figures have varied considerably since the end of the drought. After the poorly distributed rains of 1968, the Direction de l'Élevage estimated in its annual report that losses, by major zones, were approximately as shown in Table 15.

As the drought not only continued but became even more severe, the 1969 losses were only a small part of the total. In its annual report for 1974, the Direction de l'Élevage made the estimates by district shown in Table 16.

Desertification

Climatic crises like that of 1969 to 1973 make the effects of desertification brutally apparent. Desertification here means changes in the plant cover, and not a transformation to desert or to a permanently barren landscape. Before studying the effects of the recent drought it is necessary to trace changes in the vegetation over the past forty years (made possible by the recent publication of old documents), and to look for the effects of overgrazing where herds were concentrated before the drought (made possible by agrostological studies).

Changes in plant cover

Professor Aubréville, a forester and member of an Anglo-French forestry mission, has published a road log which recorded a north-east/south-west transect of the area, through Agadez, In Gall and Tahoua in 1936–37 (Patterson *et al.*, 1973).

It should be noted that the year of the mission was exceptionally wet, since 231 mm were recorded at Agadez and 611 mm at Tahoua (not 511 mm as is shown in the report). This is the highest rainfall ever recorded at Tahoua. The observations of these specialists were thus made in a particularly good year and the authors were well aware of this, but their conclusions are evidently rather optimistic—'years of great drought leading to famine are extremely rare. The last one goes back more than twenty years', and, 'it seems that dry and wet periods of short and varying duration follow one another. Up to now they do not indicate any tendency toward a permanent change in climate. The vegetation follows the same rhythm; regenerating easily in relatively wet years, and with more difficulty in the dry years.'

TABLE 16. Estimate of livestock losses from 1968 to 1974 (Ministère de l'Économie Rurale, 1974)

Zone	Cattle			Sheep			Goats			Camels		
	1968	1974	Loss (%)	1968	1974	Loss (%)	1968	1974	Loss (%)	1968	1974	Loss (%)
Agadez[1] Province	120 000	15 000	88	100 000	20 000	80	200 000	60 000	70	100 000	55 000	45
Tchin Tabaraden	300 000	175 000	42	130 000	101 330	22	325 000	202 660	38	90 000	?	

1. Note that figures for Agadez include the Saharan districts of Arlit and Bilma, outside the study area. These estimates show that losses doubled northwards between Tchin Tabaraden and Agadez.

The short description of the route followed on 9 February 1937 (Agadez, In Gall, via Teguidda n Tessoum) could have been made in 1974 without any notable change. For the section of the road covered on 10 to 12 February—In Gall, Efinateuss, Tahoua—the description is much as it would have been in 1968 or 1969. Observations on agricultural development made at Tahoua would be similar in 1974, but would now apply to an area extending 150 km further north.

The conclusion of the report merits quotation:

> As for a general increase in desert conditions in the border areas of Niger and Nigeria, the opinion of the mission is that nothing in the present natural phenomena which the mission was able to observe proves beyond doubt that such an increase has taken place. In particular, present climatic conditions do not appear to threaten imminent danger of general aridity. Although some signs seem to point towards local deterioration of forest vegetation, other equally local signs seem to indicate an advance of this vegetation.

Changes in plant cover before the drought at points with high stocking rates

Three main changes take place in the vegetation in such areas (Peyre de Fabrègues, 1971):

- — destruction of vegetation and changes in reseeding or regrowth;
- — changes in the physical structure and chemical composition of the soil (due to trampling, manure, etc.) which generally leads to changes in vegetation;
- — introduction by animals (in faeces, attached to coat, etc.) of seeds of non-native plant species, or at least of those which would not naturally be very abundant.

These influences cannot produce notable effects except in small areas where animals gather in large numbers, such as resting areas or stock routes, camps, areas around watering points, etc. The stocking rate is at its greatest there and often falls considerably a few metres outside the area in question, with the limit being extremely clear-cut.

In very crowded regions, it is common in the dry season (sometimes from November onwards) to see vegetation completely eaten away. Generally it grows again with few changes, provided that this intensive use only took place after the seeds were scattered. This is usually the case in the nomadic areas of Niger, where heavy livestock concentrations do not occur around large watering points until some time after the end of the rainy season.

The lack of any real damage is due, as already mentioned, to the fact that as long as the herds do not gather until the dry season, grazing even by large numbers does not affect the seeds which have already fallen to the ground. Trampling may even dig in the seeds and loosen and manure the land so that the germination of annual plants is facilitated. However, too much trampling cuts up and destroys the roots of perennials, which then decrease in relative numbers.

Consequently, changes in vegetation as result of stocking generally mean a transformation of the grass cover, with a steady increase in the number of species with the shortest possible cycle (as in the case of therophytes in general and of ruderals). The relative increase in perennials with roots resistant to trampling, which has been observed elsewhere, does not happen here because of the fragile structure of the sandy soils, which are too deeply disturbed by hooves.

These effects of stocking are particularly visible around water points, where a high discharge and watering facilities attract a very large number of animals. Here the livestock population is almost always larger than the surrounding pastures can support, even in satisfactory conditions, at least within a normally accessible radius. The first arrivals eat the nearest pasture first. From week to week the grazed area increases and animals must go further and further out. The result is that, where animals are very numerous, the moment rapidly comes when the distance between water (watering trough) and grass (pasture beyond the eaten-out radius) exceeds the walking capacities of the average animal. This distance is around 8–12 km, depending on the season and the animal.

From then on, animal life becomes increasingly precarious (M'Bororo cattle are more resistant from this point of view than the Azawak). The pasture will have reached its low point of the year, a situation which is more disastrous the earlier it happens, i.e. when the livestock population was greater from the beginning. The animals try to survive by conserving energy as much as possible. They no longer try to go to pasture because that would be too far, but make do with the meagre plant remains and with water.

This process recurs every year in identical manner, except for accidents such as a pumping-station breakdown. It is clear that the deterioration of rangelands as a result of stocking cannot take place beyond the area accessible to animals around a water point, whatever the number of livestock.

In the nomadic zone as a whole, it can be seen that no matter how large they are, the areas of range thus modified by a heavy stocking-rate are very small in relation to those that can have their vegetation totally transformed as a result of large variations in rainfall from one year to the next.

Trees also suffer from concentrations of animals which gather in the shade and rub against the trunks. Counts around pumping stations show that trees have disappeared at a rate of 15 per cent in two years at Ekinawan, 13 per cent in one year at Digdiga, and 4·6 per cent in one year at Ekarafan. But these counts were made at the immediate approaches to boreholes, over an area of 12·5 ha. At points 4 km from the borehole, the disappearance of trees is very low, around 3 per cent, which is not significant.

In summary, agrostologists have shown that overstocking affects only a very small area. They have described a concentric zoning of the territory in the immediate surroundings of the pumping stations where the animals rest and graze between waterings. Aerial photography very clearly shows this typical landscape, caused by gatherings of large numbers of livestock (Fig. 4).

In the centre, around the drinking troughs, is a completely bare area, 30–50 m in radius, where no vegetation can develop, because of the trampling of thousands of animals and the accumulation of their droppings. From this central area radiates a network of tracks regularly used by the herds. A microrelief is created in the soil loosened by the animals' hooves. Parallel furrows locally concentrated into a single track become incised, separated or delimited by sandy rises. The passage of animals modifies the vegetation and distinguishes the tracks from the zones they cut across.

Around the central area are several concentric rings, such as are seen on the aerial photo of the Ekinawan pumping station (Fig. 4). The first ring has sparse vegetation because of trampling and of soil enrichment by organic matter. The second, on the fringe of the first, differs in its thicker plant cover. It is only in the third ring that tracks appear, hidden in the first two by the trampling of waiting animals. The fourth is characterized by plentiful *cram-cram* (*Cenchrus biflorus*) an annual grass which likes trampled sandy soils.

The conclusion of the agrostologists is relatively optimistic. Grazing pressure is only one factor changing the vegetation, and is always combined with two others, namely rainfall and fire. It is a combination of all three which produces the most notable and lasting effects. Changes can be positive 'when they lead to an increase in plant production around water points, caused by replacement of *Aristida mutabilis* by *Tribulus terrestris* and *Citrullus lanatus*; or when a poor forage plant is replaced by a preferred or simply more productive species, such as the replacement of *Cymbopogon proximus* by *Aristida mutabilis* in some dune formations' (Peyre de Fabrègues, 1971).

In contrast, 'the transformation of grasslands can mean deterioration when there is a decline in plant productivity following a decrease in the rainfall or overgrazing during the growing period'.

The author concludes:

Changes in pasture produced by dry season grazing only last as long as that grazing continues. Indeed, it has been noted that annual, perennial and native plants have sufficient regenerative power, due to their seeds, to reappear as soon as the range is deserted for at least one year with good rainfall. The sometimes more spectacular increase in the relative abundance of annual plants after the first year in the most heavily stocked zones, and after a longer interval in burned areas, is a good reflection of what happens in rangelands, but is too diffuse to be easily measured. Nevertheless, it is an improvement, taking into account the preference of animals for annual forage plants.

The influence of rainfall, although of major importance, changes vegetation only momentarily and in a way that can reverse itself.

Finally, from an agrostological point of view, it can be said that the present composition of the plant cover, established on the basis of average observations over several years, corresponds on the whole to a stabilized subclimax. Its forage value is practically identical to that of ungrazed pasture. (Peyre de Fabrègues, 1971.)

If this report has been quoted at length, it is because it has an unexpected conclusion, rather different from those generally accepted. According to the author, stocking rates around all the pumping stations of double or triple that accepted in the water development policy, do not create irreversible or even inevitable deterioration in the vegetation. The effects are always limited in time and in space. Moreover, these conclusions are based on quantitative studies over several years using transects (four parallel lines of 16 km east–west, crossing a north–south band of 150 km). The agrostologists' conclusions are thus much more optimistic than those contained in the reports of the Direction de d'Élevage or than those of their colleagues working in other Sahel regions. However, it must not be forgotten that Peyre de Fabrègues' study was carried out mainly in 1967–68, and that, although the observations were continued in following years, the aerial photographs were also taken in 1967–68. The report does indeed stress that, of the three factors which determine vegetation changes in the pastoral zone south of the desert—rainfall, fire and stocking rates—the first, rainfall, is of crucial importance. Rainfall patterns condition all plant life, while fire and stocking rate affect only limited areas of dry vegetation. If the rainfall changes, as in recent years, pastures will no longer change in the same way. Change will be faster in areas with high stocking rates, since the three factors will have a cumulative effect.

Effects of the drought

An idea of the effects of the recent drought could have been obtained by taking the same route in 1975 or 1976 that Aubréville and his mission followed in 1936–37. The effects were immediately apparent in the tree layer.

The tree layer

According to observations made in June 1976, different parts of the area were differently affected. Almost all the high areas—dunes or plateaux—suffered most, since roots had great difficulty in reaching water. These observations confirm the quantitative studies in the Senegalese Ferlo in the same climatic zone (Bille and Poupon, 1974*b*). These studies showed that death of trees varied according both to

TABLE 17. A comparison of mortality rates of three tree species observed in 1976, according to environment (Bille and Poupon, 1974*b*)

Environment	*Acacia senegal*	*Commiphora africana*	*Guiera senegalensis*
	(%)	(%)	(%)
Summit	57·8	28·4	60
Slope	53·9	22·5	
Shelf	44·4	6·9	
Bottom of slope	52·2	1·7	
Hollow	8·6	1·4	40

the relative resilience of various species and to their topographical situation. Three species (*Acacia senegal, Commiphora africana* and especially *Guiera senegalensis*) had high mortality rates. Great differences were noted for the latter two species, depending on where they were growing. A mortality rate of 28·4 per cent at the top of the dunes and 1·4 per cent in the hollows was recorded for *Commiphora africana*; 63 per cent and 40 per cent respectively for *Guiera senegalensis*. The very high mortality rate of *Acacia senegal* varied very little according to its position (Table 17).

In a comparable area, the western part of the pastoral zone of stable dunes stretching from the foot of the Ader mountains to Tchin Tabaraden and Tassara, an equally high mortality rate was noted for *Acacia raddiana, Acacia ehrenbergiana, Acacia laeta* and *Commiphora africana* on dunes and their slopes. *Balanites aegyptiaca* was more resilient on the dunes than the preceding species and, with its vertical, dense, powerful root system, is more resilient than the *Acacias* in general which have long, but shallow, horizontal roots.

A much lower mortality rate was evident for species adapted to low-lying areas such as dune hollows and fossil valleys: *Acacia seyal, Acacia nilotica, Zizyphus mauritania*. In this zone, such shrubs as *Boscia senegalensis* suffered a great deal and *Cordia sinensis* had practically disappeared.

In contrast, on the edges of valleys and sometimes even on the dunes, *Calotropis procera* developed considerably. This is a shrub which grows remarkably quickly when grass cover is lacking. On the edge of some valleys (near Kao Kao) it forms real forests which have totally changed the landscape in a few years. In open formation it colonizes dunes, and it has considerably increased around Tchin Tabaraden in recent years. It has a low forage value, and when it takes the place of other woody species the forage potential declines. Being poor wood to work with, its branches are used mostly as the outside pegs of Tuareg tents.

The Tegama plateau region, to the north-east of the preceding one, is called Tadarest by the Tuareg because of the thick stands of *Commiphora africana* (adaras). *Commiphora africana* had a very high mortality rate, and since it was the main tree, the plateaux are dotted with dead trees. *Acacia raddiana* and *Acacia laeta* also suffered a great deal.

On the other hand, the large fossil valleys suffered much less and *Acacia nilotica, Zizyphus mauritania* and even *Boscia senegalensis* remain intact. *Calotropis procera* has developed here also, but in a more open pattern than in the preceding area.

It seems, therefore, that trees and shrubs suffered a great deal from the recent drought, especially on high ground, which was most affected by the shortage of rainfall. The drought pinpointed those topographic zones most sensitive to desertification.

Fresh tree growth has occurred however, and all the pastoralists remark that this is particularly noticeable where animals are kept. It is of course known that ruminants play a role in the germination of seeds, particularly *Acacia* seeds, which pass through their digestive system. Moreover, animals trample the seeds into the soil, and by grazing remove the grass layer which competes with trees, thus providing more water for the fresh tree growth. Domestic animals are thus necessary for the restoration of the tree and shrub layer. Surveys at the Ekarafan ranch show that there is more germination in areas with livestock than in those without. Domestic animals are part of the ecosystem, and although in excessive numbers they are harmful to its conservation, they are indispensable to its reproduction (Granier, 1975).

The grass layer

The effects of the drought on the grass layer were brutal and there was an abrupt decline in range production. In the Ferlo, production fell from 1 000 kg of dry matter per hectare in some cases to zero in 1972 (Bille, 1974). In Niger, in the south Tamesna region (the Ekarafan ranch), the primary productivity of the range was estimated to have decreased from 1500–2 000 kg of dry matter per hectare before the drought to 360 kg in 1974, as a result of the bare patches which at times covered 80 per cent of the surface. Some species, good for forage but requiring much water, such as *Schoenefeldia gracilis*, temporarily disappeared from the plant cover. At that point animals fed almost exclusively on *Cenchrus* (Granier, 1975).

This disappearance may be only temporary, since seeds from annual plants can delay germination until climatic conditions improve. Recent studies (Bille and Poupon, 1974*a*) in the Ferlo have shown that rangeland seed production, estimated from the structure of the three most common grass communities, reaches 30·6 kg/ha. A third of this annual production is eaten on the spot by animals (10·3 kg/ha). Another part is scattered by wind, rain and animals, while the largest part remains on the ground. A small part is destroyed, and the remaining seeds (17 kg/ha) can delay germination for at least two years until the return of better rainfall.

In the grass cover the drought led to a considerable decrease in forage potential, and to a qualitative change in which existing plant associations were transformed by the disappearance of some species and the growth of others. In general, such perennials as *Cymbopogon proximus, Cymbopogon giganteus, Andropogon gayanus* and *Cyperus conglomeratus* were reduced and often disappeared.

Among annual species *Blepharis linariifolia* and *Schoenefeldia gracilis* disappeared and *Aristida mutabilis* declined, in 1973–74. In contrast, on the upper parts of dunes, the areas most affected by the water deficit, *Cenchrus biflorus* and *Chrozophora brocchiana* increased.

In the 1975 rainy season *Schoenefeldia gracilis, Aristida mutabilis* and even *Blepharis linariifolia* began to reappear on fine-grained soils. Plants only disappear completely when overgrazing in the rainy season is added to drought, so that seeds are eaten before they fall. When the two phenomena occur together, they cause desertification.

Drought and desertification

The relatively optimistic opinion of the agrostologist

Peyre de Fabrègues on the effects of overgrazing around pumping stations is based on observations made before the drought, and on the fact that large concentrations of animals only take place in the dry season when seeds are in the ground. At a more general level, another agrostologist expressed a gloomier opinion when the effects of the drought were already being felt (Boudet, 1972). He observed that

> rangeland reacts distinctly to wet season grazing near temporary pools. Animals remain close to water points and, within a radius of 1–3 km, preferred species are grazed at an accelerated rate which saps their reserves to the point where their ability to seed and thus to grow again is completely destroyed. These valuable climax plants are thus gradually replaced by species with short cycles, which are disseminated by animals. These replacement plants offer less resistance to erosion. Resulting changes in rangelands vary with soil conditions.

The author studied the 'degraded plant associations' on different types of soils. On sandy soils, annual grasses (*Aristida mutabilis*) are replaced by short-cycle species (*Boerhavia repens* and *Tribulus terrestris*). On colluvial soils the numerous palatable species in the hollows (such as *Panicum laetum* and *Schoenefeldia gracilis*) can lead to extensive trampling, which loosens the upper part of the soil.

This provokes sealing of the soil surface, which in turn leads to soil denudation, since the annual species can no longer send down roots. Shrubs and trees are also affected by soil sealing 'which leaves vast barren areas, compacted and strewn with dead trees'. The author describes the vegetation patterns (*brousse tigrée*) found in the south of the nomadic pastoral zone. After a study of the climate, with its dry and wet cycles, he concludes:

> If the farmers seem to be the architects of African desertification by use of axe and fire, pastoralists are probably responsible for desertification in dry parts of Africa where crops are traditionally excluded. . . . Climatic change described in this article should warn that great care is necessary, the more since development plans in the countries concerned were drafted on the basis of experiments carried out during the 'good years' of the wet period from 1925 to 1960. (Boudet, 1972.)

One can thus conclude that after the recent drought, desertification is manifested particularly through qualitative change in the vegetation. But many of the changes are due to overgrazing and to methods of herd management which alway add to the effects of rainfall shortage. Although man has scarcely any control over climate, he can change the organization of pastoralism and promote rational use of pasture and vegetation in its broadest sense.

After the drought

New trends in land use

Since the drought rainfall has returned to normal, as shown in Table 18, and the pasture has again been able to feed the smaller herds.

Rainfall, although slightly lower than the mean at Agadez and slightly higher at Tahoua, has been well distributed. Accordingly, many Foulani pastoralists have returned and herds have increased (Table 19). Many females which aborted in 1973 have now

TABLE 18. Rainfall (in mm) in the years after the drought

Area	1974	1975	Mean
Agadez	136·4	130·9	158·0
Tahoua	421·2	421·1	395·4

given birth, and pastoralists have recorded many multiple births in small stock. The Direction de l'Élevage has confirmed this growth of herds, which appeared between 1973, when the herds reached their lowest level, and 1974.

Thus, there has been a renewal of pastoral life and the return of pastoralists with reduced capital. However, the regrouping of the 'victims' has emphasized a trend which had already begun before the drought, namely the increase in human and animal concentrations.

New settlement centres

As in the past, pumping stations continue to concentrate animals, but in smaller numbers. This problem has already been discussed.

On the other hand, parallel changes in the administrative infrastructure should be emphasized. Sedentary centres have been set up in increasing numbers in the new district of Tchin Tabaraden, previously called the 'nomadic subdivision of Tahoua' and administered from that town. Two administrative posts were first created, at Abalak in the east and at Tillia in the west. Then, within the framework of the administrative reform and of the 1964 law, the subprefecture of Tchin Tabaraden was constructed from nothing in 1965, in the heart of a region previously occupied only by nomad camps. The administrative post at Tassara completed this new organization. Tradesmen set up businesses in these small centres and nomads who had lost everything gathered there in 1973. A new administrative framework with sedentary bases henceforth connected the villages of the south and the old towns of the north with its urban tradition. Although dating from before the drought, these centres began a development process which has continued in recent years.

Before the drought, the only markets in the north, at In Gall and Agadez, had daily markets supported by many shops, and those in the south had a network of weekly markets in villages on the borders of the agricultural and pastoral zones. Chadawanka and Barmou were the two main southern markets. New weekly markets were gradually created further north, at Kao in 1962 (Wednesday), Tabalak in 1974 (Friday), Abalak in 1975 (Thursday) and Tofamanir, still further north, also in 1975 (Tuesday). The three latter markets, located on the Agadez road, immediately took on considerable importance

TABLE 19. Estimate of livestock numbers in Agadez province, 1973–74 (Ministère de l'Économie Rurale, 1974)

Year	Cattle	Sheep	Goats	Camels
1973	9000	10000	50000	50000
1974	15000	20000	60000	55000

(especially Abalak, which became the new big livestock market), and attracted very many trucks from Tahoua, Dakoro, Maradi and Nigeria. From then on the markets at Chadawanka and Barmou declined. The line of equivalent markets had moved towards the north by more than 100 km. Previously, this line could have been easily drawn along the dividing line between the agricultural and pastoral zones, through the large farming villages. Markets, pumping stations and administrative centres make up the settlement centres (some combine all three) which are now growing everywhere, but most rapidly on the Agadez road.

All the inhabited centres put pressure on the environment. The need for domestic firewood increases considerably, as does that for construction wood necessary for building mud-brick houses with terraced roofs, which require beams of relatively standard size. Craftsmen also gather in these centres where they find an outlet for their work, and their need for wood is added to the others, despite very strict legislation by the Service des Forêts (Forestry Service). Firewood is gathered by pastoralists and sold on the road from Abalak to Tahoua. Truck-drivers going to Tahoua load this wood and make a good profit by reselling it in the villages. Finally, pastoralists come to the large centres to sell fodder for animals living in or near the town.

New agricultural colonization

Agricultural colonization is taking place in two different areas: in the south there is raid-fed cultivation of millet and sorghum, here at its northern limit; in the north there is irrigated garden cultivation.

Rain-fed cultivation had advanced so far north before the drought that a northern limit was fixed by decree in 1961. This limit passes just short of the southern boundary of the study area, within the mountainous promontory of the Ader and at the northern end of the Tabalak pond. The constant advance of cultivated fields was interrupted by the drought. In the last two years, fields have again been cultivated north of Tchin Tabaraden and Abalak, and the line of new farms has again advanced about 100 km north of the legal border. These fields are cultivated as much by local nomads as by farmers from the south. Theoretically, if crops are destroyed by herds, there can be no claim for financial compensation from the owner of the herd and the herdsman, since these fields are located outside the authorized limit. However, since the drought these decrees are no longer enforced, and stray animals are subject to heavy fines as in the agricultural zone. The administration feels that in a famine period food production must be protected by all possible means. This rigorous attitude, however reasonable over a short period of time, can only encourage clearing and cultivation of more land and the addition of agricultural pressure to pastoral pressure on the land.

Irrigated farming developed in the Eghazer plain north of In Gall when artesian boreholes were opened. The first one, at In Gitan, has been exploited since 1960 by the Taytoq Tuareg (Kel Ahaggar), who cleared a series of fields and watered them through canals. The fields were located several hundreds of metres away from the borehole to put them out of the way of the herds. In addition to pastoral boreholes, new boreholes dug for geological research have been used for agriculture by many Tuareg in the area of Kel Ahaggar, Kel Fadey and Igdalen. Irrigation allows winter crops to be grown, such as wheat and tomatoes, and summer crops such as millet, sorghum and maize. The government sought to develop and support these farming endeavours and a dam was constructed at Tiguerwit, south of Asawas, in the hope of settling farmers on flood-retreat land and in the area downstream from the reservoir. A 1972 UNDP project was charged with increasing farming throughout the plain. For various reasons these initiatives failed and there are no longer any farmers around the approaches to the dam.

After the change of government, soldiers took over the organization of irrigated farming by forming community work groups. The purpose is to re-train pastoralists who no longer have herds, and to open up the area to agricultural production. At Teguidda-n-Adrar, springs have been channelled and water towers built, equipped with pumps. An area was mechanically cleared and enclosed, and farmers (70 families) were settled on it, but the area allotted to each family (0·25 ha) was insufficient. In the same area, 216 families, dependent on 12 artesian boreholes, exploit cultivated plots by means of community work groups. In all, 286 families, comprising theoretically 1330 people, live off these irrigated plots of land, where wheat, cow-peas (*Vigna unguicalata* var. *sinensis*) and tomatoes are grown in winter and millet and sorghum and again cow-peas in summer. Some plots of land were enclosed by metal fences to avoid using the traditional thorn hedges, which would have mutilated trees. Many plots suffered from attacks of rodents and grasshoppers, and harvests have not always been up to expectations. In addition to these families, supervised by the administration, others have on their own initiative started irrigated farming. As a result of these efforts, a relatively large number of families have been settled. Unfortunately, their food production does not meet their needs, and the government often has to supply provisions to prevent families breaking up once the harvest is eaten.

Here again, small sedentary groups are being created, but their importance and extent remain limited by the water discharge, since each plot must be irrigated in succession. This means taking turns, which cannot be too far apart in time, and this limit prevents the settlements from becoming too large.

Extensive spontaneous farming in the south and intensive state-supervised farming in the north represent new forms of land use in an area which was exclusively pastoral until the drought. These two types of agricultural development are reducing the pastoral area, and one wonders if they can be combined with a policy of building up the livestock population.

Three-year programme and projects

Three-year programme (1976–78)

In January 1976, a three-year programme (1976–78) defined the broad outline of activities planned in the short term.

Having estimated overall livestock losses in Niger between 1970 and 1974 (2 million cattle, 1 million sheep, 1 million goats and 60000 camels), and making allowances for the general characteristics of herd use, it was planned to build up the livestock population by the end of the three-year programme to the following percentage of the 1972 figures:

— goat population to 100 per cent;
— sheep population to 85 per cent;
— cattle population to 65 per cent;
— camel population to 90 per cent.

To achieve this, various activities are planned:

— building up the herds by supplying animals to 76000 families at an annual rate of 15200 head for three years;
— creating six breeding centres, provided with the means to improve the breed. Two are planned for the study area, namely at Ibeceten on the Tahoua–Abalak road south-west of Abalak and at Rhoual near In Gall;
— establishing six weaning stations for young cattle alongside the breeding centres, and at Téra. In the study area, two stations will be attached to the breeding centres at Ibeceten and Rhoual;
— creating ranches for intensive stock-raising. At least one of two possible will be constructed (north of Dakoro or north of Gouré).

This programme is already being partly completed, but its importance lies in defining options for the near future. Livestock loans have already begun and the conditions under which livestock can be acquired are the following:

— for large stock, repayment is deferred for three years and begins the fourth year;
— for small stock, repayment is deferred for two years and begins the third year. Repayment must be completed by the fifth year.

This system is workable as long as the herd increases at a normal rate, but repayment will certainly be more difficult in the case of large stock. In all, an expenditure of 1145·6 million CFA francs is planned to be allotted by districts according to their losses.

In the Agadez district, 80 million CFA francs have already been spent from 1974 to 1976 and 1675 cattle, 243 camels, 962 goats and 1149 sheep were distributed as repayable loans. On the other hand, the breeding centre and weaning stations for young cattle were apparently not operative before 1977.

Activities of the Technical Services

Among the activities of the Technical Services, the projects of the Office des Eaux et du Sous-sol are co-ordinated with the three-year plan. Pumping stations are planned for Ibeceten (two) and Rhoual within the framework of the breeding centres. The only other boreholes planned are located in the Agadez–Tanout–Dakoro triangle.

The Service des Forêts has a progamme with two themes: production and protection. For production, afforestation is planned on 10000 ha in the Tchin Tabaraden district, which will be planted mainly with *Acacia*. For protection the study area is directly involved in several projects:

— 400 ha of shade trees around boreholes (Niamey, Tahoua, Agadez);
— 60000 ha of grazing reserves in all districts, in which the areas have not yet been chosen;
— shelter-belts around irrigated plots in the Eghazer.

American project

This ambitious project concerns the eastern part of the study area and covers a huge triangle linking Tahoua, Tanout and Agadez. The project will be centred however on a more limited region located between Abalak and Aderbissinat (15° N., 16° N., 7° E. and 8° E.), in an area of approximately 110 km^2. The objective is to increase animal production by comprehensive regional range management. The aims are to:

— develop and test techniques for better animal production in the pastoral zone;
— reduce the devastating effects of future dry periods on traditional animal husbandry;
— create a national service to achieve these goals (men from Niger will be trained in the United States in range management and animal production techniques).

The first step will be a resource inventory, summarized in maps.

Conclusions

This report has described the organization of the pastoral zone, changes in land use, the effects of the recent drought and the plans for the near future. It seems that desertification in the Sahel is caused by a combination of factors, whose effects are all the more devastating since they are synergistic. The drought was particularly severe on vegetation in higher-lying areas, especially on the plant cover of the dunes in the central region (Tchin Tabaraden–Tassara). Where these degraded areas were also overgrazed, or trees cut down, the effects were cumulative.

This is why desertification in the study area does not mean a steady encroachment by the Sahara; it is not a front whose advance can be calculated over the last forty years. Desertification occurs at particular points: it is patchy, not linear.

The 'patches' correspond in fact to central points from which desertification advances in concentric rings as more and more pressure is put on the environment. This is no doubt inevitable, but should not be multiplied. Only strict enforcement of legislation can limit the effect of these concentrations and reduce illegal cutting of trees and uncontrolled sale of wood.

Action against desertification can only come through better range management, which will enable range productivity to be maintained. The problem of using the pastoral zone needs to be restated. Until the recent drought, water development policy gave priority to help for herds to survive during the dry season; it was a matter of getting animals through this difficult period without their becoming excessively weak and emaciated. In other words, effort was concentrated on bridging the gap in the difficult period, without worrying about the rainy season when animals easily found water and pasture. The government was more concerned with water than with pasture because it is easier to act on the water problem by modern technical means than on the plant cover and its conservation. However, the critical period for vegetation is not in the dry season, when seeds have already been sown, but in the wet season, when herds can cause irreparable damage.

Rangeland protection causes an increase in growth at first, but this is not a systematic solution for all areas: 'Non-exploitation encourages litter to accumulate in a surface layer which inhibits the growth of new plants. It also increases the wildlife population which attacks the bark of young plants and increases the mortality rate.' (Granier, 1975.) Moreover, livestock, especially cattle, encourage seed regeneration. Most important therefore is better control of grazing and systematic exploitation of little-used regions which lack water. A project was developed along these lines to deepen natural temporary pools, in order to encourage maximum dispersal of animals during the rainy season and the following months (until January, for example), rather than to create permanent pools which would produce the same concentrations as the boreholes. Above all, it is necessary to define zones for which families or groups would be responsible, and where they would practise rational pasture rotation. Wet-season nomadism must continue so that complementary regions are used.

Although the broad lines of this policy are well defined (Granier, 1975), its application remains the key to success: it is difficult to allocate a balanced area to each group, with both wet- and dry-season rangelands. But this is the direction that pastoralism has to follow to achieve the right relationship between animals and rangeland.

Although the strategy and techniques for the struggle against desertification are known, their application often conflicts with the short-term requirements of the authorities that are responsible for protecting the lives of the populations and feeding them. Thus, herd composition is a short-term problem which affects the ecological equilibrium of the area. Small stock will multiply rapidly, both through natural growth and through the loan system. Moreover a vaccination programme for small stock is planned, although the role of such a programme in the multiplication of cattle numbers before the drought is well known. It is desirable not to emphasize any one species of livestock and to keep a balance among the various animal species, since the role of cattle in vegetation recovery through seeds has already been demonstrated.

In another realm, there is a risk that the increase in rain-fed cultivation will continue in areas where legislation adopted for the agricultural zone is extended to the pastoral zone. In other words, the possibility of claiming damages from herdsmen and owners of herds which destroy crops gives priority to extensive agriculture over pastoralism in pastoral territory.

The struggle against desertification depends finally on whether it is possible to follow a coherent programme and general policies which are not reversed by short-term activities.

Appendixes

Appendix I
Note on Figure 5. Map of potential pressure of man and livestock in the dry season

The watering capacity of livestock in the dry season, according to the atlas of water holes in Niger (Greigert and Sauvel, 1970), gives figures which indicate only an order of magnitude. This map (Fig. 5) should be interpreted carefully.

1. It presents a picture of the potential situation at the beginning of the dry season. By mid-January, the date varying according to the year, numerous water-holes, such as pools and wells fed by surface flows, dry out. The livestock therefore migrate to the more important watering points.
2. The areas of highest densities (15 TLU/km^2 and above, i.e. 1 TLU/10–15 ha) do not indicate the points of highest concentration in view of:
   - the regrouping of the cattle at the end of the dry season;
   - the fact that the figures considered as the lower limit for pumping stations (5000 TLU) are well below the estimates of livestock actually watered before the drought (10000–15000 TLU at the station of Ekinawan and 10000 at the station of Egarek during many months in the seasons of 1968–69 and 1969–70).

   There is a difference between the mean annual potential pressure, estimated in the southern part of the pastoral zone at one TLU/8–15 ha, and the potential watering pressure at holes with a large water flow when the concentration of herds occurs, especially between January and May.
3. The highest potential capacities are found between 17° N. and 15° 30′ N. In this north-Sahel zone, and particularly between 4°30′ E. and 7° E., favourable forage and water resources coincide with installations established by the government.
4. The pressure on the environment is increased by newly created human settlements, namely administrative centres (Tchin Tabaraden, Abalak, Tillia, Tassara), new markets (Abalak, Tofamanir), and the Tahoua–Agadez–Algeria road, which will be tarred between Tahoua and Arlit and become a line of deforestation, with fuel wood being offered to the trucks along the road utilized by the breeders.

   Furthermore, the resumption of rain-fed agriculture after the drought, north of the legal limit, and the establishment of centres of irrigated agriculture west of Agadez together with the pioneer agricultural fronts and the centres of permanent cultivation, are also adding to the pastoral pressure.
5. Finally, the region of 'salt cure', although referring to a brief but intensive exploitation during the rainy season (August to mid-September), is shown on the map in order to indicate the complementarity in time and space of the northern and southern zones.

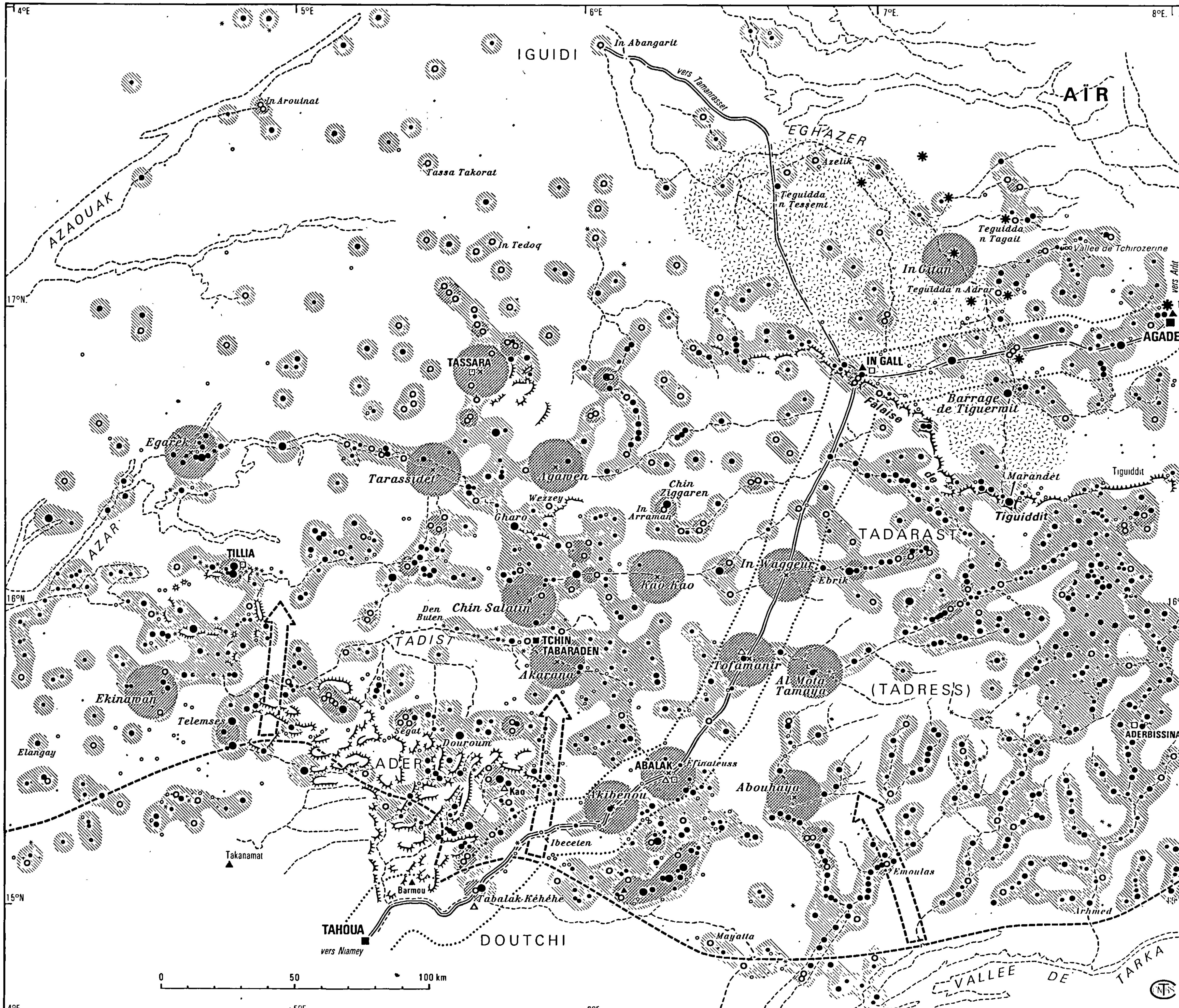


Fig. 5. Eghazer and Azawak (Azaouak) of Niger: potential pressure of man and livestock in the dry season

Legend

VULNERABILITY TO DESERTIFICATION FACTORS OR RISKS OF DESERTIFICATION

- highly sensitive
- sensitive
- moderately sensitive
- relatively sensitive
- hyperarid (unclassified)

FACTORS AFFECTING LANDSCAPE DEGRADATION BY EXTERNAL PROCESSES

Nature of outcropping rocks :

homogeneous rock with concentrated drainage lines	R
— with barchans	k
— with sand hills	c
escarpments with cappings of hard rock	

Aeolian sand formations :

thin sand veneer on bedrock	V
— with sand hills	c
thin sand sheet (undifferentiated)	N
thick sand sheet, arranged :	S
— in longitudinal undulations	l
— with giant ripples	g
— in sinuous undulations, transverse or oblique	t
— in barchans	k
— in low sand hills	c
— in rounded convex rises	m

Wind erosion

— reactivation of irregular sand sheet	a.
— wing-swept strips	b
— deflation belts	d
— corrasion belts	cor.

Water erosion

— concentrated drainage	E
— hills with gullies	r.
— valleys choked with moving sand	F

Tendency to salinization of valley bottoms in the clay zone of the Eghazer.

HUMAN AND GRAZING FACTORS

- — sedentary human concentration: administrative and trade centres (markets).
- — recent sedentary human settlement with irrigated agriculture. ★
- — hypothetical animal concentration in the dry season (October-July) leading to overgrazing.
- — animal concentration in the rainy season (salt cure).
- borehole, well ×
- administrative centre ■

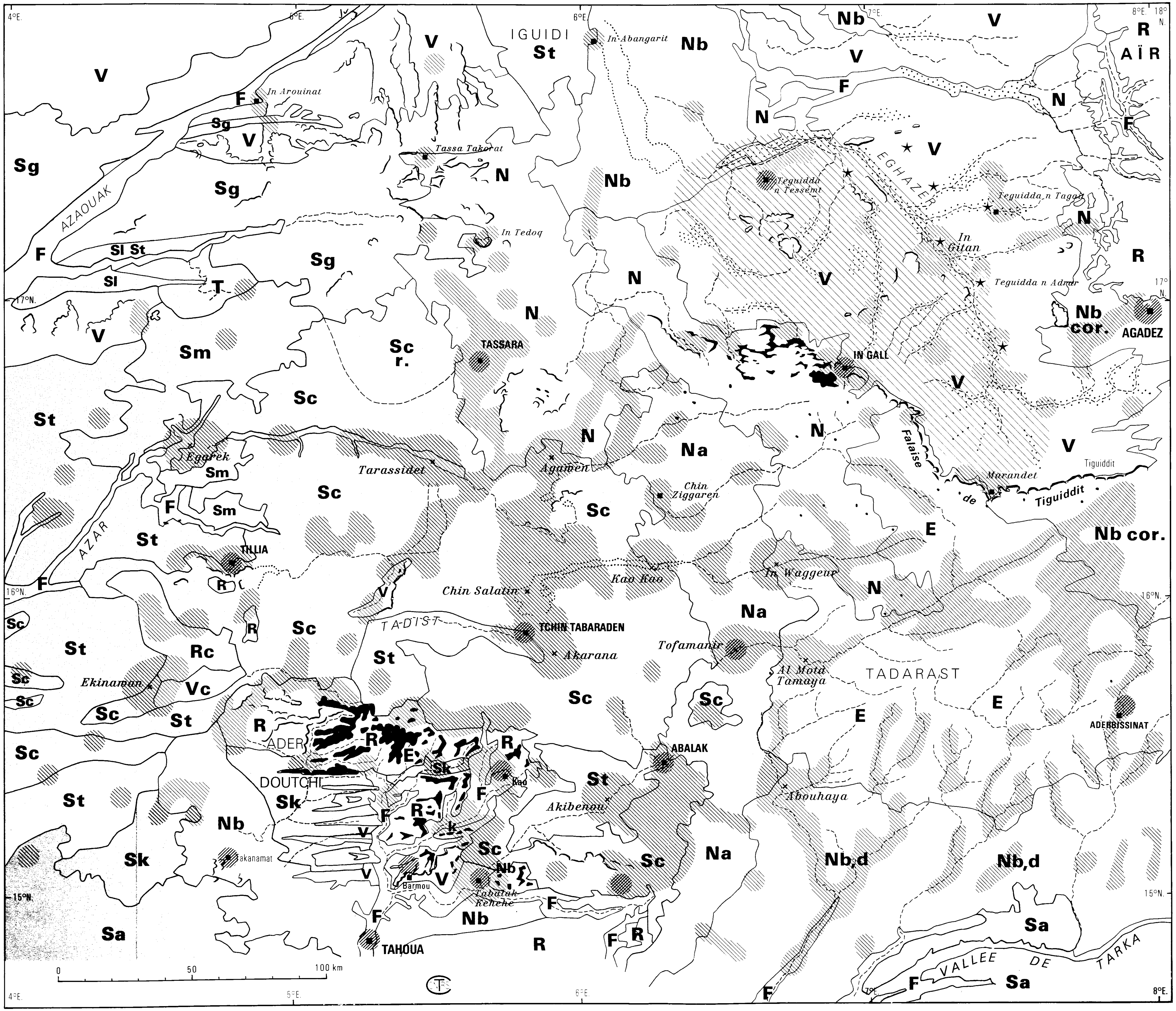


FIG. 6. Synoptic map of desertification: the Eghazer and Azawak (Niger)

Appendix II
Figure 6. Synoptic map of desertification

The vulnerability of the Sahel region south-west of the Aïr can be classified in three categories:

1. Degrees of vulnerability induced by the variations in the physical environment and the external dynamics;
2. The degree of human and livestock pressures focused on particular points and extending along preferential lines or in concentric zones;
3. The combinations of the two preceeding causes:
   (a) Among the factors of vulnerability linked to the physical environment, one notices;
      — random stabilization of sand surfaces north of the 150 mm isohyet by a discontinuous plant cover in an arid community;
      — in the true Sahel region (south of the 150 mm isohyet) a thin sand sheet;
      — in the region of thick sand which forms plant-covered dunes, vegetation denudation by water action takes place in two particular circumstances, namely on the flood-outs with a higher proportion of particles smaller than 50 μm and those areas which have undergone compaction through pedogenesis.
   (b) In this region of pastoral land use, human and animal pressures are manifested as:
      — a concentration of herds, during the dry season, around water-holes with high discharge rates, and thus by a discontinuous localized exploitation of the rangelands;
      — in the recent development of fixed human settlements, such as the new weekly market-places (Abalak, Tofamanir), on the main roads, and the network of administrative centres (Tchin Tabaraden, Abalak, Tillia, Tassara).
      — by rain-fed cultivation beyond the legal northern limits, and by the practice of irrigated agriculture in the peripheral depression south-west of the Aïr.
   (c) Only limited permanent human occupation is possible in the pastoral region north of the 150 mm isohyet, which has a reduced or non-existent tree cover that is briefly and intensively exploited during the summer.

In the central part of the region under study, the efforts of the administration were concentrated upon profiting from the most favourable environmental conditions (in an area known as that of pastoral modernization). The result has been an increased human and animal population density, together with a quantitative and qualitative modification of the vegetation cover and a recurrence of aeolian action aggravated at particular places by the exploitation of the environment. The sum total of these phenomena in limited areas leads to increased environmental vulnerability at the regional scale.

Bibliography

ACADÉMIE DES SCIENCES D'OUTRE MER. 1975. *La sécheresse en zone sahélienne. Causes, conséquences, études des mesures à prendre.* Paris, La Documentation Française. 75 p. (Notes et etudes documentaires 4.216–17.)

ALBENQUE, A. 1974–75. *Le département d'Agadez. Rapport de synthèse.* Agadez, Ministre du Plan.

BERNUS, E. 1974*a*. Possibilités et limites de la politique d'hydraulique pastorale dans le Sahel nigérien. *Cah. ORSTOM,* sér. *Sci. Hum.*, vol. 11, no. 2, p. 119–26.

——. 1974*b*. *Les Illabakan. Une tribu touarègue sahélienne et son aire de nomadisme.* Paris, Mouton & ORSTOM. 116 p. (Atlas des structures agraires 10).

——. 1975. Human geography in the Sahelian zone. In: *The Sahel: ecological approaches to land use,* p. 67–74. Paris, Unesco. (MAB technical notes.)

BILLE, J. C. 1974. Recherches écologiques sur une savane sahélienne du Ferlo septentrional, Sénégal: 1972, année sèche au Sahel. *La terre et la vie,* vol. 28, p. 5–20.

——; POUPON, H. 1974*a*. Recherches écologiques sur une savane sahélienne du Ferlo septentrional, Sénégal: la régénération de la strate herbacée. *La terre et la vie,* vol. 28, p. 21–48.

——; ——. 1974*b*. Recherches écologiques sur une savane sahélienne du Ferlo septentrional, Senegal: influence de la sécheresse de l'année 1972–1973 sur la strate ligneuse. *La terre et la vie,* vol. 28, p. 49–75.

BOUDET, G. 1972. Désertification de l'Afrique tropicale sèche. *Adansonia,* vol. 12, no. 4, p. 505–24.

BOULET, R, 1964. *Étude pédologique du Niger central.* Dakar, Centre ORSTOM. 430 p. + map. (Mimeo.)

——. 1966. *Observations pédologiques dans le Tamesna oriental (Niger). Relations sol–végétation.* Dakar, Centre ORSTOM.

CAMPS-FABRER, H.; CAMPS, G. 1972. Perspectives et orientation des recherches sur le néolithique saharien. *Revue de l'Occident musulman et de la Méditerranée* (Aix-en Provence), no. 11, 1 er semèstre, p. 21–30.

CARRÉ, P. 1974. *Vallée de Tchirozérine: bordure sud-ouest de l'Aïr. Caractéristiques des écoulements de surface en 1973.* Niamey, Mission Hydrologique ORSTOM. 8 p.

COMMISSARIAT GÉNÉRAL AU DÉVELOPPEMENT: SERVICE DE LA PROMOTION HUMAINE. (NIGER.) 1972. *Les problèmes d'abreuvement et le fonctionnement des stations de pompage, vus par les éleveurs de l'arrondissement de Tchin Tabaraden.* Niamey. 124 p. + 75 p. (mimeo.).

COMPAGNIE GÉNÉRALE D'ÉTUDES ET DE RECHERCHES POUR L'AFRIQUE (COGERAF). 1962. *Aménagements d'hydraulique pastorale, la région du nord du Tahoua.* Paris, COGERAF.

COULOMB, J. 1970–71. *Zone de modernisation pastorale du Niger: économie du troupeau.* Maisons Alfort, Institut d'Élevage et de Médecine Vétérinaire des Pays Tropicaux (IEMVT); Paris, Société d'Etudes pour le Développement Economique et Social (SEDES). 178 p. + map.

——. 1972. *Étude pour la mise en valeur du complexe du Sud-Tamesna. Economie du troupeau et note de synthèse.* Maisons Alfort, Institut d'Élevage et de Médecine Vétérinaire des Pays Tropicaux (IEMVT); Niamey, Laboratoire Nationale de l'Elevage et de Recherches Vétérinaires (Niger). 148 p. + map.

DELWAULLE, J. C. 1973. Désertification de l'Afrique au sud du Sahara. *Bois et forêts des tropiques,* no. 149, p. 3–20.

DUPIRE, M. 1962. Peuls nomades. Études descriptives des Wodaabe de Sahel nigérien. *Trav. Mem. Inst. Ethn.*, no. 64. 338 p.

FUGLESTAD, F. 1974. La grande famine de 1931 dans l'ouest nigérien: réflexions autour d'une catastrophe naturelle. *Rev. Fran. Hist. O-M.*, vol. 61, no. 222, p. 18–33.

GALLAIS, J. 1967. Le delta intérieur du Niger. Étude de géographie régionale. *Mem. IFAN* (Dakar), no. 79. 621 p.

GAVAUD, M. 1965. *Étude pédologique du Niger occidental.* Dakar, Centre ORSTOM. 3 vols. + map (1/500000).

GHOUBEÏD-ALOJALY. 1975. *Histoire des Kel Denneg avant l'arrivée des français.* Copenhague, K. G. Prasse, Akademisk Forlag.

GRANIER, P. 1975. *Note sur l'introduction des techniques d'amélioration de la production de l'élevage en zone sahélienne.* Niamey, Laboratoire d'Élevage. 37 p. (Rapport du Service d'Agrostologie 1974–75, Institut d'Élevage et de Médecine Vétérinaire des Pays Tropicaux.)

GREIGERT, J. 1966. *Description des formations crétacées et tertiaires du bassin des Ioullemmeden (Afrique occidentale).* Paris, Editions BRGM. 234 p. + carte géologique du bassin des Ioullemmeden, 1/1000000. (Direction des Mines et de la Géologie de la République du Niger, Publ. 2.)

——. 1968. *Les eaux souterraines de la République du Niger.* Niamey, Ministère des Travaux Publics. 2 vols.

——; SAUVEL, C. 1970. *Modernisation de la zone pastorale nigérienne. Étude hydrogéologique.* Orléans, Atlas BRGM.

HOORE, J. L. D'. 1964. *Carte des sols d'Afrique au 1/5000000e.* Lagos, Commission de Coopération Technique en Afrique au Sud du Sahara (CCTA).

HUGOT, H. J. 1974. *Le Sahara avant le désert.* Toulouse, Ed. Hespérides. 344 p.

INSTITUT NATIONAL DE LA STATISTIQUE ET DES ÉTUDES ÉCONOMIQUES (INSEE); SOCIÉTÉ D'ÉTUDES POUR LE DÉVELOPPEMENT ECONOMIQUE ET SOCIAL (SEDES). 1966. *Étude démographique et économique en milieu nomade.* Puteaux, SEDES. 2 vols.

LE HOUÉROU, H. N. 1972. *Le développement agricole et pastoral de l'Irhazer d'Agadez (Niger).* Rome, FAO. (Rapport de consultation au projet de l'amélioration de vie des nomades de la région d'Irhazer.)

MINISTÈRE DE L'ÉCONOMIE RURALE (NIGER). 1961. *Rapport 1961. Circonscription d'élevage de Tahoua.* Niamey, République du Niger, Direction de l'Élevage et des Industries Animales.

——. 1969. *Rapport statistique.* Niamey, République du Niger, Direction de l'Élevage et des Industries Animales.

——. 1974. *Rapport annuel.* Niamey, République du Niger, Direction de l'Élevage et des Industries Animales.

NICOLAS, F. 1950. *Tamesna. Les Ioullemmeden de l'Est ou Touâreg 'Kel Dinnîk', cercle de T'wa, colonie du Niger. Notes de linguistique et ethnologie berbère.* Paris, Imprimerie Nationale. 279 p.

NORRIS, H. T. 1975. *The Tuaregs. Their Islamic legacy and its diffusion in the Sahel.* Warminster, Aris & Phillips.

PATTERSON, J. R.; COLLIER, F. S.; DUNDAS, J.; BRYNMOR JONES; AUBRÉVILLE, A.; MATHEY, J.; BACHELIER, R. 1973. Mission forestière anglo-française Nigeria—Niger (décembre 1936–février 1937). *Bois et forêts des tropiques*, no. 148, p. 6–16.

PEYRE DE FABRÈGUES, B. 1970. *Pâturages naturels sahéliens du sud Tamesna.* Maisons Alfort, Institut d'Élevage et de Médecine Vétérinaire des Pays Tropicaux (IEMVT). 200 p. (Étude agrostologique 28.)

——. 1971. *Évolution des pâturages naturels sahéliens du sud Tamesna (République du Niger).* Maisons Alfort, Institut d'Élevage et de Médecine Vétérinaire des Pays Tropicaux (IEMVT). 135 p. (Étude agrostologique 32.)

——; LEBRUN, J. P. 1976. *Catalogue des plantes vasculaires du Niger.* Maisons Alfort, Institut d'Élevage et de Médecine Vétérinaire des Pays Tropicaux (IEMVT). 433 p. (Étude botanique 3.)

PLOTE, H. 1974. *L'Afrique sahélienne se déssèche-t-elle? Essai sur la détérioration des conditions climatiques au Sahel tropical.* Orléans, Bureau de Recherches Géologiques et Minières (BRGM), Département de Géologie et de l'Aménagement. 61 p.

RECEVEUR, P. 1960*a*. *Hydraulique pastorale. Bases d'une politique de l'eau en zone sahélienne.* Niamey, République du Niger.

——. 1960*b*. Politique de mise en valeur de la zone sahélienne. In: *Rapport annuel 1959–1960*, p. 129–50. Niamey, Ministère de l'Economie Rurale.

RIPPSTEIN, G.; PEYRE DE FABREGUES, B. 1972. *Modernisation de la zone pastorale du Niger.* Maisons Alfort, Institut d'Élevage et de Médecine Vétérinaire des Pays Tropicaux (IEMVT). 307 p. (Étude agrostologique 33.)

ROCHE, M. 1973. Note sur la sécheresse en Afrique de l'Ouest. In: Dalby, D.; Harrison-Church, R. J. (eds.), *Drought in Africa*, p. 53–61. London, University of London, School of Oriental and Asian Studies, Centre for African Studies.

SALIFOU, A. 1975. Quand l'histoire se répète: la famine de 1931 au Niger. *Environnement africain* (Dakar), vol. 1, no. 2, p. 25–52.

SIRCOULON, J. 1976. Numéro spécial sécheresse. Les données hydropluviométriques de la sécheresse récente en Afrique intertropicale. Comparaison avec les sécheresses '1913' et '1940'. *Cah. ORSTOM*, sér. *Hydrologie*, vol. 13, no. 2, p. 75–174.

SOCIÉTÉ CENTRALE POUR L'EQUIPEMENT DU TERRITOIRE, COOPÉRATION INTERNATIONALE (SCET INTERN.): SOCIÉTÉ D'ETUDES POUR LE DÉVELOPPEMENT ECONOMIQUE ET SOCIAL (SEDES); OFFICE DE LA RECHERCHE SCIENTIFIQUE ET TECHNIQUE OUTRE-MER (ORSTOM). 1976. *Essai de réflexion sur les stratégies anti-sécheresses de l'Afrique de l'Ouest.* Puteaux, SCET-Intern. 3 vols. 457 p.

SOCIÉTÉ D'ETUDES POUR LE DÉVELOPPEMENT ÉCONOMIQUE ET SOCIAL (SEDES). 1972–73. *Résultats de l'enquête économique sur la production animale au Niger.* Paris, SEDES, 2 vols. 217 p. + appendixes.

4 Desertification in the Luni Development Block, Rajasthan, India

Case study presented by the Government of India

Acknowledgements

Unesco would like to express its thanks to the Central Arid Zone Research Institute, Jodhpur, which was responsible for the preparation of this case study. The information was compiled by I. Prakash and the Recommendations and Appendix II were drafted by S. P. Malhotra and A. N. Lahiri.

Assistance was provided by the Indian Council of Agricultural Research and the Indian Department of Science and Technology.

Unesco also wishes to thank the following scientists for their valuable contributions: H. S. Mann, A. Krishnan, K. A. Shankaranarayan, R. P. Dhir, B. Ghose, S. Singh, S. K. Saxena, J. C. Kalla, M. L. Purohit, A. K. Sen, P. C. Chatterji, R. B. Das and L. D. Ahuja.

UNDP, FAO and WMO also collaborated in this study.

Introduction

The Indian Desert is unique among deserts of the world, for not a single oasis nor a native cactus breaks the monotony of the vast ocean of sand. However, by arid-land standards, it is heavily populated. Average population density is 46 persons/km^2, compared with 3 persons/km^2 in other desert areas. It also maintains a livestock population of over 23 million head, as well as a large number of wild animals. The Rajasthan Desert contains a mixture of peninsular, extra-peninsular, and Indo-Gangetic geographical features. Geologically, the desert has resisted orogenic forces and has been subjected to marine transgressions. Historically, it was the seat of the Mohenjodaro-Harappa-Kalibanga civilizations; later, the region was dominated by the Princely States and has borne the brunt of a succession of invasions by Muslim chieftains and emperors. Biogeographically, the majority of the desert biota exhibit 'western' affinities.

The Luni Development Block is located in a predominantly agricultural area of the Rajasthan Desert within the Jodhpur district; 87·9 per cent of the area is under cultivation. The Block encompasses 106 villages in a total area of 1989 km^2, and supports a human population of 95222 and 162933 head of livestock. About 80 per cent of the Block area falls within the semi-arid zone, with 310–90 mm of rainfall occurring from June to September.

The terrain in this area, as in most of the Rajasthan Desert, consists of a varyingly wind-transformed old alluvial plain. Soils are predominantly brown, and light-textured, but there is also a sizeable area of grey-brown soils. Hills and eroded rocky surfaces are limited in extent but serve as watersheds for the many drainage networks. Only a few of these watercourses actually reach the Luni River, which flows across the southern part of the Block. The Luni River and its major tributary in the area, the Mitri, have well-developed adjoining strips of young alluvial sediment, which occupy 165·4 km^2 or 8·3 per cent of the Block area. In terms of exploitable ground water, this zone is the most prized in the area. Though located in the xeromorphic scrub and open mixed xeromorphic woodland vegetation zone, the present-day vegetation in both agricultural and open grazing land in the Luni Block and the Rajasthan Desert has deteriorated or has been greatly transformed.

Agriculture in the region is characterized by mixed farming. Most households maintain small herds of cattle on crop residues and other annual or perennial vegetation, including top-feed trees and shrubs left standing in the agricultural lands. Human and stock drinking needs are met for 3–6 months from the village ponds and for the rest of the year from dug wells.

As in the entire Rajasthan arid zone, human population in the Luni Block has undergone a linear increase since 1901, and the density of population has increased from 16·2/km² in 1901 to 48·07 in 1971. In terms of sex ratio, the female proportion has increased from 908 (1951) to 915 (1971) per thousand males. The land-use pattern indicates that there has been a decline in the area under fallow, from 24 per cent of the area in 1964–65 to 12·7 per cent in 1974–75. The intensification of arable farming associated with the increase in population has tremendously intensified the pressure on land, natural resources and rangelands in the Luni Block. It was estimated that the forage deficit of 50 per cent in 1957 would increase to 53–54 per cent in 1972. Likewise, the fuel requirement of the population has increased by 150 per cent during the last decade.

The process of desertification in the study area is evident from such factors as the degradation of the vegetative cover, sand drift and wind erosion, accelerated water erosion, reduced soil fertility, salinization and a decline in water resources. The causes of desertification are attributable to an interaction of increased human population, social customs, livestock pressure, destruction of woody vegetation, impact of rodents and locusts, the inherent vulnerability of the landscape, and climatic stress.

The process of desertification is particularly evident in the vegetation component of the ecosystems, which has suffered from the prolonged drought of 1961–70. In almost all the land-resource units, the productive climax plant association has changed to a degraded vegetation type with an increase in unpalatable species. Data on frequency and density of various grasses, shrubs, and trees have been quantitatively discussed to assess the effect of biotic factors.

Rodents have been a particular problem. They not only consume and destroy natural and cultivated vegetation, but also excavate large amounts of stabilized sand, which are readily drifted by the strong desert winds.

Observations made in 1976 show that during a span of eighteen years, sand movement has led to an increase in the number of sandy hills over an area of 166 km². Recently, sand mobilization has caused the hummocks created by sand accumulation along fence-lines to deepen by 15–30 cm and widen by 1–2 m. Prior to 1958, an area of 83 km² of once productive land had been salinized beyond use, and since 1958 salinity has spread laterally to another 40·3 km². As a result of increased exploitation of ground water from 1968 to 1976, the discharge potential of the wells has fallen greatly. Water quality has also declined in most of the wells in the Luni Block.

Of the total area of the block, 20·11 per cent falls within the arid zone. About 48·80 per cent is of high-to-medium vulnerability to desertification processes. About 92·50 km² or 4·65 per cent of the total area is highly vulnerable due to the enlargement of settlements. Dunes, sandy cover, shifting sand and hummocks affect about 645·0 km² (32·43 per cent of the area), placing these lands in the high-to-medium vulnerability category. The rest of the area is affected by water-erosion hazards associated with dunes or salinity or both.

Description of the area

Climate

The climate of the Luni Block can be classified as

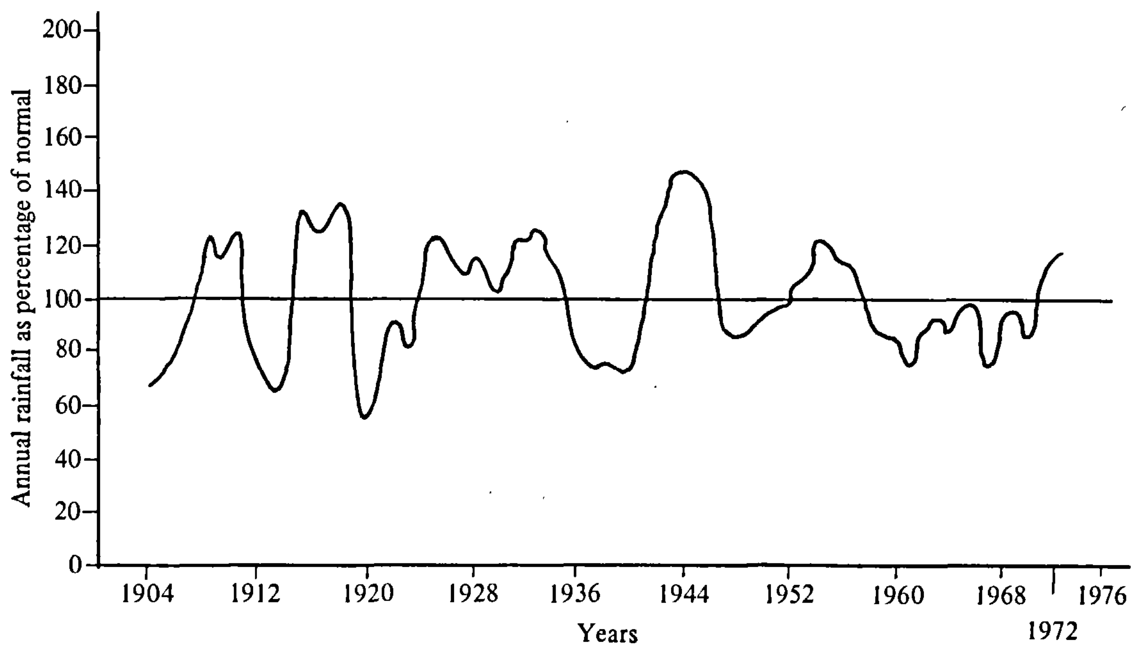


FIG. 1. Above- and below-normal annual rainfalls at Jodhpur (mean annual rainfall = 359·8 mm)

arid, with Thornthwaite's moisture index varying from −43 to −47. However, by the criterion of the limit of the Precipitation (*P*)/Potential evapotranspiration (*ETP*) index for arid zones, with *ETP* values computed by Penman's method, 20 per cent of the area of the Luni Block towards the west falls in the arid zone, while the remaining 80 per cent of the area falls in the semi-arid zone.

Rainfall

Mean annual rainfall in the Luni Block varies from 310 mm to 390 mm, of which 90–93 per cent occurs during the monsoon period, from June to September. The coefficient of variation between years varies from 51 to 56 per cent. Rainfall in the region increases from west to east, with considerable year-to-year variations. The rainfall deficit and surplus patterns and their probable frequency at Jodhpur are as follows:

Rainfall deficit pattern	*Rainfall surplus pattern*
Expected once every five years; 180–230 mm	Expected once every five years: 450–540 mm
Expected once every ten years: 130–170 mm	Expected once every ten years: 530–650 mm
Percentage frequency of high deficit rainfall years (≤ 50% of normal): 10–17	Percentage frequency of high surplus rainfall years (≥ 150% of normal): 16–17

The above data indicate that flood years and drought years occur quite frequently in the Block, and that there is good reason for harnessing surplus rainfall in favourable rainfall years. The data also indicate (Fig. 1) that there were four spells each of above-normal and below-normal rainfall in Jodhpur from 1901 to 1956, and that there has been a decreasing trend in rainfall since 1956. Between 1901 and 1975 the longest spell of below-normal rainfall conditions occurred during the years 1961–71.

The following list shows the years in which rainfall at Jodhpur was in large deficit (drought years) and in large surplus (flood years). The actual rainfall figures for these years are shown in parentheses:

Drought years (with annual rainfall less than 50% of normal, namely 179·9 mm)	1902 (175·3)	1905 (89·1)
	1911 (146·8)	1915 (132·3)
		1918 (37·8)
	1921 (161·0)	1925 (137·7)
	1960 (134·8)	1963 (178·7)
	1968 (178·8)	1969 (92.7)
	eleven years	
Flood years (with annual rainfall greater than 150% of normal, namely 539·7 mm)	1908 (850·0)	1916 (658.9)
	1917 (1176·2)	1926 (544·6)
		1927 (561·6)
	1933 (635·8)	1943 (634·5)
	1944 (778·2)	1945 (567·3)
	1956 (581·9)	
	1964 (540.5)	1970 (594·8)
	1973 (585·4)	1975 (661·9)
	fourteen years	

Thus from 1901 to 1975, there were eleven drought years out of which seven occurred prior to 1925 and four occurred from 1960 onwards. The probabilities of occurrence of such drought years and flood years work out to 14·7 per cent and 18·7 per cent respectively. Assuming a deficit year to be a year in which annual rainfall is 80 per cent of normal (287·8 mm) or less, there have been thirty deficit years in the last seventy-five years (i.e. 40 per cent or two out of every five years).

Crop and natural vegetation growth are very much affected by prolonged rainfall-deficit periods, namely, those extending to thirty days or more. Droughts extending from thirty to seventy-five days have occurred in the Luni Block fifty-two times between 1901 and 1960. These prolonged droughts affect, on the average, 30 per cent of the wet season.

Temperature

In January, the coldest month in the Luni Block, the mean maximum and minimum temperatures are 24° and 9·6°C respectively. With the approach of western disturbances, cold waves occur and temperatures fall considerably. The lowest minimum temperature recorded thus far is 2·2°C, which occurred in January. Frosts are rare but have occurred in the past during the months from December to February, with maximum frequency in January. The period from March to June constitutes the hot-weather season. May, with a mean maximum temperature of 41·1°C, is the hottest month of the year, followed by June with a mean of 39·9°C. The highest temperature recorded to date is 48·9°C, which occurred in May. With the onset of the monsoon season in July the average maximum and minimum temperatures drop to nearly 35° and 25°C respectively. The diurnal variation, which is in the order of 14°–16°C during other seasons, becomes 8°–10°C during the monsoon season. After the retreat of the monsoon, which usually takes place in the third week of September, the temperature again increases, reaching a second peak in October. Thereafter, temperatures begin to fall with the approach of winter (December to February).

Humidity

Relative humidity is low in the hot weather months of March, April, and May, reaching its maximum during the monsoon months. The lowest mean value of 24 per cent occurs in April, and the highest value of 70 per cent occurs in August. December and January have a mean value of 39 per cent; in February the mean value is 33 per cent. There is a diurnal variation in relative humidity of 20–30 per cent throughout the year.

Evaporation

The mean annual evaporation, as recorded by the USA Class A Pan evaporimeter at Jodhpur during the period 1960–75, is 350 cm. The least evaporation occurs in winter with an average daily value of 6·1 mm/d. The mean summer evaporation is 15·6 mm/d, which is exceedingly high owing to the high radiation, the saturation deficit, and the high wind speeds that occur in the well-exposed site of the evaporimeter. Evaporation during the monsoon season approximates 9·0 mm/d but as a number of observations on extremely rainy days are missed owing to overflow, the actual value would be slightly less. Post-monsoon evaporation is 7·0 mm/d.

Winds

Mean wind speeds over 24 hours are 10 km/h or more from January to September. Values exceeding 15 km/h occur during May to July, with the highest value of 19·1 km/h occurring in June. From October to December wind speed is lowest, ranging from 6 to 9 km/h. The lowest mean value of 6·2 km/h occurs in November. From May to September the wind direction is southwesterly and very steady, but during the rest of the year the directions are variable. In the winter months the wind generally blows from the north-east (Krishnan, 1968).

Major land resource units

A major land resource unit is a mapping unit used in semi-detailed and basic resource reconnaissance surveys. The area represented is expected to have sufficient homogeneity in land form, soil, vegetation, surface and ground water resources, and climate to permit specific recommendations on upgrading production on a sustained basis. The geomorphological classification is at the scale of land-form units and sub-units, and the soil mapping between family and phase or their associations and complexes. Regarding vegetation, emphasis is not placed on components related to land use, but on plant species reflecting natural habitat characteristics. Thus, though the present classification has a genetic bias, overriding consideration is given to the nature and magnitude of limitations such as erosion hazard, soil depth and salinity, and the optimum land use and management practices required. The unit also takes into account response to management.

A survey of natural resources was carried out in 1967 as part of an integrated study of the area and a report followed in 1969. Investigations showed that the whole area could be divided into twelve major land resource units (Fig. 2). To this may be added one more, comprising the areas in which irrigation has been introduced, allowing a great increase in annual productivity. The irrigated areas are located in all twelve of the above-mentioned land units, but more particularly in the young alluvial plains, and form 0·79 per cent of the area of the Block. A summarized description of the resources of the ecosystems, their present potentials and proposed management practices is given in Appendix I. These data show that old, alluvial plains with light- to medium-textured soils and a static ground water table averaging 18 m below ground level with subdivisions into (a) flat plains and (b) sandy undulating plains, each occupy 38·3 and 26·4 per cent of the area of the Block respectively. Old alluvial plains with medium- and heavy-textured soils occupy 14·2 per cent whereas younger alluvial plains with good underground water potential, though saline, occupy another 8·3 per cent. Sand dunes occupy 4·9 per cent. Hard-pan soils and gravelly pediments occupy respectively 2·2 and 2·1 per cent of the area, with hills, piedmont plains, river beds, saline flats and depressions forming the rest.

Human and livestock population

The latest census, carried out in 1971, showed that the Luni Block had a human population of 95922 spread over an area of 1989 km^2, giving a population density of 48·23 persons/km^2. The percentages of children (0–14 years of age), young (15–34), middle-aged (35–54), and old persons (55 and older), were 44·4, 32·6, 15·8 and 6·2 respectively. The number of females of reproductive age (15–44 years) was 4267 out of every 10000 females. The percentage of married women among all women of reproductive age came to 95·06 per cent. Of the wage earners in the Block, 83 per cent are engaged in farming, and an additional 7 per cent work as labourers on farms.

Agriculture in the region is a mixed farming system with most households maintaining sizeable numbers of cattle feeding on crop residues and grazing on cultivated and village common lands. The livestock population as shown in the 1972 census was 162933 head, of which 36·39 per cent were cattle, 29·83 per cent were goats and 24·77 per cent were sheep. The rest included buffaloes (4·57 per cent), camels (3·78 per cent), donkeys (0·11 per cent) and horses (0·04 per cent). In terms of adult cattle units, the Luni Block had 26 units/km^2.

Present land use

The Luni Block, like much of the arid Rajasthan region, is a dominantly agricultural area. Statistics for the year 1974–75 show that 87·86 per cent of the total area is under cultivation, 75·20 per cent having actually been cropped and 12·66 per cent under fallow; 3·19 per cent of the area is under common village or grazing lands, 4·25 per cent under rural settlements, communications, etc., and 3·40 per cent consists of rock exposures, hills and saline depressions. Only 1 per cent of the area is under forest and another 1·17 per cent has been shown as cultivable but at present lying idle. Table 1 shows the 1976 figures for different types of land use in the Luni Block and these are illustrated in Figure 3.

Causes of desertification

The Luni Block is submitted to high biotic pressure which is increasing in spite of limited, and in some cases dwindling, natural resources. An increase in the incidence of cultivation, greater exploitation of woody biomass for fuel and timber, a decrease in the area of lands available for grazing, digging of shrub roots for fuel, and harvesting of grasses, shrubs and trees to supplement human and cattle needs in times of scarcity are some of the ways in which increased human pressure is manifesting itself. One must also consider the natural vulnerability of desert ecosystems, i.e. the high sensitivity of the natural vegetation to excessive grazing; the light texture of the soils, which leads to low surface stability; the strong wind regime; and the proneness of certain locations to salinization as a result of interference in drainage etc.

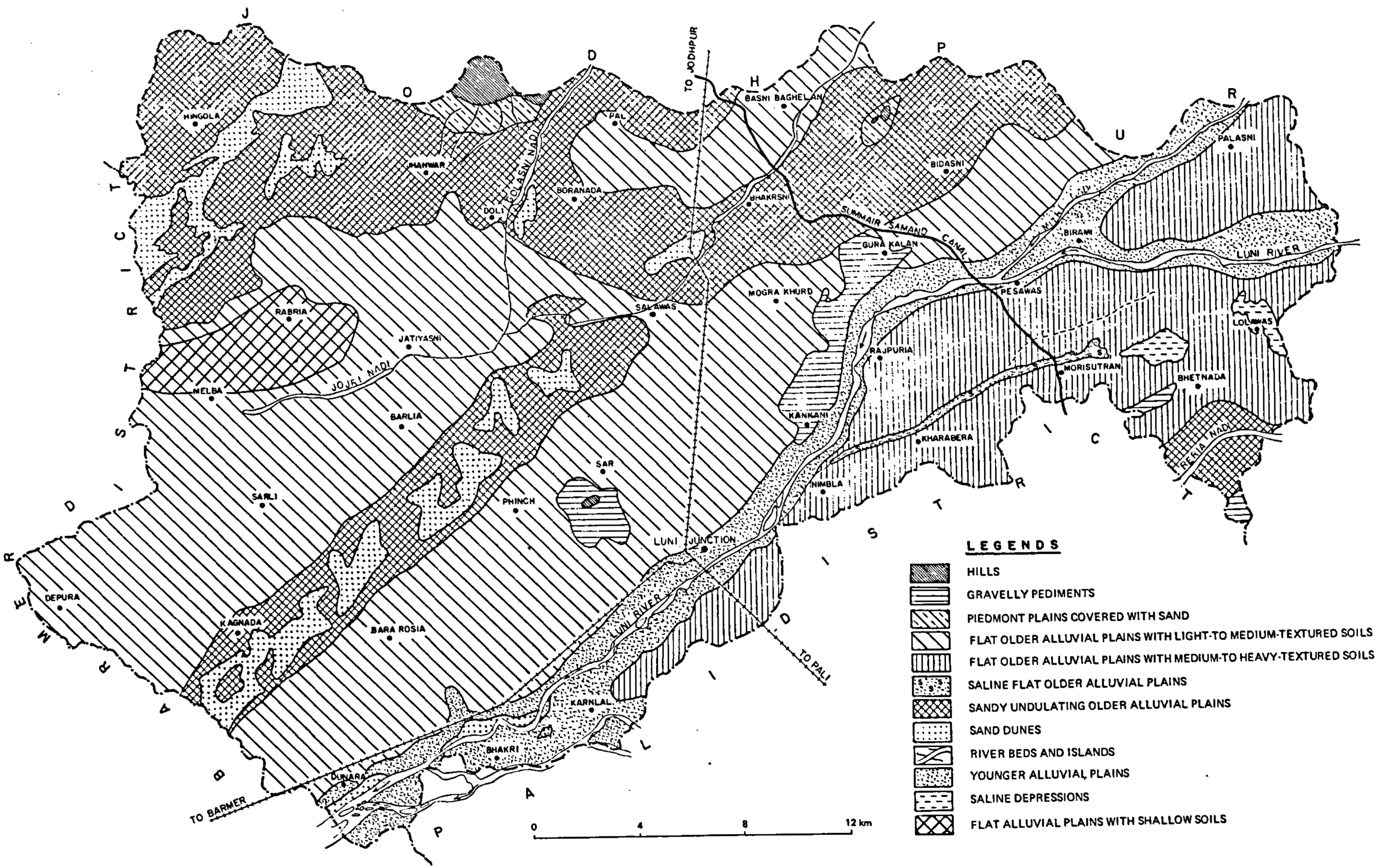


Fig. 2. Major land resources units (MLRU) in the Luni Development Block

TABLE 1. Present (1976) land use in the Luni Block

Land use	Area (km²)	Area (%)	Remarks
Settlements	21·55	1·08	Lands not available for cultivation. Total area = 117·58 km² (5·91 per cent)
Roads and communications lines	48·69	2·45	
River beds and water features	47·34	2·38	
Permanent pasture or village common (*oran*) lands	156·64	7·89	Also includes dune and saline areas
Stony, rocky and gravelly wastes (hills, pediments and sloping piedmont lands)	27·92	1·40	Waste lands. Total area = 114·15 km² (7·23 per cent). During favourable rainfall years the farmer cultivates the sandy waste areas also
Sandy wastes (sand dunes and some interdunal lands)	87·64	4·40	
Saline waste (saline depressions, saline flats and river beds)	28·59	1·43	
Cultivable land including short and long fallows:			Total area = 1570·63 km² (78·97 per cent
Double-cropped irrigated land (intensity of cultivation 100 per cent)	15·54	0·78	
Single-cropped (A_1) (intensity of cultivation 40–80 per cent) occurring in flat older alluvial plains, and younger alluvial plain	1018·19	51·19	
Single-cropped (A_2) (intensity of cultivation 30–50 per cent); flat older alluvial plains	463·00	23·28	
Single-cropped (A_3) (20–30 per cent); sandy plains, marginal sand dunes and saline lands	73·90	3·72	
	1989·00	100·00	

Demographic and social conditions

The human population of the Luni Block numbered about 36000 in 1901 and had increased by over 250 per cent by 1971 (Table 2). A review of the percentage changes by decades reveals a decrease in population during the periods 1901–11 and 1911–21. During the latter decade, this decrease was mainly due to disease epidemics in the region. From 1931 to 1951, the population increased at relatively moderate rates, which rose considerably during the decades 1951–61 and 1961–71. As a result, the population density per km² increased from 16·21 in 1901 to 48·07 in 1971. The ratio of females to every 1000 males increased from 908 in 1951 to 915 in 1971. The increasing sex ratio from one decade to another reveals the potential for further increments of population.

The population of the arid zone of Rajasthan also registered a linear increase, from 3·57 million in 1901 to 10·24 million in 1971, i.e. an increase of over 300 per cent. The data further revealed that the rate of growth in the population of the Luni Block as well as in the arid zone of Rajasthan was much higher than in India as a whole (Table 2).

Coupled with this are the social values which encourage people to have more children. The positive sanctions in the society outnumber the negative ones. Early marriage and begetting of children are integral parts of the social ethos of these people. Any deviation from the established norm is not only looked down upon as grossly aberrant but also as wholly incompatible with the social fabric of the community. Divorce is a rarity, if not altogether unknown, and widowhood is soon followed by remarriage. While begetting a son is considered a must in order that the family line remain unbroken, a daughter born in the family among several commuities which have a system of customary exchange marriages is also held in importance as she has to be given in marriage in exchange for a prospective husband from the family of the daughter-in-law. Coupled with this strong and deep-rooted adherence to the custom of marriage and procreation, improved medical care in recent times has greatly minimized

TABLE 2. Population change by decade in the Luni Block, Arid Rajasthan, Rajasthan and India

Year	Luni Block		Arid Rajasthan		Rajasthan		India	
	Population	Decade change (%)	Population (million)	Decade change (%)	Population (million)	Decade change (%)	Population (million)	Decade change (%)
1901	36432	—	3·57	—	10·29	—	236·28	—
1911	32189	−11·64	3·88	+ 8·68	10·98	+ 6·70	252·12	+ 6·70
1921	29297	− 8·98	3·58	− 7·73	10·29	− 6·29	251·35	− 0·30
1931	37685	+28·63	4·88	+36·31	11·75	+14·19	279·02	+11·00
1941	46365	+23·03	5·28	+ 8·20	13·86	+17·95	318·70	+14·22
1951	55549	+19·80	6·16	+16·66	15·97	+15·20	361·13	+13·31
1961	73408	+32·15	7·99	+29·70	20·16	+26·24	439·24	+21·63
1971	95922	+30·66	10·24	+28·16	25·77	+27·83	547·37	+24·62
Overall increase from 1901 to 1971								
	59490	163·29	6·67	186·83	15·48	150·43	311·09	131·66

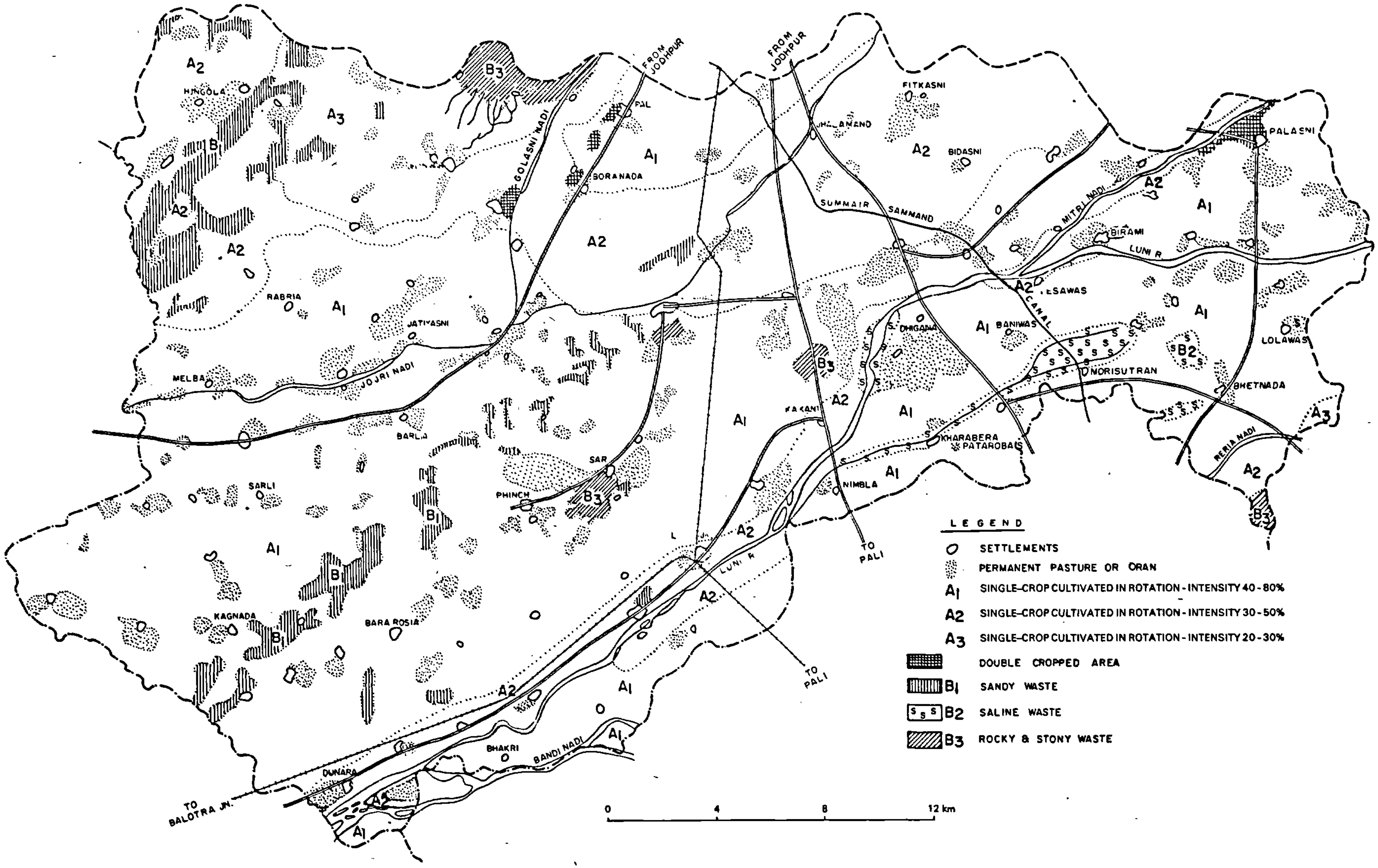


FIG. 3. Present land-use map of the Luni Development Block (1:126720)

mortality at birth and has prolonged the life span. Family planning has yet to make any inroads into the social life of the population, owing to its inherent weakness of neglecting the cultural variables.

The demographic features described above thus reveal that the population has not only grown at a substantial rate in the past but also exhibits a significant potential for future growth. Additionally, the widespread illiteracy, coupled with the caste and faction-ridden, orthodox, and tradition-bound nature of the popultion has not led to the adoption of innovations to any substantial extent. However, the tendency for traditional joint households to break into nuclear families is further responsible for more and more use of marginal lands (Mann *et al.*, 1974). If unchecked, therefore, population growth is likely adversely to affect the fragile ecosystems of the Luni Block and desertification processes will continue at an accelerated rate given the present resource base and traditional technology.

Livestock population

The data on the composition of the livestock population for three selected years reveal that the animal population has not undergone a noticeable change, the exception being the number of goats, which has increased from 18·8 to 29·9 million over a period of fifteen years. This change has been in favour of the animal which is most destructive to the vegetation. It is apparent that, despite an overall decrease in livestock population, the relative increase in goats and cattle may have worsened the conditions of survival for other animals, owing to a decrease in available fodder (Table 3).

Increase in cultivation

Tod (1929) records that in the year A.D. 1212 when a scion of the Rajputs, who subsequently founded the ruling dynasty, arrived in the desert region he found the whole region occupied. The eastern portion in Pali was settled by a community of Brahmins called Palliwals. The Jodhpur area was colonized by a number of tribes which owed allegiance to a head with his capital at Mandore (10 km away from present-day Jodhpur town). Further west, in drier habitats around present day Nagaur, lived a community of Mohile distributed in 1440 villages. Similarly even Jaisalmer and Bikaner were inhabited. In the first place, this shows that the entire present-day Rajasthan desert had been colonized by the beginning of the present millennium. Second, the highly adapted and evolved form of present-day agricultural practice indicates that many centuries of human experience must have gone into its making. Records reveal that most villages present today existed even in the early nineteenth century, with agriculture equal in importance to animal rearing. This situation apparently persisted until the 1930s, when the sharply rising population necessitated an increase in the area under cultivation. Figure 4 shows two sample areas of the Luni Block with the extent of cultivated areas in 1931 and 1958. It shows that a phenomenal increase has occurred in cultivated area during this period.

Land-use data from 1964–65 onwards at intervals of three years show that the areas under forests and hills have remained almost constant or have undergone a marginal increase (Table 4). Areas of non-cultivable and cultivable waste lands have shown a marked decline. Table 4 also shows that there has been a large decrease in the area under fallow: from 24·23 per cent in 1965–65 to 12·66 per cent in 1974–75. Thus an intensification of arable farming activity is most evident. The analysis thus shows that with the rising population there was a rapid rise in cultivated area until about the late fifties. With the entire cultivable land having been brought under cultivation, subsequent changes have involved a decrease in the area of fallow lands.

TABLE 3. Livestock population of the Luni Block

Livestock	Percentage of total livestock		
	1957	1964	1972
Cattle	35·21	38·82	36·39
Buffaloes	5·67	5·56	4·57
Sheep	37·73	38·02	24·77
Goats	18·84	15·20	29·83
Horses	0·03	0·06	0·04
Donkeys	0·20	0·15	0·11
Camels	2·32	2·18	2·78
	99·90	99·99	99·48
Total livestock	208766	177753	162933

Pressure on vegetation resources

Although the livestock population was 0·21 million in 1957, it had dropped to 0·16 million by 1972. However, the subsequent rate of forage production has not shown any sign of improvement. The small decrease in animal population in the Luni Block has been associated with the conversion into crop land of over 20 per cent of the land producing forage since 1963. Thus it can be concluded that the livestock population has remained excessive in relation to the carrying capacity of areas of diminished forage production.

Whereas in the year 1957 the Luni Block had a deficit of over 50 per cent in the demand for forage, the deficit increased to above 59 per cent in 1964, followed by a small decline in 1972 (53 per cent deficit). The data clearly reveal that the disproportionate pressure of the livestock population since 1957 must inevitably have caused serious excessive exploitation of the already shrinking grassland areas (Table 5).

Additionally, socio-religious feelings and deeply engrained beliefs towards animal life often override prudence, and the associated rituals add to the deterioration of the already meagre resources. Thus culling or killing old and useless cattle are regarded as strictly taboo and it was observed in many villages that the useless cattle were an added burden on the grazing and feed resources of the region. Such cattle are fed until they meet a natural death, in spite of the lack of forage and poor economic conditions.

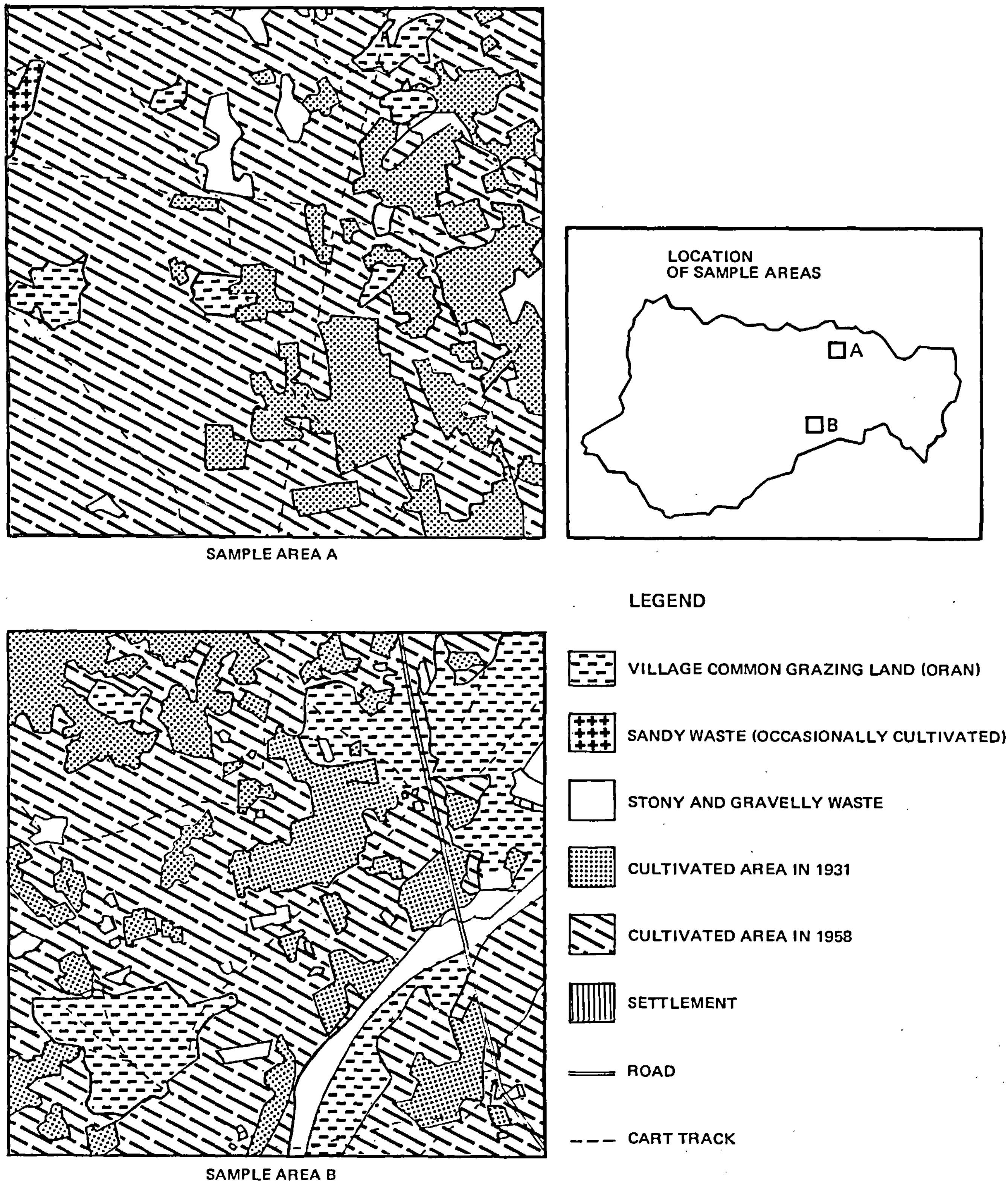


FIG. 4. Land under cultivation in two sample areas, 1931 and 1958

Exploitation of woody vegetation

The over-exploitation of dwindling vegetation resources, which has occurred since the beginning of history, was accentuated during the times of the Princely States and is now critical in arid areas of Rajasthan. Owing to over-cultivation, the regeneration of trees and shrubs is being hampered by the cultivator, for he maintains a minimum tree and shrub population in the cropped fields and uproots

TABLE 4. Land-use changes in the Luni Block in the period 1964–75 (compiled from unpublished annual progress records of land-use data, Jodhpur Tehsil)

Land-use categories	Average extent		1965–65		1968–69			
					Actual area		Change since 1964–65	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Forests	257·45	(0·13)	249·00	(0·13)	263·00	(0·13)	14·00	(5·62)
Hilly area	1161·18	(0·59)	1243·00	(0·64)	1201·00	(0·61)	−42·00	(3·37)
Barren lands	5003·54	(2·56)	7146·00	(3·69)	4295·00	(2·18)	−2851·00	(39·89)
Land other than cultivated	9716·54	(4·97)	6625·00	(3·42)	3928·00	(4·53)	2303·00	(34·76)
Grazing and pasture land	6561·72	(3·36)	7002·00	(3·62)	8127·00	(4·12)	1125·00	(16·06)
Total non-agricultural land	22700·43	(11·61)	22265·00	(11·50)	22814·00	(11·57)	549·00	(2·46)
Other, cultivable lands	2856·09	(1·46)	3579·00	(1·85)	3880·00	(1·97)	301·00	(8·41)
Fallow	33496·90	(17·14)	46895·00	(24·23)	39259·00	(19·92)	−7636·00	(16·28)
Irrigated cropped area	*1682·36*	*(0·86)*	*1268·00*	*(0·65)*	*2384·00*	*(1·21)*	*1116·00*	*(88·01)*
Unirrigated cropped area	*124884·09*	*(68·92)*	*119550·00*	*(61·76)*	*128762·00*	*(65·32)*	*9212·00*	*(7·70)*
Total cropped area	126566·45	(69·18)	120818·00	(62·42)	131146·00	(66·54)	10328·00	(8·54)
TOTAL REPORTED AREA	195419·87	(100·00)	193557·00	(100·00)	197099·00	(100·00)	—	—

the rest. This results in a lowering of woody biomass production. Trees and shrubs are indiscriminately cut, not only from their own fields but also from government-owned and other unoccupied lands. They are used for top-feed for livestock, thorn fencing and the construction of thatched huts.

The annual fuel wood requirement of the population inhabiting the Luni 'Panchayat Samiti' has been estimated at being equivalent to 0·254 tonnes of coal or 1512 kcal/person. The estimated total standing wood crop and the annual wood consumption rates are shown in Table 6. The data reveal an even more dismal picture than that for arid Rajasthan as a whole, whereby the annual wood requirement is very large compared with the total amount available on the ground.

Most of the villagers in rural areas procure firewood free from their own fields or from unoccupied lands. The digging of *phog* (*Calligonum polygonoides*) is a regular vocation and provides employment for a large number of people, while making use of camels not otherwise occupied. The digging of the roots loosens the soil and accelerates wind erosion. *Prosopis cineraria, Capparis decidua* and *Zizyphus-nummularia* are the main victims of this activity. When they are cut at the base, the stocks either coppice through root suckers or the above-ground stump gives rise to a new shoot. The trees assume the shape of shrubs, or prostrate cushioned forms. Large stands of *Anogeissus pendula, Acacia senegal* and *Prosopis juliflora* are cut for making charcoal.

TABLE 5. Livestock numbers, forage requirement and deficit in the Luni Block

Item	1957	1964	1972
Total livestock	208766	177753	162933
Equivalent cattle units	76491·10	77061·80	71634·31
Forage requirement (tonnes)	191227·75	192654·50	179086·27
Forage produced (tonnes)	93942·06	77874·46	83784·13
Deficit (tonnes)	97285·69	114780·04	95302·14
Deficit as percentage of need	50·87	59·58	53·22

Whereas *P. juliflora* is able to regenerate, the other two species fail to coppice. Unless alternative sources for meeting fuel needs are developed, this practice is likely to continue to add to desertification processes in the area.

Foliage utilization as top-feed is a long established practice. *Zizyphus nummularia*, a thorny desert shrub with a wide ecological range, is exploited to its maximum. Every year the plants are cut at ground level. Their leaves, called *pala*, are sun-dried and stored; they have a 15–18 per cent protein content and are used as a concentrate food for livestock. Although this shrub is hardly allowed to achieve full growth, it has a remarkable capacity to coppice through its root suckers. Every year during November and December trees of *Prosopis cineraria* are lopped for top-feed (protein content 13–15 per cent). Lopping has a definite adverse effect on the growth of these trees in the low rainfall zone (below 260 mm) although no appreciable effect has been detected in the higher rainfall areas. Several other species such as *Azadirachta indica, P. juliflora, A. senegal* and *Ailianthus excelsa* are also exploited for top-feed and this has an adverse effect on their productivity.

All the material used for fencing crop fields and building houses and villages is drawn from the dwindling desert vegetation. The quantity required has not been estimated, but it is clear that the erection of fences over a vast area is causing a severe depletion of the woody vegetation. The houses in the rural areas are constructed with mud walls, reinforced with branches of *Capparis decidua, Zizyphus nummularia, Calotropis procera*. The thatched roof is supported by a single straight middle trunk of a tree, usually *Prosopis cineraria* or *Acacia nilotica*, suggesting that one room in a household costs the desert one tree. The framework and the roof are composed of a variety of vegetation. Most of the trees, shrubs and herbs removed are, unfortunately, good sand binders.

People in remote parts of the desert cut most of the *Calotropis procera* and leave them to dry prior

1971–72				1974–75			
Actual area		Change since 1968–69		Actual area		Change since 1971–72	
(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
262·00	(0·13)	−1·00	(0·38)	263·00	(0·13)	1·00	(0·28)
1200·00	(0·62)	−1·00	(0·08)	1208·00	(0·61)	8·00	(0·66)
5355·00	(2·90)	1260·00	(29·33)	5493·00	(2·79)	−62·00	(1·11)
10009·00	(5·23)	1081·00	(12·10)	8369·00	(4·25)	−1640·00	(16·38)
7513·00	(3·92)	−614·00	(7·55)	6294·00	(3·19)	−1219·00	(16·22)
24539·00	(12·80)	1725·00	(7·56)	21627·00	(10·97)	−2912·00	(11·86)
2308·00	(1·21)	−1572·00	(40·51)	2320·00	(1·17)	12·00	(0·51)
23245·00	(12·14)	−16014·00	(40·79)	24940·00	(12·66)	1695·00	(7·29)
1552·00	*(0·81)*	*−832·00*	*(34·89)*	*1556·00*	*(0·79)*	*4·00*	*(0·25)*
139826·00	*(73·03)*	*11064·00*	*(8·59)*	*146606·00*	*(74·41)*	*6780·00*	*(4·84)*
141378·00	(73·84)	10232·00	(7·80)	148162·00	(75·20)	6784·00	(4·79)
191490·00	(99·99)	—	—	197018·00	(100·00)	—	—

to the monsoon. Subsequently, rain water causes rotting, leaving only the long staple fibre. This fibre has a wide variety of uses—for example, in preparing ropes of all dimensions, but its use has caused the disappearance of *Calotropis* from many parts of the arid area. Likewise, another shrub, *Leptadenia pyrotechnica,* is over-utilized for making ropes.

Food habits of desert-dwellers

Plant production in the desert is insufficient to satisfy the requirements of the people and in order to meet this shortage in their diet, they have developed the rather odd habit—luckily, restricted to this region—of collecting huge amounts of air-dried seeds and pods of trees and shrubs for the subsequent preparation of curry. The collection and sale of these products have become regular occupations in the desert. Harvesters concentrate on seeds of *Acacia senegal* (*rumta*), fruits of *Capparis decidua* (*rer*) and pods of the *Prosopis cineraria.* One can safely state that all the fruits of the *Zizyphus nummularia* (*ber, jhadberi*) growing in accessible parts of the desert are harvested for human consumption. SEeds of the grasses *Panicum turgidum, P. antidotale, Cenchrus biflorus, Echinochlos colomum* are mixed with millet, for *chapati* (pancake) preparation, especially during drought years. The grass seeds are supposed to add to the nutritive value of the food. The scale on which seed collection is made throughout the desert region adds to the already serious handicap in the natural process of regeneration of certain species in this inhospitable terrain. This practice of including seed in the human food is so well established that sociologists will have to pay special attention to the problem in planning an educational programme for the illiterate population. In addition, it must not be forgotten that these plant seeds are also consumed by native ants, birds and desert rodents, which adds to over-exploitation of seed resources.

TABLE 6. Exploitation of woody biomass (tonnes)

	1963	1973
Fuel wood requirement	32703	42732
Wood for other requirements	1662	2338
Total stands wood crop on forest, barren and fallow lands	153695	81215

Pressure of rodents and locusts

Rodents occur abundantly, in almost all habitats in the desert and are an important factor in the desertification process. Besides maintaining a perpetual pressure on rangelands, rodents contribute seriously to soil erosion (Prakash, 1976). Out of the seventeen species found, ten are of economic importance. In various desert habitats their number fluctuates from 7·4 to 523/ha, while biomass varies from 0·435 to 2·641 kg/ha. Their dietary demands (1044 kg/ha) are so insatiable that a resident population of *Meriones hurrianae* can consume the total forage production (1100 kg/ha) during the monsoon season, thus leaving nothing for the livestock. Feeding chiefly on seeds, rodents also ravage the sprouting vegetation, lowering its regeneration rate, and strip the bark off 20–30 per cent of the 1–8-year-old saplings planted for dune reforestation. Their burrowing activity is injurious to soil conservation. The merion gerbils alone are estimated to escavate 61500 kg/km^2/d in cultivated fields during summer and 1043800 kg/km^2/d in uncultivated area in north-eastern Rajasthan. Some very successful measures for rodent and pest management have been evolved and standardized by the Central Arid Zone Research Institute.

It is evident from the history of locust invasion of the Rajasthan Desert during this century that vegetation must have been destroyed on a large scale. Moreover, the swarms enter the desert in May and June when, owing to the hot summer weather, the vegetation is already at its weakest. Every piece of green vegetation that is fighting to survive is devoured by locusts, leaving the sandy surface at the mercy of

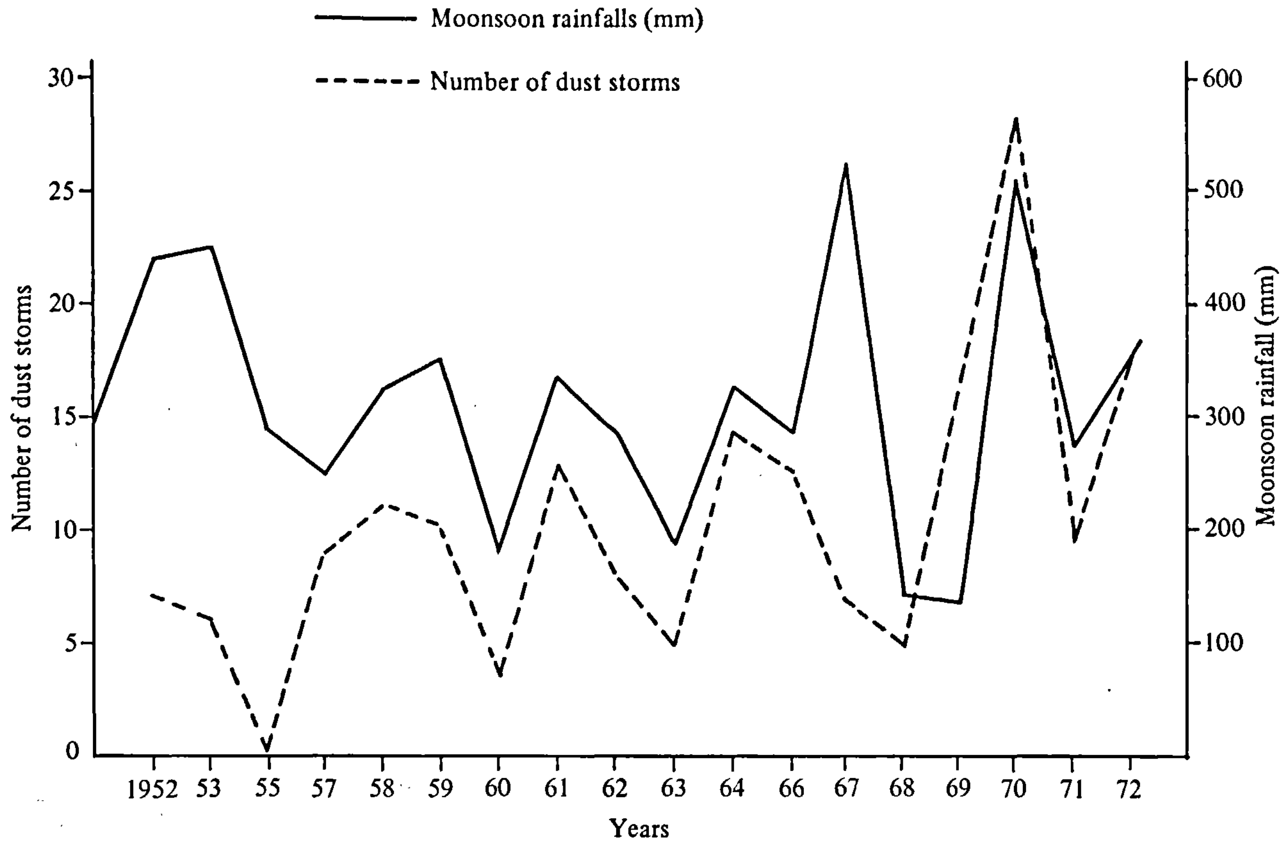


FIG. 5 Relationship between frequency of dust storms and monsoon rainfall

the strong summer winds. It is well known that even large trees are totally defoliated and sometimes even collapse under the sheer weight of the insects. Thus during sixty-five years of this century the desert locust has been a major agent in increasing desertic conditions.

Climatic fluctuations

Rainfall

The five-year mean of annual rainfall in Jodhpur expressed as a percentage of average rainfall for the period 1901–75 indicates that, prior to 1956, although there were fluctuations, in general above-average rainfall conditions seemed to have occurred more frequently (Fig. 1). The below-average conditions that occurred during certain years were of rather short duration. After 1956, annual rainfall shows a decreasing trend, and the below-average rainfall condition that lasted from 1962 to 1971 was rather prolonged—the longest, in fact, to occur between 1901 and 1975. In order to examine the rainfall conditions during the period from 1951 to 1975 more closely, the actual annual rainfall (expressed as a percentage of average) recorded during this period was examined, and this confirmed the decreasing pattern of rainfall from 1955 to 1971, in spite of some fluctuations and a short increasing trend thereafter.

Figure 5 shows the frequency of dust storms and subsequent monsoon rainfall (mm) for 1952–72. On average 8·3 dust storms per year occur at Jodhpur, but this frequency varies considerably from year to year. One interesting result that appears is that, during the year subsequent to a year in which rainfall falls steeply and is very much below normal, there is a sharp rise in the occurrence of dust storms. Thus large dust movement occurs in the year after a drought year. Similarly, during the year subsequent to a year of excessive rainfall, the dust-storm frequency is extremely low. Figure 5 shows that there is a decreasing trend of rainfall in Jodhpur during the period after 1952, and, consequently, an increasing trend in the incidence of dust storms. This has a considerable significance for wind erosion and the desertification process. Drought years and below-average rainfall conditions result in sparse vegetation which, with excessive pressure from livestock and man, causes soil to be blown more vigorously in the subsequent year. This results in the occurrence of a large number of dust storms during the windier months, April to June, of the subsequent year. This appears to be the main cause of the desertification process occurring in the Luni Block.

TABLE 7. Thornthwaite aridity indices of stations near the Luni Block

Period	Mean aridity index				
	Jodhpur	Pali	Siwana	Balotra	Shergarh
1941–50	73	69	81	82	83
1961–70	78	74	77	86	89

TABLE 8. Forage required and forage available in protected pastures subject to indiscriminate grazing by sheep

Pasture type		1965–66	1966–67	1967–68	1968–69	1968–70	1970–71
A. Cultivated							
C.C.–L.S.	(1)	1311·5	916·1	1438·7	1136·0	418·62	The grass disappeared in totality
	(2)	96·6	1427·6	2243·5	2369·3	4164·1	
	(3)	−1214·9	−511·5	−804·8	−1233·2	−3745·5	
C.C.–C.S.	(1)	1757·5	735·5	1162·5	312·5	46·9	
	(2)	129	1441·5	2287·7	2451·7	4235·2	
	(3)	−1627·8	−706·0	−1125·2	−2139·2	−4188·4	
C.C.–C.S.–L.S.	(1)	1672·7	712·6	1193.0	761·2	143·8	
	(2)	213·6	1521·9	2298·5	2555·84	3824·2	
	(3)	−1459·0	809·3	−1105·5	−1794·6	−3680·4	
B. Natural	(1)	1169·6	983·8	2139·0	651·8	159·2	
	(2)	113·6	1478·7	2337·4	3004·8	4780·9	
	(3)	−1056·0	−494·9	−198·4	−2353·0	−4621·7	

C.C. = *Cenchrus ciliaris*. (1) = Forage available (kg/ha).
C.S. = *C. setigerus*. (2) = Forage required by the grazing sheep (kg/ha).
L.S. = *Lasiurus sindicus*. (3) = Surplus/deficiency.

Trends in the aridity index

Based on the mean climatic data, Thornthwaite's aridity index—which expresses water deficiency as the percentage of water need—varies from 73 to 79 in the Block. Table 7 shows the mean aridity index of a few stations close to the Luni Block during the periods 1941 to 1950 and 1961 to 1970. The figures confirm the tendency towards a more arid climate after 1952.

Inherent vulnerability of the landscapes

Vulnerability of soil and land surfaces

As can be seen from the data presented on land resource characteristics (Fig. 2), the land surface in the Luni Block is dominated by plains with light- to medium-textured soils and with either flat or hummocky surfaces. These plains soils have a 6–12 per cent clay content and a 3–8 per cent silt content. Even with partial management organic matter content is low, from about 0·25 to about 0·35 per cent. The soils show weak aggregation and, under the prevailing wind regime, are prone to erosion, leading to the formation of hummocks and dunes.

The plains with medium- and heavy-textured soils are associated with appreciable salinity in the substrata, which, with adverse changes in the hydrologic regime such as those due to interference with the natural drainage system, rise to the surface.

The piedmont plains and hills possess 1–5 per cent and 20–35 per cent slopes respectively and are highly susceptible to sheet and gully erosion.

Vulnerability of natural vegetation

Climato-botanical studies (Satyanarayan, 1963; Champion and Seth, 1968) suggest a xeromorphic thorn forest as the climax vegetation of the region. Barring variations due to salinity or shallowness of soil, this vegetation should have been composed of a *Prosopis cineraria–Capparis decidua–Zizyphus nummularia* community with a preponderance of perennial grasses such as *Cenchrus ciliaris, C. setigerus* and *Lasiurus sindicus.* However, this community is highly susceptible to changes towards an excessive biotic cover.

A long-term study has been carried out at Jodhpur to evaluate certain grazing trends on four types of sown and natural pastures which were subjected to indiscriminate grazing. It was found that an unmanaged number of sheep (Marwari ewes) could totally deplete the land of forage production in six years (Table 8). Sown pastures could withstand the pressure of indiscriminate grazing only for one year. The next year, in all types of pastures, there was a deficit in production. During subsequent years the gap between the production and requirement gradually increased, and finally all the sown perennial grasses were lost. During the course of experimentation several of the sheep died and a large number of abortions occurred—all due to lack of food. The mothers ignored their young as they were unable to suckle them. Sheep maintained in the Central Arid Zone Research Institute (CAZRI) did not develop diseases, but the sheep reared by shepherds died in large numbers from contagious infections, particularly when undernourished. These data indicate that merely protecting the natural ranges is not enough; grazing must follow a controlled pattern.

Grasslands become degraded very quickly through over-grazing. Enclosures to exclude animals were maintained by CAZRI in various bioclimatic zones of the desert biome for a period of seven to ten years. Before protection was provided most of

TABLE 9. Degradation of grasslands (after Kaul and Chakravarty, 1968)

Predominant grass type	Yield (kg/ha)	
	Under exclosure	Unchecked grazing
Lasiurus grassland	369–1607	—
Dichanthium grassland	682–3085	210–290
Cenchrus grassland	300–1743	100–224
Eleusine grassland	127–526	127–157
Sporobolus grassland	194–982	50–194

these enclosures were in a highly regressive stage with very low (50–100 kg/ha) or no production of forage. Optimum production from various grasslands and a higher stage of succession were obtained in these exclosures with some reseeding and soil-conservation methods during the period (Table 9). After ten years, some areas (Ustran) were again left open to large cattle populations without any restriction on grazing. The deterioration was very rapid and most of the established grasslands attained extreme retrogressive stages in a period of two to three years.

Processes of desertification

Recent landscape changes

Currently accumulating evidence suggests that constancy of climate during the Pleistocene Period was the exception rather than the rule in this region. The late Pleistocene was a period of fluctuations within a general condition of moisture deficit. However, the object of the present study is not the natural, climate-induced desertification but the changes to the landscape brought about by the interference of man. Before taking up detailed treatment of the subject, some conditions of the study need to be emphasized. Ideally, the magnitude and rate of change can be gauged from a comparison of an undisturbed area with an area having a known human influence. Unfortunately, such a comparison is not available in the region. The interference of mankind in this area, as for the arid zone as a whole, is so strong and all-pervading that not even the smallest area remains in its pristine form to serve as a reference. This contingency has been overcome in the following way. The study area has small areas of religious holdings where, though grazing is permitted, trees are not allowed to be cut or disturbed. These areas have therefore been utilized in collecting evidence on the composition and density of tree vegetation. Estimates of the shrub and grass vegetation have been obtained from enclosures maintained by CAZRI and other agencies for about twenty years. Features thought to be associated with and resulting from active human interference have been utilized to measure geomorphic and soil-fertility changes. These features include active sand sheets, field hummocks and fence-line accumulations associated with the cultivation and enclosure of fields. Fortunately, during the last forty-five years, which represents the period of greatly increased human activity, more reliable evidence has become available. This includes topographic maps for the years 1931 and 1962, aerial photos for the year 1958, and interpretation of this material in investigations for a basic resource survey at various scales during 1961–62 and in 1976. As aerial photos provide the most detailed, expressive and accurate records, the geomorphic evidence of change is divided into two periods: before 1958 and after 1958.

The changes which have occurred in the landscape are examined here under the following six headings: degradation of natural vegetation; landform changes resulting from increased surface instability caused by cultivation and severe over-grazing; soil-fertility changes ensuing from wind and water erosion processes; surface-salinity increase owing to interference with natural drainage; change of ground-water conditions; and finally the reversal of desertification following the development of ground-water use.

Present status and extent of degradation of vegetation resources

Of the various landscape elements, natural vegetation is the component which has undergone maximum modification. Various land-use units, namely the cultivated lands, including fallow lands, common village grazing lands, as well as wastelands, show strong influence of human activity. As far as the vegetation is concerned the regularly cultivated lands are transformed rather than desertified. These lands produce on average 300–400 kg/ha of grain for human consumption and 1500 kg/ha of residues for the domestic cattle. The cultivated lands also provide top-feed and allow moderate grazing on natural vegetation left after the harvest of the standing crop. Undoubtedly in the process these lands have undergone not only transformation but also depletion of the natural vegetation. The common village grazing lands invariably occur as small pockets of 5–100 ha in the immediate vicinity of the village. These lands are open all year round, and though the cutting of trees is prohibited by convention, trees are cut and carried away. The lands also carry a pond with its catchment area, to meet cattle and human water consumption. The total area occupied by these lands amounts to 63 km^2 or 3·2 per cent of the Block. The wastelands, likewise, are distributed as fragments of inferior land with limitations of shallowness of soil, salinity, or topography. These are wastelands only from the viewpoint of their unsuitability for agriculture and, like the above unit, they may serve as open grazing lands. Their extent within the Block is 93·5 km^2 or 4·7 per cent of the area. Sand dunes, covering 4·09 per cent of the area, are cultivated irregularly and in most years lie fallow and, hence, are predominantly grazing lands (Table 10).

Under the prevailing climate the hills can support a tree community comprising *Acacia senegal–Anogeissus pendula–Grewia tenax* with a crown cover of 45·9 per cent and an above-ground standing biomass of 4750 kg/ha. The associated grass community of *Eleusine compressa–Aristida funiculata*, with 2–3 per cent cover, produces another 280 kg/ha. On open grazing lands the trees are replaced by prostrate bushes representative of this community and *Euphorbia caducifolia* with a total biomass of 100–400 kg/ha. The grassland vegetation is made up of undesirable *Tephrosia purpurea* and *Oropetium thomeaum* with a ground cover of 0·2–0·7 per cent and a standing biomass of 35 kg/ha. On hills that have undergone medium degradation *Capparis decidua–Acacia senegal* communities prevail, with a plant population of 87/ha, crown cover of 3·5 per cent, and standing biomass of 2440 kg/ha.

A similar pattern of degradation is found in gravelly pediments and piedmonts. Ecological investigations show that older alluvial plains with light- to medium-textured soils should support an open

TABLE 10. Natural vegetation and its extent of degradation on various ecosystems in the Luni Development Block

Major land resource units	Potential vegetation	Slightly degraded	Moderately degraded	Degraded	Highly degraded
NON-CULTIVABLE AREAS					
Hills and outcrops	*Acacia senegal* *Anogeissus pendula*	*Acacia senegal*	—	*Euphorbia caducifolia* *Capparis decidua*	*Oropetium thomaeum*
Plant specimens/ha	724	87	—	132·0	—
Crown cover (%)	45·9	3·5	—	5·7	3·0
AGB[1] (kg/ha)	4750	2440	—	1600	1400
Annual yield of pasture (kg/ha)	300	250	—	150	100
Area (%)	negligible	0·1	—	0·4	0·2
Piedmont	*Salvadora oleoides* *Prosopis cineraria* *C. decidua*	*Euphorbia caducifolia* *Zizyphus nummularia*	*Capparis decidua* *Z. nummularia*	*Capparis decidua*	*Oropetium thomaeum*
Plant specimens/ha	213·0	131·0	131·4	197·0	—
Crown cover (%)	10·03	8·4	5·4	4·3	0·5–1·0
AGB (kg/ha)	3500	2900	2080	2450	1500
Annual yield of pasture (kg/ha)	350	250	250	200	100
Area (%)	0·1	negligible	negligible		
Gravelly pediment	*Acacia senegal* *Prosopis cineraria*	*Maytenus emarginatus* *Z. nummularia*	*Euphorbia caducifolia* *Salvadora oleoides*	*Capparis decidua*	*Oropetium thomaeum*
Plant specimens/ha	473·5	395·0	370·0	159·5	—
Crown cover (%)	15·7	11·4	9·5	4·7	0·8
AGB (kg/ha)	2480	3460	6370	1950	1800
Annual yield of pasture (kg/ha)	300	200	150	100	100
Area (%)	negligible	negligible	1·8	0·25	0·05
Saline older alluvial flats	*Acacia nilotica* *Prosopis juliflora*	*Prosopis juliflora*	*Capparis decidua* *Z. nummularia*	*Haloxylon salicornicum*	*Cressa cretica* *Sporobolus marginatus*
Plant specimens/ha	41·0	32·0	40·0	69·0	—
Crown cover (%)	4·5	3·2	2·0	3·1	0·5
AGB (kg/ha)	1970	1330	200	200	50
Annual yield of pasture (kg/ha)	400	250	200	150	150
Area (%)	negligible	negligible	0·2	negligible	0·2
Saline depressions	*Acacia nilotica* *A. jacquemontii*	*A. jacquemontii* *Lycium barbarum*	*C. decidua* *Z. nummularia*	*Suaeda fruiticosa*	*Sporobolus marginatus*
Plant specimens/ha	35·4	154·0	213·0	164·0	—
Crown cover (%)	8·5	7·5	5·0	4·7	5·0
AGB (kg/ha)	1640	1250	840	620	470
Annual yield of pasture (kg/ha)	300	200	200	100	100
Area (%)	negligible	negligible	negligible	negligible	0·4
River bed and islands	*S. oleoides* *Tamarix articulata*	*A. jacquemontii* *Tamarix* sp.	*Tamarix* sp.	*Tamarix erecoides*	*Enchinochlos colonus*
Plant specimens/ha	67·3	175·0	120·0	900·0	—
Crown cover (%)	9·5	8·2	5·0	5·0	2·1
AGB (kg/ha)	2570	1540	540	330	150
Annual yield of pasture (kg/ha)	200	200	150	100	100
Area (%)	negligible	negligible	negligible	1·4	negligible
Sand dunes	*Acacia senegal* *Maytenus emarginatus*	*S. oleoides* *C. decidua*	*M. emarginatus* *S. oleoides*	*A. jacquemontii* *L. barbarum* *Calotropis procea*	*Panicum turgidum* *Cenchrus biflorus*
Plant specimens/ha	228·0	121·0	68·0	282·0	47·5
Crown cover (%)	15·0	5·3	5·3	11·2	3·7
AGB (kg/ha)	4040	1860	1490	570	290
Annual yield of pasture (kg/ha)	800	600	400	250	150
Area (%)	0·8	0·7	0·5	2·5	0·4

Continued overleaf

TABLE 10 *continued*

Major land resource units	Potential vegetation	Slightly degraded	Moderately degraded	Degraded	Highly degraded
REGULARLY CULTIVATED LANDS[2]					
Flat older alluvial plain, light to medium textured soil	*P. cineraria* *Z. nummularia* *C. decidua*	*P. cineraria* *C. decidua*	*C. decidua* *P. cineraria*	*P. cineraria* *Z. nummularia* *Calotropis procera*	*C. decidua* *Tephrosia purpurea*
Plant specimens/ha	390·5	52·0	282·0	390·0[3]	232·0
Crown cover (%)	17·6	4·8	25·4	6·5	5·7
AGB (kg/ha)	7560	850	16810	500	280
Annual yield of pasture (kg/ha)	1600	800	500	350	250
Area (%)					
Flat older alluvial plain with heavy soil	*S. oleoides* *P. cineraria*	*P. cineraria* *S. oleoides*	*C. decidua* *Z. nummularia*	*C. decidua*	*T. purpurea* *Crotalaria burhia* *Indigofera oblongifolia*
Plant specimens/ha	91·0	192·0	547·0	101·5	8000·0
Crown cover (%)	15·3	12·4	6·7	3·5	2·5
AGB (kg/ha)	14590	2050	1840	1360	620
Annual yield of pasture (kg/ha)	1000	600	400	250	150
Sandy undulating older alluvial plain	*Prosopis cineraria* *Tecomella undulata*	*Prosopis cineraria* *M. emarginatus*	*C. decidua* *M. emarginatus*	*C. decidua*	*Tephrosia purpurea* *Crotalaria burhia* *Aerva persica*
Plant specimens/ha	60·0	64·0	302·0	332·0	11000·0
Crown cover (%)	18·4	3·0	9·1	11·8	3·3
AGB (kg/ha)	6470	2420	5510	1670	670
Annual yield of pasture (kg/ha)	130	700	500	300	250
Younger alluvial plain	*Acacia nilotica* *Prosopis cineraria*	*S. oleoides* *P. cineraria*	*Tamarix articulata* *Z. nummularia*	*Acacia jacquemontii* *Lycium barbarum* *P. cineraria*	*Crotalaria burhia* *Cyperus rotundus*
Plant specimens/ha	67·5	51·7	92·4	112·0	5400·0
Crown cover (%)	12·4	7·5	5·4	2·4	3·7
AGB (kg/ha)	4270	1750	1540	330	450
Annual yield of pasture (kg/ha)	700	400	300	200	100

1. Above-ground biomass.
2. Subsequent land resource units have only 2·3 per cent of their area under grazing lands, the rest being under regular cultivation.
3. With degradation number of shrub species or undershrubs increases but total biomass decreases. Low plant density and high biomass with higher species indicate higher successional status.

woodland community of *Prosopis cineraria–Capparis decidua–Zizyphus nummularia* with 390 plants/ha, a crown cover of 17·6 per cent, a standing biomass of 7500 kg/ha, and a ground flora consisting of *Cenchrus ciliaris, C. setigerus* and *Eleusine compressa* with an annual productivity of 1600 kg/ha. None of the present-day common village grazing lands exhibits a predominance of *P. cineraria*; they are dominated instead by the extremely low-value *Capparis decidua.* The ground flora is practically devoid of useful species, with a grazeable biomass yield of 250–350 kg/ha compared with a potential of 1600 kg/ha. The ground flora here is dominated by unpalatable *Tephrosia purpurea.* On alluvial plains with medium- to heavy-textured soils the climax community is made up of *Salvadora oleoides–Prosopis cineraria.* In common village grazing lands under moderate deterioration this community has been degraded to low seral stages dominated by *C. decidua.* True tree forms are generally lacking. Only relicts of potential grass species are to be found. Instead of these, the ground flora is almost exclusively constituated of low-value or unpalatable species like *T. purpurea, Crotalaria burhia* and *Indigofera oblongifolia.*

Sand dunes and very hummocky plains, where the cutting of trees has been restricted, support *Acacia senegal–Maytenus emarginatus* communities with a density of 228 plants/ha, crown cover of 14·9 per cent and a standing biomass of 4040 kg/ha. A 4–6 per cent grass cover yielding 800 kg/ha is also present. In moderately deteriorated situations the communities have been reduced to *Salvadora oleoides–Capparis decidua* communities with 121 plants/ha, crown cover of 5·3 per cent and a standing biomass of 1860 kg/ha. Under severely overgrazed conditions, scrubby communities of *Capparis decidua–Balanites aegyptiaca–Zizyphus nummularia* occur, with 376 plants/ha and a standing biomass of only 370 kg/ha, which constitutes a reduction of over 91·3 per cent of the potential. Within the ground cover, the climax component *Panicum turgidum* has almost

TABLE 11. Geomorphological manifestations due to natural and biotic factors in the Luni Development Block

Major land resources unit	Area (ha)	Areas affected principally by climato-genetic geomorphological processes	Areas affected principally by biotic activities (ha): Before 1958				Since 1958				Areas vulnerable in future	
			Wind deflation	Wind deposition: Undulation	Wind deposition: Thin sheets	Salinity	Wind deflation	Wind deposition: Undulation	Wind deposition: Thin sheets	Salinity	Wind deflation/ deposition (undulation)	Salinity
1. Flat older alluvial plain with light- to medium-textured soils	76250 (39·7)[2]	—	—	—	—	—	—	—	1770 (0·9)	—	1770 (0·9)	—
2. Flat older alluvial plain with light- to medium-textured soils, with hard pan at shallow depth	4430 (2·3)	—	—	—	—	—	—	—	—	—	—	—
3. Flat older alluvial plain with medium- to heavy-textured soils	28320 (14·7)	—	—	—	—	830 (0·4)	—	—	—	1560 (0·8)	—	4030 (2·0)
4. Saline flat older alluvial plain	700 (0·4)	700 (0·4)	—	—	—	—	—	—	—	—	—	—
5. Sandy undulating older alluvial plain	52430 (27·3)	—	6790 (3·4)	29310 (14·8)	16330 (8·2)	—	6790 (3·4)	16699 (8·4)	16330 (8·2)	—	16330 (8·2)	—
6. Sand dunes	9670 (5·0)	9670 (5·0)	—	—	—	—	—	—	—	—	—	—
7. Younger alluvial plain	16540 (8·6)	—	—	—	—	—	—	260 (0·1)	—	830 (0·4)	—	—
8. Saline depressions	870 (0·5)	870 (0·05)	—	—	—	—	—	—	—	—	—	—
9. River beds and islands	2700 (1·4)	2700 (1·4)	—	—	—	—	—	—	—	—	—	—
TOTAL	191910 (100)	13940 (7·3)	6790 (3·4)	29310 (14·8)	16330 (8·2)	830 (0·4)	6790 (3·4)	16959 (8·5)	18100 (9·1)	2390 (1·2)	18100 (9·1)	4030 (2·0)

1. Biotic activities assisted by drought condition prevailing from time to time.
Hills, gravelly pediment and pediment plain do not show significant geomorphological changes due to biotic interferences.
2. Figures in parenthesis indicate percentage of the total area of the Block.

disappeared and has been replaced by annual grasses such as *Cenchrus biflorus, C. prieurii* and several species of *Eragrostis* and *Aristida,* with a biomass of merely 150–250 kg/ha.

Changes in cultivated lands

The cropped lands after harvest support an appreciable number of annual and perennial grasses and shrubs which provide moderate grazing. In addition, arable lands invariably carry a stand of top-feed species which yield nutritious green foliage during acute scarcity periods. *Zizyphus nummularia* is cut and harvested as a valuable feed. *Capparis decidua* bushes are cleared, whereas *Prosopis cineraria* is maintained. This selective treatment, together with the lopping and harvesting of useful species and its consequent effect on regeneration and multiplication, has produced an equilibrium which is 75 per cent below the climax in composition and 60 per cent in standing biomass. Famine leads to mass cutting of trees to barter for food. Nearly 30 per cent of the area carried a far-below-average stand of the useful *P. cineraria.* Among the ground flora, degradation due to severe grazing is very apparent. The potential ground-cover species *Lasiurus sindicus, Cenchrus ciliaris* and *Cymbopogon jwarancusa* have been replaced by low-value *Crotalaria burhia, Cenchrus biflorus, Aristida funiculata* and *Tephrosia purpurea.*

Induced instability of the soil surface

Geomorphicological changes in the Luni Block resulting from prolonged human occupation have been considered in two periods, i.e. up to the year 1958, and afterwards. In 1958, a detailed interpretation of aerial photographs on the scales of 1:30000 or 1:40000 provided an assessment of man-induced changes up to that time. Subsequent surveys, the most recent of which occurred in 1976, have provided a measure of change that has progressively extended the information recorded on the 1958 aerial photographs (Table 11).

TABLE 12. Available nutrient content of soils subject to different processes of sand movement

Name of soil-mapping unit	Number of samples	Available plant nutrient content		
		Organic C (%)	P (kg/ha)	K (kg/ha)
Light-textured soils of flat plains with moderate incidence of wind erosion	42 (mean)	0·16	13·00	138
	Standard deviation	0·05	2·43	62
Light-textured soils of hummocky plains with severe incidence of wind erosion	27 (mean)	0·14	10·76	134
	Standard deviation	0·06	4·63	68
Dunes with severe wind erosion	18 (mean)	0·11	10·72	128
	Standard deviation	0·06	4·96	68

The situation in 1958

Aerial photo interpretation shows that a major part of the Block, principally the northwestern, northern, southwestern and central parts, presents clear manifestations of increased sand activity attributable to human interference. Geomorphic evidence shows that an area of 524·30 km², or 26·4 per cent of the Block, has been covered by a sand sheet 20–200 cm thick, by hummocks about 1 m high, and in places by transverse and longitudinal sand ridges 3–6 m high, thereby turning what were once flat, alluvial plains into undulating hummocky sandy plains.

Less conspicuous features caused by sand mobility, such as fence-line hummocks, are present throughout the flat aggraded plains with light- to medium-textured soils, covering another 762·5 km² or 38·3 per cent of the area.

The slopes of stabilized dunes in the south-east and extreme north-west have been deeply furrowed as a result of accelerated wind erosion resulting from cultivation. This has led to the reactivation and deflation of dunes and the spread of sand to adjoining, formerly flat lands in the form of sand sheets and dune-like accumulations 1–3 m deep around coppiced shrubs.

Changes since 1958

Observations made in 1976 show that, over the span of eighteen years, sand movement leading to a further accentuation of sandy undulations has taken place over an area of 166 km² or 8·3 per cent of the Block.

TABLE 13. Available nutrient content of field and fence-line deposits in areas of moderately eroded, light-textured soils

Site	Number of samples	Available nutrients		
		Organic C (%)	P (kg/ha)	K (kg/ha)
Field proper	42 (mean)	0·15	13·00	138
	Standard deviation	0·04	2·80	48
Fence-line deposit	46 (mean)	0·10	16·7	176
	Standard deviation	0·06	7·6	73

Simultaneously, 67·90 km² have undergone deflation. Observations in Gangana show that recent sand movement has led to an increase of 15–30 cm in the thickness of sand on old fence-line hummocks, increasing their width by 1–2 m. Even greater increases in height (1–2 m) have occurred in the central, south-eastern, and north-eastern areas. This phenomenon has corresponded to an increase in the thickness of sand sheets. The area so affected is 163·3 km², or 8·2 per cent of the total area of the Block. The stabilized dunes in the extreme northwest also show increased sand piling of 1–2 m on the flanks and 3–5 m on the crests.

Water and stream-bank erosion are taking place locally. Accelerated water erosion in the piedmonts and pediments has led to the dissection of the once stabilized dunes by numerous rills and gullies. In the villages along the Luni River, particularly Nimbla, which has an area of 2·60 km², land which was once double-cropped has been turned completely barren as a result of lateral shifting of the river. The village areas here are subject to inflow of fresh river sand on to the old alluvial plains and the consequent formation of sand hummocks.

Reduced soil fertility

Bench-mark surveys could have provided information on the fertility status of soil under a natural, undisturbed ecosystem for comparison with the soils of land under intense human use. In the absence of these surveys, other indices have had to be found. These are:

- measurement of the fertility status of soils subjected to different processes of sand movement, such as the difference between light-textured soils on flat and hummocky plains respectively;
- measurement of the soil fertility of fence-line deposits compared with that of the field proper;
- measurement of the fertility status of soils known to have been managed under conservational farming, compared with the fertility of soils in traditionally managed sites.

Fertility differences are assessed only in terms of the available form of plant nutrients.

Areas undergoing severe erosion, with thick deposits of loose sand, have appreciably lower values of nutrients, particularly of organic carbon and phosphorus (Table 12). This clearly shows that wind erosion and sand movement induced by human activity are leading to a perceptible decrease in nutrients. Data for areas which have been subjected not to massive sand movement, but to movement occurring largely within the bounds of fields or within groups of fields, show that fence-line depositions are somewhat richer in phosphorus and potassium than in the main field (Table 13). Organic carbon, however, is lower in these areas, apparently due to the fact that organic residues are lighter and have been carried even further by wind. The results again show that continuous arable farming is contributing to deterioration of soil productivity. Improved farming techniques and the use of shelter belts and stubble mulch for a period of twenty years have led to an improvement in soil fertility (Table 14).

The soils of the Luni Block are characterized by a well-developed zone of calcium carbonate concre-

TABLE 14. Comparative fertility status at ideally managed and conventionally managed sites

Site	Number of samples	Available plant nutrients content		
		Organic C (%)	P (kg/ha)	K (kg/ha)
Ideally managed	28 (mean)	0·17	10·78	191
	Standard deviation	0·03	2·04	53
Conventionally managed	14 (mean)	0·14	9·32	174
	Standard deviation	0·07	4·53	72

tions at depths of 30–120 cm. The degree of development of this zone is variable and soil mapping in 1967 showed that a strongly developed zone at a depth of 50–60 cm occurs over 254 km^2 or 12·8 per cent of the Block. In addition to this, over an area of 44·3 km^2, the pan is so strongly indurated that even roots of tough perennial species cannot penetrate. Soil depth in this area has already been reduced to a significant degree by wind erosion. Because of a lack of quantitative data, it is not possible at this stage to indicate the present contribution of human interference in accelerating the process, but a situation has developed wherein every centimetre of soil lost reduces the agricultural productivity of these lands, which is already inferior to that of adjacent lands with deeper soil cover. The problem is particularly serious in the 44·3 cm^2 area mentioned above.

Changes in salinity conditions

With the onset of the major arid phase about 40000 years ago, the deterioration of fluvial systems and massive sand movements caused disorganization or burial of former streams. This activity in the far eastern part of the Block led to a segmentation and the formation of an inland basin across the course of the Agaria Nala and other stream channels in the area. Over the years, the increasing aridity has turned these into saline depressions. This transformation had already begun before the onset of human activity. Man contributed to this process by the construction of village ponds across the remnant drainage channels, the extension of the cultivated area to cover the courses of small drainage lines, and lately by constructing the Summair Samand Canal across the former channels. All these activities have resulted in a rising water-table and increased salinization. Salinity due to the construction of tanks has developed between Lolawas and Bhetnada and around Kharabera Bhistan and Kharabera Patarobas. Evidence shows that, prior to 1958, 8·3 km^2 of once-productive lands had been salinized beyond use. Since 1958 salinity has spread laterally from the affected areas, turning fertile lands in parts of the villages of Nimbla, Moklasar, Lolawas and Bhetnada into saline wastes. During this period an additional area of 15·60 km^2 has been thus affected, and it is feared that, if the situation continues, the problem could spread to another 40·30 km^2.

Changes in water resources

Surface water is collected from small catchment areas of 10–50 ha and stored in ponds, or *nadis* as these are locally called, with a capacity in most cases of 30000–70000 m^3. In an average rainfall year, water lasts in these ponds for 3–6 months; there are one or two such ponds in each village. After the *nadis* dry up, fresh seepage water is extracted through shallow holes dug in the immediate vicinity of the pond. For the rest of the year, the villages rely on deep-dug wells, the water of which is invariably brackish to saline. Irrigation water is obtained entirely from deep wells largely concentrated in the younger alluvial plains of the Luni and its tributaries. The irrigated area of the Block in 1974–75 was 15·56 km^2, or 0·79 per cent of the area (Table 15).

Surface-water resources

Observations were made during the years 1966 and 1976 on the capacity of seventy-three village ponds. The results show that, after a ten-year period, 19·2 per cent of these ponds had a reduced capacity, 13·7 per cent had increased capacity and 67·1 per cent had no change in capacity. These ponds silt up rapidly and observations indicate that dredging by the villagers themselves or through the famine relief fund is quite effective, but is not carried out sufficiently often.

Ground-water resources

Observations were made on deep wells in 1966 and 1976 to compare the variation of hydrological parameters. The results are given in Table 16. The data clearly indicate that as a result of increased exploitation of ground water from 1968 to 1976 there has been a significant deterioration in water resources. The discharge potential of most of the wells has fallen greatly, except in 4·8 per cent of the cases where further deepening has allowed a greater discharge. Water qulity also shows a decline, with a much greater proportion of wells falling in the highly saline category with an electrical conductivity of over 6 mS. Static water-table observations present a more varied picture, with 33·6 per cent more wells falling in the category of less than 6 m depth to the water-table, and 16·4 per cent more wells in the category of more than 12 m to the water-table. The rise in the static water-table is entirely due to the unprecedented occurrence of the closely spaced wet years of 1973 and 1975, which led to a sharp rise in water level in wells situated along natural drainage lines. The data on the extent of exploitation are even more revealing. The degree of exploitation is based on the length of time during which wells can supply water. The results

TABLE 15. Water consumption in the Luni Block (in million m^3)

Purpose	1966	1974	1976
For human and livestock consumption	1·65	1·64	2·49
For irrigation	4·82	5·92	9·54
TOTAL	7·47	7·56	12·03

TABLE 16. Changes in underground water resources

Water resource	1966	1976	Change since 1966
Discharge potential of wells			
Percentage of wells having a discharge potential of:			
1 litre/s	15·8	61·9	+46·1
2–5 litre/s	77·9	28·5	−49·4
5–10 litres/s	6·3	4·8	−1·5
11 litres/s	—	4·8	+4·8
Quality of well waters	7·5	17·1	+9·6
Percentage of area having salinity of underground water of:			
2 mS			
3–6 mS	62·5	32·0	−30·5
7 mS and above	30·0	50·9	+20·9
Static water-table	33·6	67·2	+33·6
Percentage of wells having static water-table below ground surface of:			
6 m or less			
7–12 m	58·8	8·8	−50·0
12 m and above	7·6	24·0	+16·4
Extent and degree of exploitation	71·8	—	−71·8
Percentage of area:			
Unexploited			
Underexploited	4·2	11·6	+7·4
Moderately exploited	17·8	11·6	−6·2
Over-exploited	6·2	76·8	+70·6

show that in a period of only ten years the area where ground water has been over-exploited has increased from 6·2 per cent in 1966 to 76·8 per cent in 1976. Thus, from a level of under-exploitation, the Luni Block has in just ten years entered one of over-exploitation. The catastrophic consequences of this progressively increasing exploitation can be only too well imagined.

Desertification hazard in the Luni Block

The foregoing account shows that the high and ever-increasing human pressure and the dense livestock population have had a profoundly adverse effect on the natural landscape in the Luni Block. There is not one area that does not bear the imprint of human or livestock activity—be it land under arable use, which occupies by far the greatest area, or the small, scattered areas of open grazing land. If any variation is seen in the intensity of this pressure or of its consequences it is not because of any selectivity of human pressure, but because of the inherent instability of the landscape.

The dominant soil in the Block is light-textured. Highly intensive arable farming in an arid environment, and the need to keep the lands as clear as possible of natural vegetation so as to conserve moisture and improve the chances of success of a crop in the ensuing rainy season, have led to instability of the soil surface. This situation has interacted with the strong wind regime of the region and accelerated the process of wind erosion. As a result, 26·4 per cent of the area which was once a relatively flat plain has been converted into a plain with characteristic hummocks. The change has been accompanied by a significant loss of soil fertility and reduced soil depth above the layer of carbonate concretions. Human effdorts to control the problem through the construction of barrier fences and ploughing back of deposited sand have so far had little success, simply because the efforts are inadequate in face of such a huge problem. The increase in the area under cultivation has also interfered with natural drainage and has led to a rise of highly saline water close to the surface in a particularly vulnerable area in the extreme eastern portion of the Block. This has resulted in the salinization of 40·3 km^2. The picture for grazing lands is no brighter. Although socio-religious control has to an appreciable extent checked the loss of perennial vegetation, the grazing value of the lands has been diminished to 10–15 per cent of the potential. Sloping lands on gravelly pediments and hills are also beset by the severe problem of water erosion.

The synoptic map of desertification hazards in the Luni Block (Fig. 6) shows that 20·11 per cent of the total area of the Block is arid (Table 17). About 48·80 per cent of the area is of high-to-medium vulnerability to desertification processes. About 92·50 km^2 or 4·65 per cent is highly vulnerable, owing to the enlargement of settled areas. Dunes, sandy cover, shifting sand and hummocks affect about 645·0 km^2 (32·43 per cent of the area), placing this area also in the high-to-medium vulnerability category. The remainder of the high–medium vulnerability area is affected by water erosion hazards together with dunes or salinity or with both. Of the total area of the Block 51·20 per cent is of medium-to-slight vulnerability to desertification. Some regions are affected either by water erosion (1·6 per cent) or by poor germination of seeds (7·4 per cent) or by both (2·6 per cent).

The arid zone in the Luni Block is affected by a relatively high density of human and livestock population. Desertification hazard is very high in the north-west and in an elongated belt in the south-west of the semi-arid zone. The area of high desertification hazard constitutes 590 km^2 (29·66 per cent of the total area). Another 2·13 per cent of the area is classed as of slight desertification hazard, in which

TABLE 17. Intensity of desertification hazard in the Luni Block

Units	Area (in km^2)	Percentage of total area of the Block (1989 km^2)
Desert and subdesertic zones		
1. Desert	—	—
2. Arid zone	400·00	20·11
3. Semi-arid zone	1589·00	79·89
4. Subhumid zone	—	—
Natural vulnerability		
1. High to medium	971·50	48·84
2. Medium to slight	1017·50	51·16
Desertification hazards		
1. High	590·00	29·66
2. Medium	1356.80	68·17
3. Slight	42·20	2·12

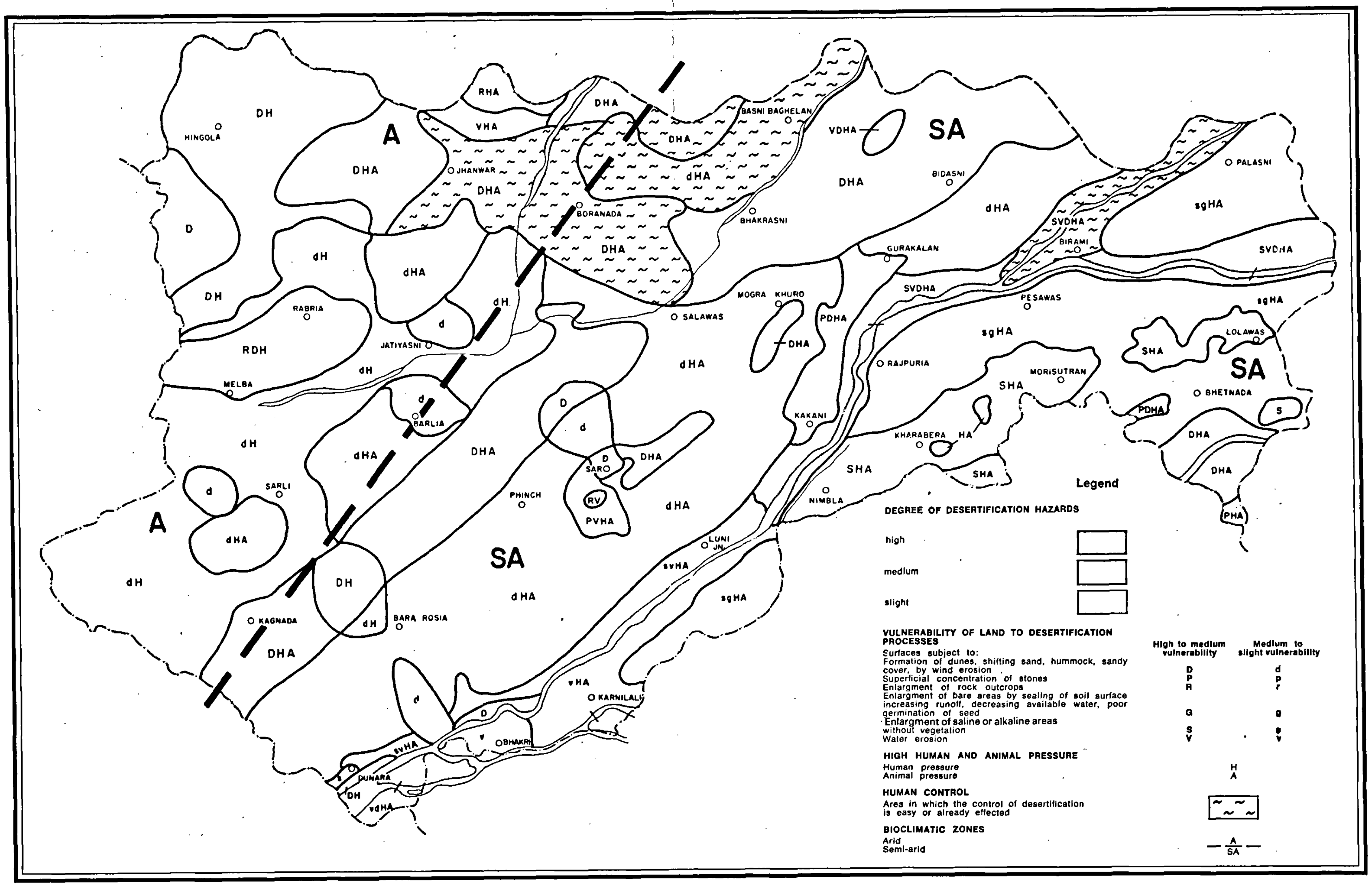


FIG. 6. Synoptic map of desertification hazards in the Luni Block (1:126720), Jodhpur, India

TABLE 18. Areas of Block (as percentages) with different degrees of sensitivity to desertification as experienced through water resources, vegetation and soil fertility

Degree of sensitivity	Water resources	Vegetation resources	Soil fertility
High	10·7	9·2	4·0
Medium	68·1	28·6	31·3
Low	21·2	62·2	64·7
	100·0	100·0	100·0

either the figures of livestock and human populations are not available, or their relative pressure is very low. It has been estimated that 223·80 km^2 or 11·25 per cent of the area can be managed easily through irrigation from ground water, which is already in process. However, it is essential that long-term management takes account of the replenishment of ground-water resources, as all water resources are being depleted and salinity is gradually increasing.

In addition, as discussed above, it has been possible to make observations on other manifestations of the desertification process: the change in water resources, the loss of soil fertility and the degree of deterioration of natural vegetation. The data obtained on these aspects have been interpreted in terms of the sensitivity of the region to the particular factor concerned. Both surface and ground-water components have been considered in the discussion on sensitivity to deterioration of water resources. In the case of surface water, the water-storage capacity has been considered, while in the case of ground water, degree of exploitation, salinity, and static water level have been considered. Each factor was given a score and the totals were used to obtain an index of sensitivity for any particular area. The same system was used for vegetation, where the loss of standing biomass and the change in the composition of grazeable biomass productivity were pooled together to obtain a measure of sensitivity. With respect to soil fertility, inferred loss in soil organic matter, phosphorus, and potassium were considered. The relative areas within each category of sensitivity for the three chosen parameters are given in Table 18.

Recommendations

Population control

The Luni Development Block sustains a relatively high density of population (48 persons/km^2), and in addition to its high growth rate in the past (158 per cent during 1901–71), it exhibits a potential for a continued growth rate in the future. This warrants the immediate introduction of family-planning measures to reduce the widening gap between birth and death rates and to avoid a further population explosion.

Social education and transfer of technology to the field

By and large, the people have remained subjugated, superstitious, illiterate, caste and faction-ridden, traditionalist, and laden with innumerable taboos. The adoption of more modern agricultural and other developmental technologies, family-planning measures, etc. has made only small headway. It is therefore essential to formulate and execute an educational programme on a mass scale stressing the fullest possible participation of communities in the programmes of family planning and the adoption of more modern developmental technologies. Ethno-agricultural studies are required fully to understand and evaluate the age-old proven local practices in agriculture and animal husbandry.

It should be noted that the launching of Operational Research Projects by the Indian Council for Agricultural Research (ICAR) on topics such as arid-land management, drip and sprinkler irrigation, etc, are successfully setting examples for combating the processes of desertification. Mention should also be made of the National Programme for Rodent Pest Management launched by ICAR, and the planting of trees on a country-wide scale.

Animal husbandry and nomadism

A rapid increase in the livestock population, despite a substantial reduction in the extent of grazing lands, has been leading to the over-exploitation of grazing lands and the partial starvation of livestock. This warrants the immediate introduction of rangeland management and development on scientific lines, as well as action on a concerted basis for the genetic improvement of livestock with an emphasis on quality rather than quantity. At present, the forage and stock water resources often dwindle, and people turn to nomadism. The nomads have been aggravating the situation further by the indiscriminate use of water and vegetation resources, leading to a further accentuation of desertification. The visits of nomads are nowadays most unwelcome for the settled population. As the economy of the nomads has already suffered a heavy decline, their immediate sedentarization is necessary.

Rational land use

Owing to the lack of a diversified resource base (the development of which is essential), the increasing population has overcrowded the already over-exploited agricultural land. This has led increasingly to the cultivation of marginal lands and consequently to a lower production per unit area and a substantial reduction in rangelands. It has been estimated that at least 21–24 per cent of the lands presently cropped should be converted to pastures and used for other silvo-pastoral purposes to ensure continuous production and resource conservation. About 58 per cent of the area is covered by loose sandy soil, the stabilization of which is important for the production of grass and afforestation. Techniques of sand-dune stabilization by the use of proper mulching, sylvicultural nursery techniques, and grass establishment are fortunately available.

Afforestation, including the establishment of shelter belts and wind-breaks to provide mechanical obstacles to reduce wind velocity and deflect it upwards, is very necessary to arrest the process of desertification. An earlier recommendation for the creation of a green belt approximately 400 miles long and 5 mile wide, parallel to the international border, establishing shelter-belts along selected roads and railway lines, running transversely to the direction of winds, urgently needs to be carried out.

Harnessing solar and wind energy

The harnessing of solar energy is essential to provide the inhabitants with an alternative source of energy and to protect the woody biomass of the desert. The arid region of Rajasthan receives ample radiation from the sun, with an annual average of $5{\cdot}715 \times 10^{21}$ J. Solar energy can be utilized for a number of rural applications such as the pumping of water, solar drying, solar desalination, solar cooking and solar lighting. Similarly, the wind-speed data are encouraging for the introduction of windmills, which can pump water during nine months of the year. The use of solar and wind energy has been amply demonstrated at CAZRI in Jodhpur, and the successful manufacture of implements such as solar water heaters, solar cookers, solar driers, and sail-wing type windmills provides a lead in this direction. Furthermore, the utilization of solar energy for industrial purposes can assist in overcoming the existing gap in the availability of other forms of conventional energy in the Rajasthan Desert.

Development of water resources

The most important and obvious factor limiting the development of the arid zone is the serious lack of water in the region. Concerted attempts are to be made to bring in water from adjoining areas. Careful planning is needed to utilize run-off for aquifer recharge. Progress in the exploitation of ground water in the Rajasthan Desert has been satisfactory, but optimum utilization has yet to be generally attained. There is a need for cheap and adequate power for the effective exploitation of ground water and this requires the attention of engineers and technologists. In many cases the ground water is unsuitable for drinking and even for crop production. Desalination and the use of brackish water present a problem which must be solved by teams of specialists.

Relief planning

Often in the grip of famine, the Luni Block exhibits a low productivity response to technical inputs such as improved seeds, fertilizers and pesticides. However, the farmers in the Luni Block pay as much for these items as do the farmers in the irrigated or assured rainfall areas which allow two or three crops a year. Credit facilities, interest rates and food-grain buying prices are almost uniform throughout the country, although the returns from investments in the desert are very much lower and highly uncertain from year to year. This problem has not been considered, and warrants planning. Huge sums of money have been spent from time to time on distress, famine-relief measures, but it is now well recognized that the resources allocated to short-term relief have rarely been organized to yield long-term benefits. Relief allocations have sometimes been too liberal or too conservative, and the provision of central assistance exclusively through the wage component of relief projects has restricted the productive use of relief employment. As the states were unable to invest other complementary relief funds, a large number of water-supply, road, and minor irrigation works were left uncompleted.

Reform must involve essentially the integration of development and relief planning in areas usually affected by drought. Specific allocations for statistically probable events should be explicitly assigned in formal plans and in the budget. Allocations for such 'crisis management' should be based on critical historical reviews, and priorities should be laid down after formulating fairly reliable estimates.

International collaboration

The arid zones cut across international boundaries. The entire area stretching from the Sahara to the Thar appears to be meteorologically homogeneous, and the physiographic and anthropogeographic conditions of the region are often comparable. It need hardly be stressed that experiences gained in one area can, with suitable modifications, be utilized in similar areas elsewhere in the region. This warrants frequent meetings between scientists engaged in research, to provide a free interchange of research experience.

In the light of the magnitude of the problem, different development measures may have to be taken at different locations, irrespective of international boundaries. The formulation of a central body with the assistance of international organizations like UNEP, incorporating membership of the different countries affected by the threat of desertification, will be of great benefit in ameliorating the desertified environment. Such a central body should be in a position to conduct a planned documentation of research, an intensification of research activity, and the transfer of management and technology between the various affected countries.

Intensification of research

In view of the multifarious problems outlined in this study, the importance of research leading to the development of the Rajasthan Desert can hardly be overstressed. In the light of the complexities involved in understanding the nature of the processes leading to the spread of desertification, an immediate intensification of systematic multidisciplinary research on a concerted basis is warranted. The strengthening of research activities should preferably be undertaken at institutions where the infrastructure facilities already exist.

Appendix I. Ecosystem resources, their present potential and proposed management practices

Major land resource units	Hills	Piedmont plains covered with sand	Gravelly pediments	Flat, older alluvial plain: Light- to medium-textured soils	Flat, older alluvial plain: Light- to medium-textured soils; hard pan at shallow depths	Flat, older alluvial plain: Medium- to heavy-textured soils	Saline older alluvial flats	Sandy undulating older alluvial plains	Sand dunes	Younger alluvial plains	River beds and islands	Saline depressions
Area: ha	1380	1350	4260	76250	4430	28320	700	52430	9670	16540	2700	870
%	(0·7)	(0·7)	(2·1)	(38·3)	(2·2)	(14·2)	(0·4)	(26·4)	(4·9)	(8·3)	(1·4)	(0·4)
Relief (m)	25–90	10–20	5·6	1–2	0·5–1	0·5–1	0·25–0·75	0·5–6	5–25	1–1·5	0·75–1	0·25–0·75
Rock type	Sandstone	Sandstone	Sandstone	Alluvium underlain by granite and other volcanic rocks	Volcanic rocks	Alluvium underlain by granite	Younger alluvium	Alluvium underlain by granite and other volcanic rocks	Aeolian deposits underlain by granite	Alluvium underlain by granite and other volcanic rocks	Younger volcanic rocks	Older alluvium and granite
Depth to water-table (m)	21·2	17·5	2·1	3·5–30·1	30·8	2·5–7·4	—	3·5–4·40	15·7	0·6–5·0	—	—
Discharge potential (litres/s)	2	3		3	2	9	—	3	1	6	—	—
Water quality (EC, in mS)	0·4	0·4	18·8	0·9–14·2		4·2–18·3	—	0·8–27·5	—	1·4–22·4	—	—
Physiognomy of the natural vegetaion and dominant species												
Trees	*Acacia senegal Salvadora oleoides*	*Salvadora oleoides Prosopis cineraria*	*Euphorbia caducifolia Acacia senegal*	*Prosopis cineraria*	*Prosopis cineraria*	*Prosopis cineraria*	*S. oleoides P. cineraria*	*P. cineraria Maytenus emarginatus*	*M. emarginatus Acacia senegal*	*P. cineraria A. nilotica*	—	—
Shrubs	*Capparis decidua*	*Capparis decidua Leptadenia* sp.	*Capparis decidua Maerva ovalifolia*	*Capparis decidua Zyziphus nummularia*	*Capparis decidua*	*Capparis decidua Zyziphus nummularia*	*Capparis decidua*	*Capparis decidua Zyziphus nummularia*	*Lycium barbarum Leptadenia A. jacquemontii*	*A. jacquemontii Lycium Calotropis* sp.	*Tamarix erecoides*	*Prosopis juliflora*
Herbage	*Lepidagathis* sp. *Fagonia cretica*	*Crotalaria burhia Tephrosia purpurea*	*Fagonia* sp. *Oropetium thomacum*	*Crotalaria burhia Aerva persica*	*Pnephalium indicum Tephrosia purpurea*	*Tephrosia purpurea Fagonia cretica*	*Tephrosia purpurea*	—	*Crotalaria burhia*	*Crotalaria burhia Tephrosia Aerva persica*	*Cyperus rotundus*	*Cressa cretica Sporobolus* sp.
Estimated cover (m^2)	573·69	1026·64	951·48	475·53	93·034	515·96	1527·36	299·76	1096·92	238·64	500	7·5
Cover of perennial vegetation (%)	5·74	10·27	9·52	4·76	0·93	5·96	15·27	3·00	10·97	2·39	5	7·5
Above-ground biomass of perennial species (kg/ha dry wt)	1604	3551	6372	843	1136	382	14596	2416	4214	329	330	1607
Above-ground biomass of annual herbage species (kg/ha dry wt)	100–150	200–300	100–300	816	—	300–600	—	500–1300	600–1300	500–1400	—	300–600

Appendix I *continued*

Major land resource units	Hills	Piedmont plains covered with sand	Gravelly pediments	Flat, older alluvial plain: Light- to medium-textured soils	Flat, older alluvial plain: Light- to medium-textured soils; hard pan at shallow depths	Flat, older alluvial plain: Medium- to heavy-textured soils	Saline older alluvial flats	Sandy undulating older alluvial plains	Sand dunes	Younger alluvial plains	River beds and islands	Saline depressions
Soil type	Almost devoid of soil	Regosol	Lithosol	Light brown sandy	Pan soil	Grey brown earths with some dark brown sands	Solonetz	Light brown sandy Hummocky	Regosol	Regosol	Regosol	Solonchak
Textural group	Gravel or bare rock	Fine sand	Gravelly sand	Fine sandy to loamy sand surface	Loamy sand	Loamy fine sand to fine sandy loam surface	Heavy fine loamy	Fine sandy	Fine sandy	Medium sandy	Medium sandy	Loamy and heavier
Soils depth (cm)	Not applicable	Variable	15–40	Often 90–120	30–60	70–110	Over 150	Over 150	Over 150	Over 150	Variable	Over 150
pH	Not applicable	Often over 8·0–8·5	8·0–8·3	7·9–8·7	8·0–8·6	7·9–8·2	8·4–8·9	8·3–8·5	8·0–8·5	8·1–8·7	8·3–8·9	8·1–8·6
Available soil moisture (mm)	Not applicable			72·5	52·7	95·2	220 but some water intake problem	56·5	32·9	—	—	—
Total soluble salts (EC 1:2, in mS)	Not applicable	0·16	0·24	0·22	0·25	0·26	0·28–2·83	0·18	0·16	0·28	0·28–2·6	0·78–6·4
N.P.K. content of		(0·06–0·15)	(0·09–0·19)	(0·15–0·63)	(0·2–0·48)	(0·3–0·5)	0·2	0·11–0·18	0·1–0·21	0·17–0·32		
organic matter (%)[1]		(0·10)	(0·15)	(0·25)	(0·28)	(0·37)		(0·16)	(0·14)	(0·25)		
Available P (kg/ha)[1]		(7–9)	(5–7)	(6–14)	(4–14)	(6–12)		(5–11)	(5–10)	(5–8)		
		(8·0)	(6·0)	(9)	(10)	(10)	(6)	(8)	(7)	(7)		
Available K (kg/ha)[1]		(133–266)	(108–204)	(133–374)	(133–291)	(224–481)		(125–299)	(133–266)	(108–232)		
		(191)	(159)	(237)	(187)	(299)	(514)	(212)	(191)	(178)		
Density of population (habs/km²)	55	49	34	46	48	40	66	23		47	28	66
Active population (%)	35·48	26·43	43·42	33·66	34·62	38·19	31·98	36·66		33·04	40·86	36·52
Occupational distribution of earners (%):												
(a) Cultivator	84·42	88·86	95·15	86·43	76·07	83·77	84·07	96·17		73·49	100·00	84·88
(b) Agriculture labour	6·43	5·34	3·64	6·07	8·85	7·02	5·22	1·92		11·07	—	7·56
(c) Livestock, forestry	2·73	0·70		1·07	2·62	4·38	0·75	—		3·36	—	2·22
(d) Household industry	2·34	1·39	—	1·07	1·64	0·88	1·49	0·38		2·01	—	2·91
(e) Other than household industry	0·58	0·70		0·36	1·31	1·32	0·75	0·38		2·35	—	0·58
(f) Construction	—	—	—	0·36	0·33	—	0·25	—		—	—	0·58
(g) Trade and commerce	1·17	0·46	—	0·71	1·97	0·88	1·99	—		1·68	—	0·58
(h) Transport and storage	0·19	0·23	—	0·71	3·28	—	1·00	0·38		2·68	—	1·16
(i) Other services	2·14	2·32	1·21	3·22	3·93	1·75	4·48	0·77		3·36	—	1·16

Annual requirement of wood for fuel purposes (tonnes)	1821	2738	479	10643	7394	1253	6859	2091	4916	243	395
Annual requirement of wood for purposes other than fuel (tonnes)	108	162	28	631	438	74	407	124	292	14	23
Land use (%)											
(a) Forest	—	—	—	—	—	0·188	—	—	—	—	—
(b) Irrigated	0·1	0·8	0·012	0·275	1·246	0·01	0·495	—	56·02	—	—
(c) Unirrigated	69·6	59·7	42·471	68·968	63·797	63·448	71·014	66·810	59·382	69·041	50·968
(d) Tree groves and orchards	—	—	—	—	1·331	—	—	—	—	—	—
(e) Fallow land	22·0	18·5	27·002	21·752	21·957	15·997	17·801	24·397	22·205	25·072	34·017
(f) Cultivable waste	3·4	7·8	1·858	4·126	2·071	9·948	4·981	7·120	2·811	5·382	5·527
(g) Area not available for cultivation	4·6	12·9	28·055	4·877	9·595	10·405	5·706	1·671	9·998	0·503	9·487
Livestock (number/100 ha)											
(a) Cattle	32	33	46	46	41	173	42	15	25		59
(b) Buffaloes	4	8	5	6	6	25	7	2	2		8
(c) Sheep	12	16	45	39	28	69	33	31	21		1
(d) Goat	29	14	41	50	45	120	57	23	22		19
(e) Camels	2	2	8	5	4	2	4	3	1		1
TOTAL	79	73	145	146	124	389	143	74	91		88
Mammalian fauna (rodents) (kg/ha)	0·8					1·82			0·45		

1. Range of values (above) and mean value (below).

Appendix II
Technology and desert development

There is a growing realization that the improvement of the desert environment is not solely a technological challenge; it is a challenge to all desert dwellers concerning their capacity to implement known technologies, their co-operativeness in measures for conservation, and their willingness to accept a disciplined use of limited resources for gains which may be largely reaped by succeeding generations.

Resource inventory through integrated surveys

Some of the technologies are the responsibility of government, such as integrated surveys directed towards the identification of problems and the preparation of resource inventories of defined regions. The multidisciplinary surveys undertaken by CAZRI involve aerial photo interpretation and have provided accurate assessment of soil, vegetation, land capability, water resources, extent of erosion, settlement patterns, transportation, etc., over an area of 45269 km^2 located in the Rajasthan, Haryana, Gujarat and Mysore states of India.

Grasses in soil conservation

Most of the problems of land deterioration and the accentuation of desert-like conditions are due to the pressures of human population and livestock. It has been experimentally found that simple exclosure of livestock can double the forage yield of desert rangeland over a period of three years. Such exclosure followed by management practices such as weed control with herbicides and the nominal use of fertilizer (22·5 kg/N/ha) can give an increase in forage yield of 20–70 per cent. Forage yield can be further increased on shallow soils in undulating topography by contour furrowing. It has been proved beyond doubt by experiments conducted at CAZRI that a grazing schedule with fixed carrying capacities and utilization thresholds in various condition-classes of grasslands (such as excellent, good, fair and poor, based on botanical composition), can provide a sustained production of forage over an indefinite period. Unrestricted grazing causes a deterioration in vegetation cover, leading to exposure of the soil and accelerated erosion, largely by wind.

Agriculture and erosion problem

While the prevention of indiscriminate grazing comes under the responsibility of the desert dwellers, they are also responsible for avoiding the extension of cultivation without regard to the land's capacity. About 40 per cent of the land in Western Rajasthan is being cultivated today—even the dunes have not been spared. While it is well known that marginal and submarginal lands should not be cultivated, the technologies related to conservational farming must be widely adopted in the arid and semi-arid areas. It has been found that where stubbles of 45 cm or more in height are left in the field, soil loss is reduced by about 30–50 per cent; often this is associated with a marginal increase (*c.* 10 per cent) in the yield of the subsequent pearl millet crop. Similarly, cropping between strips of grass plots (crop to grass ratio, 6:1) increases the crop yield by 6–17 per cent. Legumes can be grown beneficially when intercropped with grasses. In arid ecosystems the introduction of grasses in the cropping pattern offers various advantages, such as reduced erosion, improved soil condition, and a reasonable return when the crop fails in the event of drought.

Mitigation of environmental constraints

Among the diverse constraints on plant production in the arid areas, frequent drought is the most serious problem. In some years when the rains are very late (after the 20th of July) it has been found advantageous to grow certain legumes such as *Cyamopsis tetragonoloba* (*guar*), which require about half the water needed for pearl millet, which is grown most extensively in Western Rajasthan. While this technology has been adopted by many farmers, the simple drought-evasion technique of transplanting pearl millet has not gained acceptance. The plants are raised in nurseries at the beginning of July, followed by transplantation at the time of suitable rains—even up to the middle of August. Yields of around 2600 kg/ha for the variety HB 4 have been produced in experimental fields. In drought years, certain minor millets such as *Panicum miliaceum* and *Setaria italica*, which complete their life cycles within 44–45 days, have been found to have considerable promise. Similarly, in rain-fed semi-arid areas, soil fertility conducive to optimum plant vigour helps to avoid the adverse effects of short droughts. These gains can be further consolidated by the adoption of control measures for rodents, locusts, white grub and other insect pests, for which the techniques have been standardized and perfected.

Water management and related technologies

While ample scope exists for popularizing the concept of water management and other technologies, these methods have yet to be adopted by farmers on a large scale. Except in the Jaisalmer area, where ancient catchment management for cultivation enables the local farmers to grow excellent wheat and mustard crops in an area receiving only about 100–150 mm rainfall, catchment cultivation is rarely encountered in the Indian arid zone. Again it has been shown experimentally that man-made micro-watersheds with a ratio of catchment area to cultivated area in sandy flat lands of 0·5 can also give valuable yields of pearl millet, sesame, moong, grain sorghum etc., thereby offsetting the losses from crop failure in a drought year. In the substations of CAZRI located in the remote desert area, rain-water has been collected since the early 1960s from natural slopes (3–6 per cent) in covered cement tanks or *tanka* ($200 \times 10^3\,m^3$) for human and animal consumption in addition to recycling the water for irrigation through sprinkler systems. Although the State Government has introduced this technique in many places, local inhabitants have shown little interest.

It is appreciated that simple rather than sophisticated methods have a better chance of rapid acceptance in the arid areas. But the success of such operations depends on the motivation and will of the people. It has been found that a subsurface barrier layer of clay 1 cm thick at a depth of 60 cm in sandy soil can significantly increase the yield of pearl millet as well as certain vegetable crops like *tinda* (*Citrullus vulgaris* var. *fistulosus*). Water harvesting coupled with such a subsurface barrier increased yields by about 200 per cent. Desilting of village tanks (located mostly in depressions), which is essential to maintain tank capacity, may yield sufficient silt to enable such techniques to be implemented, at least in limited areas. The replenishment of these village tanks can also be improved by lining the run-off channels with *janta* emulsion.

Hazards of agriculture and water use

Judicious use of limited resources and the prevention of irrational human exploitation are necessary to improve the desert ecosystem. The old practices of leaving the land fallow and cultivating by animal-drawn plough, which provide the favourable minimum of tillage, are rapidly disappearing with increasing use of tractors in the Indian desert. This is obviously accentuating erosion hazards. Similarly, modern irrigation techniques have yet to reach the farmers, and efficient use of the limited well-water is a pressing need. Experiments have shown that limited use of water (26 cm only) with adequate fertilizers (80 kg/ha each of N and P_2O_5) can produce a wheat yield of about 2100 kg/ha, while in the absence of the nutrients but with unrestricted irrigation, it may drop to only 600 kg/ha. Therefore, it may be more advantageous to divert the limited water over a larger area, optimizing the other inputs instead of relying entirely on the intensive irrigation presently practised in restricted areas. Other technologies such as trickle irrigation have given remunerative yields from crops like potatoes, bottle gourds, ridge gourds, water-melons, etc. Sprinkler irrigation has produced a 33–36 per cent increase in the yield of wheat compared with check-basin and border-strip methods. In the trickle system it has been possible to use saline water with a conductivity as high as 10 mS for potato crops. Adoption of these improved techniques may be possible through co-operative ventures among farmers in suitable lands. Despite the benefits to be obtained from irrigation, great caution should be exercised to avoid unrestricted use of well-water. Irrational use has often led to depletion of high-quality water, and salinity has developed in many wells. Strict control over water use is most necessary, as the fossil-water reserves in certain areas are very limited. If fossil water in the Lathi Series is used for agriculture, it is only expected to last for about 100 years. Since replenishment has been shown experimentally to be very poor and restricted only to the catchment areas, there is an urgent need for legislation to control use of ground-water resources in the arid areas of Rajasthan.

Forestry and energy needs

Despite the necessity for agriculture, there are serious reservations among scientists regarding its practice where rainfall is less than 200 mm. In view of the population pressure, as mentioned previously, a serious search for alternative types of land use is necessary where ploughing is restricted. Deterioration of the arid areas through human activity is not a myth. In the For at Jaisalmer, thousands of *Tecomella undulata* (commonly known as 'Teak of the desert') logs have been used as reinforcement for roofs, but today a visitor driving within hundreds of miles of Jaisalmer would see very few trees of this species. Human need for fuel has also led to the indiscriminate cutting of trees and shrubs. Charcoal-making from *Prosopis juliflora* in Pali and the use of *Calligonum polygonoides* for fuel in the Bikaner area are common examples. Since India is blessed with abundant solar energy (a daily value of 5·5 kW/m^2), the development of solar energy has gained considerable importance. CAZRI has developed miscellaneous low-cost solar-energy appliances (solar water heaters, solar ovens, solar cabinet driers, etc.) which are designed to meet the energy needs of local inhabitants and thus, over a period of time, diminish the present practice of denuding the vegetation for fuel. But the crux of the problem is the popularization of the necessary technology.

Forest produce and sylvi-pasture

One of the most important areas of desert development is the identification and large-scale multiplication of plants with important application to industry. *Acacia nilotica* and *A. senegal* are used for gum, *Cyamopsis tetragonoloba* for *guar*-gum, *Citrulus colocynthis* and *jal* (*Salvadora oleoides*) for oil for soap-making and many other desert plants have great economic importance. It is reassuring to find that conscious efforts are under way to exploit these resources and that in Jodhpur town today there are six factories extracting *guar*-gum.

While some economic plants such as *Commiphora wightii* (yielding *gugul*) have their natural habitat in rocky desert areas, trials of exotic species involving 112 *Eucalyptus* sp., sixty-five *Acacia* sp. and eighty-two other miscellaneous species from various countries have helped to identify their adaptabilities under the different soil and rainfall conditions of the Indian Desert. Research has further indicated the relative merits of different tree species with regard to their influence on the growth of ground-cover grasses. Some trees, such as *Prosopis cineraria* and *Tecomella undulata*, have been found very promising in sylvi-pastoral experiments where the build-up of organic matter has also been found to be enhanced.

Sand-dune stabilization

Sylvi-pastoral techniques have also been very useful in stabilizing bare sand dunes which threaten human habitation and agriculture in the desert areas. The technique which has been developed here consists of:

— the protection of shifting dunes from biotic interference;
— the establishment of micro-windbreaks on the windward side of dunes in 5-m parallel strips or 5-m square chess-boards;
— the sowing of grasses and the transplanting of adapted trees and shrubs which have been raised in earthen containers on the leeward side of the micro-windbreaks.

An economic analysis of this stabilization has indicated that the average cost of Rs. 760/ha will be repaid after the end of the thirteenth year. It has been found that about 50–70 mm of moisture exists within a depth of 1 m in unstabilized dunes and helps in the establishment of these plants and that the 50 per cent of nitrogen which remains in the form of readily available nitrate helps to provide nutrition. It has also been found that this reclamation technique brings about a gradual but lasting build-up of organic matter.

Arid horticulture

The only fruit-tree encountered in abundance in the desert tract is *ber* (*Zizyphus nummularia*), which has small red berries. With a view towards its potential for improvement, budding techniques were perfected by which it has been possible to transform these *Zizyphus* bushes into *ber* varieties such as *gola* and *seb*, which are characterized by large, luscious, and tasty fruits with a production range of about 40–60 kg/tree.

It thus appears that various techniques are now available to put the land to its best use, depending on its capability. But the success of these techniques largely depends on the active participation of the people who live in this particular environment. If the challenge of habitat improvement is to be accepted by the masses and the government, a massive effort must be made through education and extension, so that the people become receptive to the technologies which have been evolved.

Bibliography

CENTRAL ARID ZONE RESEARCH INSTITUTE (CAZRI). 1964. *Recent development in Rajasthan.* Jodhpur, CAZRI.

——. 1970. Bibliography of CAZRI (Central Arid Zone Research Institute), Publications 1959–1960. *Bull. Arid Zone Res. Assoc.*, p. 1–32.

——. 1974. *Summer Institute on the Desert Ecosystem and Its Improvement.* Jodhpur, CAZRI.

CHAMPION, H. G.; SETH, S. K. 1968. *A revised survey of the forest types of India.* Delhi, Manager of Publications.

CHATTERJI, P. C.; SAKSENA, R. K.; SHARMA, M. L. 1965. *Geology and hydrogeology of Chohton development block, WEstern Rajasthan.* Jodhpur, Central Arid Zone Research Institute (CAZRI). (Report Division 1.)

DAS GUPTA, K.; KHILANANI, V.B.; BHANDARI, U. M. 1973. An approximate assessment of exploitable ground water potential of Rajasthan. In: *Proceedings of the Winter School on the Development of the Rajasthan Desert.* Jodhpur, Indian National Science Academy.

DHRUVANARAYAN, V. V.; SHRI, N.; MURTHY, K. N. K. 1964. Efficient use of water resources in Indian arid zone. In: *Proceedings of the Symposium on Problems of the Indian Arid Zone*, p. 25–7. New Delhi, Government of India, Ministry of Education.

GARG, H. P. 1975. *Solar energy utilisation research.* Jodhpur, Central Arid Zone Research Institute (CAZRI). (Technical Monograph 3.)

GOOR, A. Y. 1955. *Report to the Government of India on control of the arid zone of Rajasthan.* Rome, FAO. 29 p. (Rep. 378. T.A. 272/S/10. Proj. IND/FO.)

GUPTA, I.C.; ABICHANDANI, C. T. 1967. Seasonal variation in the composition of saline irrigation waters of Western Rajasthan. *Ann. Arid Zone*, vol. 6, no. 1, p. 100–16.

INDIAN NATIONAL SCIENCE ACADEMY. 1973. *Proceedings of the Winter School on the Development of the Rajasthan Desert.* Jodphur, Indian National Science Academy.

INTERNATIONAL GEOGRAPHICAL CONGRESS. 1968. *Proceedings of the Symposium on the Arid Zone, held at CAZRI, Jodhpur.* Calcutta, National Committee for Geography.

JACOB, K. 1972. Some important aspects of reclamation and development of the Western Indian desert. *Ind. Nat. Sci. ACad.*, vol. 1, p. 45.

KAUL, R. N. (ed.). 1970. *Afforestation in arid zones.* The Hague, W. Junk N.V. 435 p.

——; CHAKRAVARTY, A. K. 1968. Range development in Western Rajasthan. *Ann. Arid Zone*, vol. 7, p. 258–64.

KRISHNAN, A. 1968. Delineation of different climatic zones in Rahasthan and their variability. *Ind. J. Geog.*, vol. 3, p. 33–40.

MALHOTRA, S. P. 1968. Nomads of the Indian arid zone. In: *Proceedings of the Symposium on the Arid Zone, held at CAZRI, Jodhpur*, p. 117–22. Calcutta, National Committee for Geography.

——; BHARARA, L. P.; PATWA, F. C. 1969. Resources and food situation in various tracts within the arid zone of Rajasthan. *Ind. Sociol. Bull.*, vol. 6, no. 4, p. 213–21.

MANN, H. S.; MALHOTRA, S. P.; KALLA, J. C. 1974. Desert spread—a quantitative analysis in the arid zone of Rajasthan. *Ann. Arid Zone*, vol. 13, no. 2, p. 103–13.

MINISTRY OF DEFENCE (INDIA). 1962. *Symposium on Arid Zone Problems.* Jodhpur, Defence Laboratory.

MINISTRY OF EDUCATION (INDIA). 1964. *Proceedings of the Symposium on Problems of the Indian Arid Zone.* Jodhpur.

MINISTRY OF IRRIGATION AND POWER (INDIA). 1971. *Dynamics of shifting sand dunes in Western Rajasthan and their rehabilitation.* New Delhi, Central Water and Power Commission.

NATIONAL COMMISSION ON AGRICULTURE (INDIA). 1974. *Interim report on desert development.* New Delhi, Government of India.

NATIONAL INSTITUTE OF SCIENCE (INDIA). 1952. *Proceedings of the Symposium on the Rajputana Desert.* New Delhi.

PRAKASH, I. 1976. *Rodent pest management. Principles and practices.* Jodhpur, Central Arid Zone Research Institute (CAZRI). 28 p.

——; GHOSH, P. K. (eds.). 1975. *Rodents in the desert environment.* The Hague, Dr. W. Junk B.V. 628 p.

ROY, B. B.; PANDEY, S. 1970. Expansion or contraction of the Great Indian Desert. *Proc. Ind. Nat. Sci. Acad.*, vol. 36, no. 6, p. 331–43.

SATYANARAYAN, Y. 1963. Ecology of the Central Luni Basin, Rajasthan. In: *Proceedings of the Symposium on the Indian Arid Zone*, vol. 2, p. 32–97. Jodhpur, Central Arid Zone Research Institute (CAZRI).

SEN, A. K. 1972*a*. *Agricultural atlas of Rajasthan.* New Delhi, Indian Council for Agricultural Research (ICAR).

——. 1972*b*. Agroclimatic regions of Rajasthan. *Ann. Arid Zone*, vol. 11, nos. 1 and 2, p. 31–40.

——; MANN, H. S. 1975. Exploration, utilization and quality of ground water in Rajasthan. In: *Proceedings Congress Symposium*, International Geographical Union (IGU), Commission on Arid Zone.

TOD, J. 1929, 1932. *Annals and antiquities of Rajasthan.* London, Routledge & Kegan Paul. (Vol. 1: 1929; Volume 2: 1932.)

UNESCO. 1971. *Proceedings of the Seminar on Integrated Surveys, Range Ecology and Management, Jodhput, 9–27 November 1970.* New Delhi, Unesco, Field Science Office for South Asia.

UNIVERSITY OF JODHPUR. 1972–73. *Symposium on Natural Resources of Rajasthan.*

VERSTAPPEN, H. T. H. 1968. *Geomorphology at the Central Arid Zone Research Institute (CAZRI), Jodhpur.* Paris, Unesco. (498/BMS.RD/AVS.)

VISHNU-MITTRE. 1975. Problems and prospects of palaeobotanical approval towards the investigation of the history of the Rajasthan desert. In: *Workshop on the Problems of the Desert in India.* Jodhpur.

5 Desertification in the Greater Mussayeb Project, Iraq

Case study presented by the Government of Iraq

Acknowledgements

Unesco would like to express its thanks to the Foundation for Scientific Research of Iraq, which was responsible for the preparation of this case study, and to the co-authors J. S. Dougrameji and M. A. Clor.

Assistance was provided by the following institutions in Iraq: the Agricultural Research Department; the Greater Mussayeb Project; the Institute for Applied Research on Natural Resources; the State Organization on Soil and Land Reclamation and the Regional Planning Department, Ministry of Planning.

Unesco also wishes to thank the following scientists for their valuable contributions: W. A. Fakhri, S. R. Al-Dagistani, R. H. Al-Abaidi, A. J. Mashkov and K. Dettmann.

UNDP, FAO and WMO also collaborated in this study.

Introduction

Background to the Greater Mussayeb Project

The Greater Mussayeb Project (GMP) is located in the centre of the Mesopotamian Valley (Fig. 1), approximately 90 km south of Baghdad, 20 km from Babylon, and 400 km from the Persian Gulf. It covers a strip of land about 40 km long and 16 km wide (83710 ha) with its longest axis oriented roughly north-east–south-west. Seventy-five per cent of the project area is supplied with water from the main (Mussayeb) canal, whose intake is on the left bank of the Euphrates, 10 km upstream from the Hindiya Barrage (Fig. 2).

Soil conditions in the Greater Mussayeb Project area, like those in most of the Mesopotamian Plain, have been modified by centuries of irrigation. As early as 4000 years ago, this 'cradle of civilization' was under irrigated cultivation. Traces of ancient ditches, scattered pottery, and *tells* (abandoned villages), found throughout the area, testify to the successive growth and decline of early town states. The disappearance of these communities may well have been connected with a progressive salinization of the surrounding lands resulting from over-irrigation.

Over-irrigation of these lands was continued until very recently by the sheikhs, feudal lords who commanded large work forces. Selecting arable lands for the cultivation of wheat and barley, the sheikhs irrigated soil through ditches dug to the Tigris or Euphrates. When canal silting and increased soil salinity eventually reduced the productivity of the land, the sheikhs would move their tribes to other areas and the process would begin again.

By 1950 it was estimated that approximately 60 per cent of Iraq's agricultural land—most of which lies in the lower Mesopotamian Plain—had been seriously affected by salinity. As a result, 20–30 per cent had been entirely abandoned, and each year an additional 1 per cent was being lost.

The Greater Mussayeb Project, the first project of its kind in Iraq, was initiated by the government in 1953. From 1953 to 1956 an irrigation and drainage network was installed and a semi-detailed land classification completed. The irrigation and drainage system follows a rectangular pattern, dividing the area into uniform plots, 500 m in length and 333 m in width (66·6 donums or 16·7 ha).

The first settlers took up residence in 1956–57, but, by 1960, only 1775 farm-units out of a total of 2705 had been effectively occupied. About one-third of this land had been distributed to people having no previous agricultural experience, and as a result

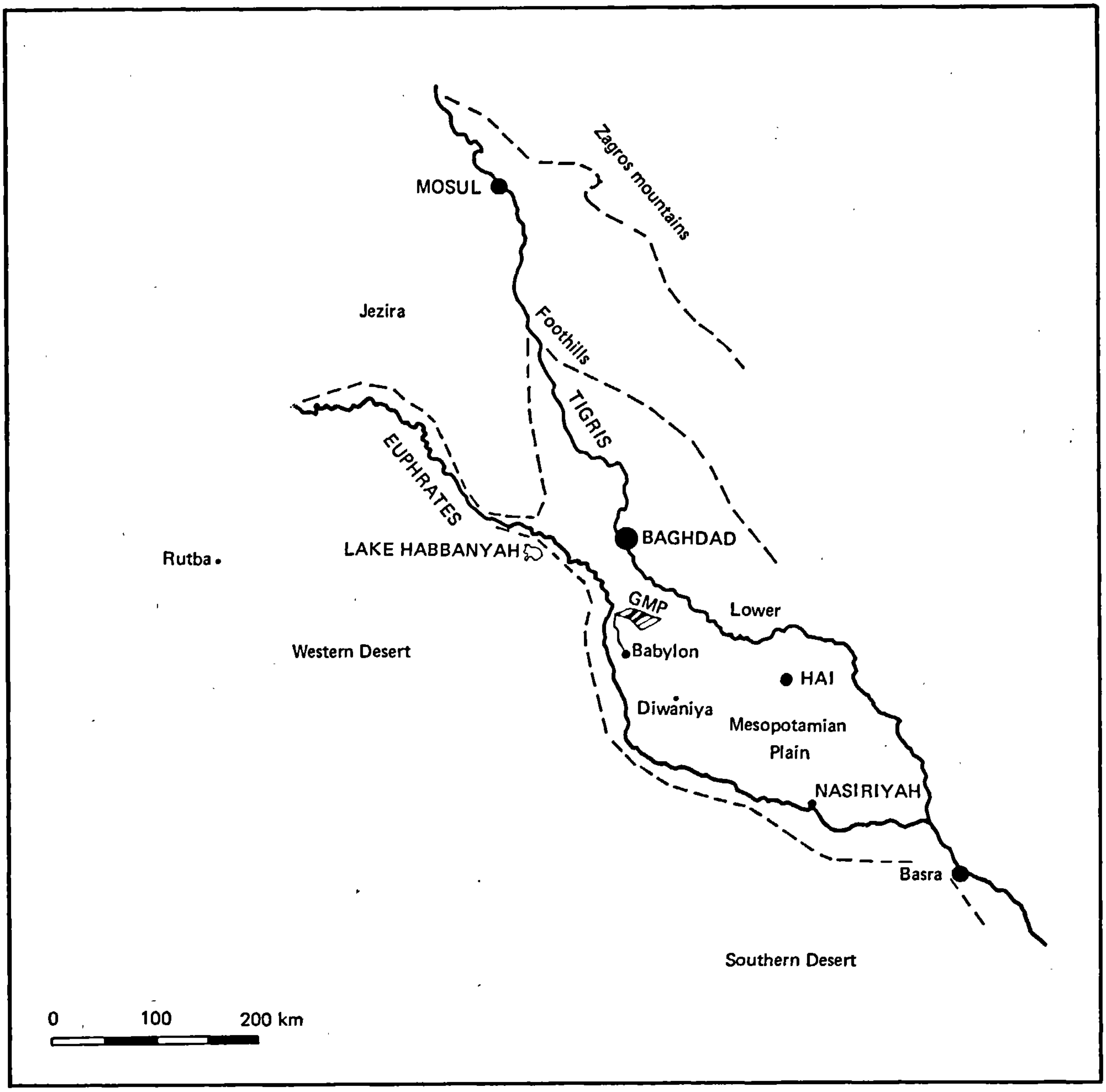


FIG. 1. Location of the Greater Mussayeb Project (GMP), Iraq

many of these properties were eventually sold or abandoned to pastoral nomads.

The project was further plagued by administrative and technical problems. Lacking the necessary authority, funds and equipment for proper canal maintenance, the project's small supervisory unit was unable to prevent a rapid deterioration of the drainage system from siltation and weed growth. With effective drainage blocked, soil salinity soon rose, causing a decline in crop productivity. Thus in 1964, a decade after the project's initiation, it was feared that it might become a technical, social and economic failure.

However, in 1965 the government introduced measures to rehabilitate the project, endowing the Greater Mussayeb Project Authority with wider inter-sectoral powers and requesting UNDP assistance, and a number of administrative and technical improvements followed. In 1968, the President of the Republic, General Ahmad Hassain Al-Bakr paid a personal visit to the project. After appraising the situation, he ordered major changes and an allocation of funds for the rehabilitation and development of the project. Activities foreseen under this programme are still under way.

Objectives of the Greater Mussayeb Project

The decision to establish the Greater Mussayeb Project was prompted by a number of considerations. Primarily it was an attempt to reverse the desertification process in the lower Mesopotamian Plain. At

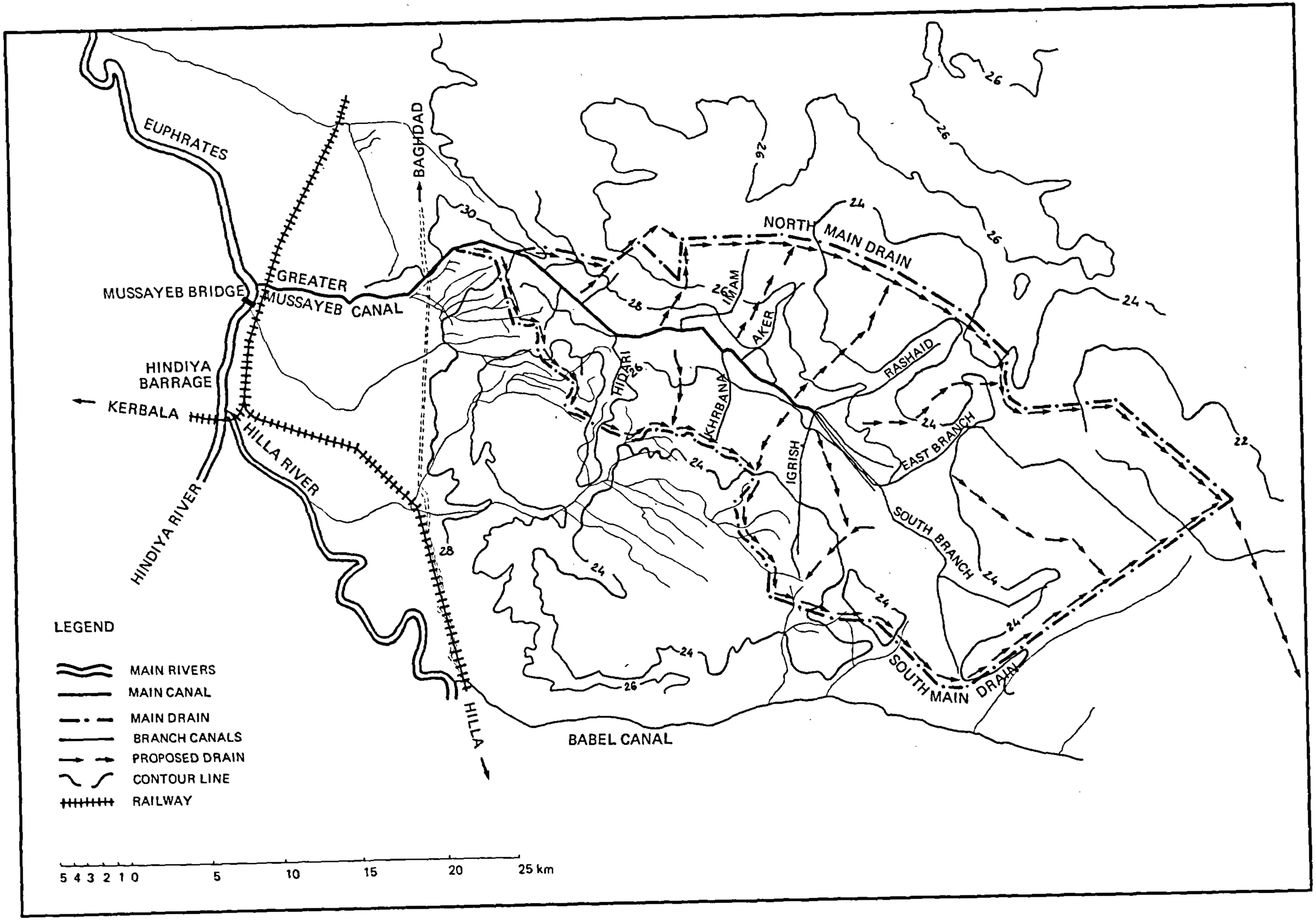


FIG. 2. The Greater Mussayeb Project

TABLE 1. Annual rainfall variability characteristics (UNDP/Unesco 1975)

Station	Mean (mm)	Maximum (mm)	Minimum (mm)	Standard deviation	Coefficient of variability
Baghdad	146·9	336·0	72·3	57·0	0·39
Hai	139·3	261·5	79·2	54·0	0·39
Diwaniya	119·0	270·3	47·1	43·6	0·36
Nasiriyah	111·5	221·1	27·8	47·2	0·42

TABLE 2. Mean monthly rainfall (in mm) (UNDP/Unesco 1975)

Station	October	November	December	January
Baghdad	3·7	17·2	22·9	25·3
Hai	3·2	20·3	23·1	24·9
Diwaniya	3·9	15·5	20·2	21·2
Nasiriyah	2·2	16·8	20·4	19·2
Station	**February**	**March**	**April**	**May**
Baghdad	24·4	22·7	23·3	8·1
Hai	20·8	19·3	18·2	9·5
Diwaniya	15·0	16·9	17·8	8·4
Nasiriyah	13·4	15·8	16·6	7·1

the same time it was an effort to intensify crop production, replacing the traditional *nirin* system with modern practices of reclamation and drainage. The *nirin* system was based on a natural lowering of the water-table during periods in which the land was left fallow. Salts which accumulated near the soil surface were leached by the rains. Normal practice was to cultivate during one winter season and leave the land fallow over the two succeeding summer seasons. This system resulted in a low cropping intensity incompatible with the high cost of a modern irrigation project.

Finally the Greater Mussayeb Project was a conscious effort to break with the traditional feudal society. Distribution of land to local landless farmers and the organization of work on a co-operative basis gave this project an unquestionable social as well as technical and economic significance.

Thus, in its objectives, through its implementation, and for its social and economic implications, the Greater Mussayeb Project presents an interest of broader than national scope. On the national level, solutions to the problems outlined in this study will no doubt contribute to the economic development of the lower Mesopotamian Plain, where at present a number of comparable irrigation projects introducing intensive agricultural patterns are at various stages of preparation or development.

Data on initial basic resources

The following data were used in designing the irrigation and drainage network of the initial project.

Climate

As a meteorological station within the project area was only established in June 1972, data from earlier-established stations surrounding the project were used to characterize the climatic conditions in Mussayeb. These stations are Baghdad, Kut-Al-Hai, Diwaniya and Nasiriyah.

In central and southern Iraq the weather is dominated by the following air masses:

In winter:
- by modified maritime tropical air, a warm humid air mass originating in the Persian Gulf or even further east;
- by polar continental air, a cold dry air mass from the polar regions;
- by polar maritime air, cool moist air masses from the Mediterranean Sea, brought in by depressions from the west.

In summer:
- by tropical continental air, an extremely dry and hot air mass originating in Saudi Arabia and Africa;
- by modified maritime tropical air, which may also affect southern Iraq.

Rainfall

The dry season in Iraq occurs between the months of October and May. Mean annual rainfall is estimated at about 120 mm, with high inter-annual variability (Table 1). Mean monthly accumulation and mean frequency of daily rainfall are shown in Table 2.

TABLE 3. Mean monthly, mean maximum and mean minimum temperatures (°C)

Station	January	February	March	April	May	June	July	August	September	October	November	December
Mean monthly												
Baghdad	10·0	12·3	16·3	22·0	28·4	33·0	34·8	34·4	30·6	24·6	17·1	11·0
Diwaniya	10·5	12·9	17·1	22·7	29·0	32·7	34·2	33·8	30·4	24·9	17·7	11·9
Habbaniyah	9·5	12·0	16·1	21·7	28·1	32·7	34·8	34·2	30·0	24·1	16·8	11·0
Mean monthly maximum												
Baghdad	15·8	18·7	22·7	28·7	35·8	41·0	43·4	43·3	39·8	33·4	24·6	17·7
Diwaniya	17·1	19·7	24·4	30·1	34·8	41·0	42·7	42·9	40·1	34·5	25·6	18·6
Habbaniyah	15·6	18·6	23·0	28·9	36·0	40·9	43·4	43·3	39·5	33·0	24·2	17·6
Mean monthly minimum												
Baghdad	4·3	5·9	9·6	14·6	20·0	23·4	25·3	24·6	21·0	16·2	10·3	5·2
Diwaniya	4·1	5·8	9·6	14·5	20·0	23·1	24·3	23·6	20·3	15·8	10·7	5·4
Habbaniyah	4·4	6·0	9·6	14·9	20·1	23·7	25·8	25·0	21·2	16·2	10·5	5·0

TABLE 4. Mean monthly relative humidity (in %)

Station	January	February	March	April	May	June
Baghdad	71	62	52	44	31	22
Diwaniya	70	55	51	44	33	29
Habbaniyah	73	62	55	47	35	26
Station	**July**	**August**	**September**	**October**	**November**	**December**
Baghdad	23	24	27	36	56	71
Diwaniya	28	29	32	39	56	70
Habbaniyah	25	27	30	39	61	73

Temperature

Only in January does the mean monthly minimum temperature drop below 5°C (Table 3). Minimum daily temperatures fall below 0°C for about ten days a year. Maximum temperatures rise above 35°C for about 150 days a year, exceeding 40°C on more than 100 days.

Wind

Prevailing wind directions are the following: at Baghdad, N. 320°E. (NW.); at Diwaniya N. 320°E. (NW.); and at Habbaniyah N. 305°E. (WNW.). Mean monthly wind velocities are generally in the range 9·0 to 16·2 km/h, but on rare occasions deep depressions originating in the Mediterranean region produce steep pressure gradients and wind speeds of 40–45 km/h. Very short-lived local winds of high velocity may also occur during the peak of the thunderstorm season, i.e. in late winter and early spring. Most of these storms blow in a westerly or north-westerly direction; others blow in an easterly to south-easterly direction, and a few blow in a southerly direction. Of the 33 storms recorded in Baghdad the highest wind speed noted was 155 km/h, blowing from the west.

Relative humidity

In summer, relative humidity is generally about 10 per cent during the day rising to 50 per cent at night. Mean monthly relative humidity is shown in Table 4.

TABLE 5. Crop coefficients and total consumptive water-use values for various crops (from Knappen, Tippets, Abett, McCarthy, 1952*a*, 1952*b*)

Crop	Crop coefficient K[1]	Total consumptive water use (mm)
Alfalfa	0·85	1949
Maize	0·80	829
Cotton and beet	0·75	1059
Grain	0·80	558
Orchards	0·70	1083
Rice	1·25	1366
Bean	0·70	617
Vegetables	0·65	1164
Cover crops	0·60	416

1. Ratio of water consumed to evaporation from an open water surface under similar climatic conditions.

Consumptive water use

Consumptive water use values for various crops were calculated for the central part of Iraq by the consultants Knappen, Tippets, Abett, McCarthy (1952*a*, 1952*b*) using the Blaney and Criddle formula (Blaney and Criddle, 1950). Table 5 shows the total water requirements and crop coefficients for a number of different crops.

According to the original 1952 project plan, the *nirin* (fallow) system was to be abolished, and a certain number of summer crops were to be introduced as part of the new intensive cropping system. However, it was decided that in areas already under cultivation (the Miri-Lasma areas), the existing *nirin* system would be maintained and the main canal would supply water to both cropping patterns.

Areas under the *nirin system* (*c.* 21 000 ha) averaged a cropping intensity of 62 per cent, and were distributed as follows:

Winter crop	*Gardens*	*Cotton*	*Other summer crops*	Total
50%	4–5%	3–5%	2–5%	59–65%

Water demand would be highest in March and April when winter cropping and early cotton cultivation coincided. Canal capacity was therefore determined with that period in mind. Taking this peak period as unity, the relative monthly water requirements for the areas under the *nirin* system were calculated as follows:

November	*December*	*January*	*February*	*March*	*April*
0·80	0·73	0·50	0·55	0·95	0·80
May	*June*	*July*	*August*	*September*	*October*
0·45	0·50	0·50	0·50	0·50	0·50

TABLE 6. Cropping pattern for years with normal to low water storage

Crop	Winter crops (%)	Summer crops (%)
Clover and pastures	20	20
Maize		10
Cotton		10
Vegetables	10	10
Beans and pulses		5
Grains	30	—
Orchards	5	5
Vetch and cover crops	10	—
TOTAL	75	60

Areas under the intensive cropping system (*c.* 83 000 ha) had a crop intensity which varied according to the total amount of water stored in the Habbaniyah reservoir.

For years with normal-to-low water storage the cropping pattern (Intensity I) shown in Table 6 was designed. The estimated average net monthly water requirements for this cropping pattern (in mm) are as follows:

November	*December*	*January*	*February*	*March*	*April*
420	290	270	350	760	960
May	*June*	*July*	*August*	*September*	*October*
720	1040	1100	1030	870	820

During years of high water storage, the winter cropping pattern shown above would be maintained, but the area devoted to summer crops, mainly cotton, would be increased by 25 per cent. The average water requirements (in mm) for this cropping pattern (Intensity II) were calculated as follows:

November	*December*	*January*	*February*	*March*	*April*
420	290	270	350	760	1270
May	*June*	*July*	*August*	*September*	*October*
1110	1460	1550	1460	1230	1110

Monthly water requirements for the entire project area (i.e. *nirin* system area plus intensive cropping system areas) were calculated for periods of both normal to low water storage (*nirin* plus Intensity I) and high water storage (*nirin* plus Intensity II) as shown in Table 7. A certain water loss between intake and field, estimated at 35 per cent of the discharge at the head-work, should also be taken into account (Nugteren, 1956) but is not accounted for in Table 7.

TABLE 7. Monthly water requirements for the total Greater Mussayeb Project area (in million m^3)

Month	*Nirin* plus Intensity I	*Nirin* plus Intensity II
January	26·8	26·8
February	30·7	30·7
March	67·0	67·0
April	75·5	95·5
May	55·4	81·8
June	75·0	102·0
July	81·7	107·0
August	77·0	105·2
September	64·0	87·0
October	58·6	78·0
November	41·2	41·2
December	33·4	33·4
TOTAL	686·3	855·6

Soils

Geology and geomorphology

The Mesopotamian Valley is a broad syncline formed since the Pliocene period, which has gradually been filled by river, wind erosion, and shallow marine sediments. It is the sub-aerial portion of a delta which extends into the Persian Gulf, and its upper sector shows a number of terraces reflecting past variations in rainfall and in sea-level.

The formations outcropping in the catchment area of the Tigris and Euphrates rivers are predominantly limestone, with subordinate amounts of anhydrite. Additional sulphates were deposited in the form of gypsum or gypsiferous marls around the beginning of the Alpine orogeny, when the marine sedimentary basin became shallower, and ultimately split into separate basins and dried up completely. The presence of these minerals has resulted in a high concentration of calcium and sulphate ions in the valley sediments, which consist predominantly of silt and clay.

The area is further characterized by *tells*, ancient relics of early human settlements. Filled and covered by wind-blown sands, *tells* appear as small, roughly circular mounds with gently sloping sides. They vary from 1 to 20 m in height, and from 50 to 300 m in diameter, in some cases reaching diameters of 500 m. These *tells* show considerable signs of erosion, resulting in the deposition of a kind of colluvial detritus in the surrounding terrain. The detritus is chiefly composed of fragments of pottery and the debris of former settlements, and constitutes much of the surrounding soil, particularly in the upper layers. The number of *tells* in the area has not been determined, but there must be well over a hundred located on both sides of the old irrigation canal.

Sand dunes, mobile masses of sand-sized particles consisting mainly of salt-cemented clay and silt pellets, also occur widely in the project area. This wind-driven material constitutes a continual threat to crops and irrigation installations.

With the exception of the *tells*, sand dunes, and silt ridges formed along ancient canals, the project area is nearly level to very gently undulating. Elevation varies from 31 m in the north-west to 24 m above sea-level in the south-east, even though the sea is over 400 km away. Consequently natural drainage is poor to non-existent.

The land surface is formed by recent irrigation deposits, beneath which lie deposits of the Euphrates flood-plain. The layer of Holocene sediments is assumed to extend to a depth of about 12–15 m below the land surface. Alluvium of Pleistocene age extends to depths of 60–100 m. In places this formation is gravelly and sandy, in others a continuous sequence of silt and clay layers extends several tens of metres beneath the land surface.

Soil types

The soils have developed in parent material of recent alluvial deposits of the Euphrates River, consisting of a complex succession of layers of different textures and colours, ranging from sands to fine silty clay loams and clays of greyish brown colour. Owing to the predominantly ascending movement of water in the soil profile, soil formation is weak and confined to the development of some weak-to-medium structures, especially in the fine textured soils.

Although the general characteristics of the Mussayeb area were found to be quite comparable to those in similar land units of the Hilla area, the Mussayeb area showed the following differences: the distribution of salt was more even; there was more drifting of clay pellets; and the heavy clay deposits in the depression between the Euphrates and Tigris, once a lake, contained black alkali soil. Most of this latter soil was excluded from the reclamation and irrigation project.

Two soil series were identified in this part of the alluvial valley:

1. *Hilla series.* These soils consist of relatively fine material such as loam, silty loam, clayey loam and sometimes silty clay loam. Surface and subsurface soil colour is dark grey. Some fine loam layers occur in the substratum. The soil structure is weak angular blocky to sub-angular blocky. The entire profile is very porous, and permeability is high. Soil of this series is slightly saline, belonging partly to the internal solonchak type but primarily to the external solonchak salinity type. The ground-water table occurs at depths between 1·0 and 2·5 m. In terms of irrigability (see later discussion on land classification) these soils were classified in Class 2 and are suitable for grain, row crops and legumes.
2. *Babylon series.* These soils consist of dark brown to brown, sometimes dark grey brown, silty, clay loam, often grading into clay loam, silty clay, or clay. They are porous with an angular blocky surface structure. The top 2 cm are often altered to a hard, platey and non-porous crust showing many cracks during dry conditions. These soils are slightly saline to saline. Most soils of this series are Sabkha or normal solonchak soils. The ground-water level is between 1·5 m and 2·5 m from the surface. In terms of irrigability these soils appear in Classes 2 and 3, and are suited for cereal cultivation and grazing land.

Chemical properties of the soils

Salinity was the most prominant chemical feature of the project soils; common salts included NaCl, $CaCl_2$, $MgCl_2$, $CaSO_4{\cdot}2H_2O$, Na_2SO_4, $MgSO_4$. Chlorine (Cl^-) was the principal anion and sodium (Na^+) the principal cation, except in the surface of Sabkha soils, where Ca^{++} and Mg^{++} were the principal cations. Salt concentration varied according to the age, depth, and location of the soil.

Carbonate content was also high (20–30 per cent or higher), while gypsum content was low, with a range of a few per cent. The soil reaction was alkaline, with pH values between 7·6 and 8·5. The cation exchange capacity (CEC) of the soil varied vertically and horizontally according to clay content, clay type, and salt concentration, but was about 30.

Three main types of soil salinity were identified:

1. *Internal solonchak soils.* These soils are non-saline in the upper part and saline in the lower part.
2. *External solonchak soils.* These are saline throughout, often with salts of NaCl, Na_2SO_4 and $MgSO_4$ on the surface.
3. *Sabkha soils.* These soils are saline, with high amounts of deliquescent salts in the surface layers. They are much darker-coloured than the normal dry soils. Characteristic salts were $CaCl_2$, $MgCl_2$ and $MgSO_4$.

Internal and external solonchak soils were the principal types in the project area. Most of the soil salinity was directly related to ground-water salinity. Salt concentration was highest in the capillary zones, while in the layers below the average ground-water level, soil and ground-water salinity were in equilibrium.

Fertility status, organic matter and mineral composition

An analysis of soil samples taken from the project area indicated low nitrogen, low available phosphate, low organic matter (less than 0·5 per cent) and moderate available potassium. Although part of the area was under cultivation, there was no indication that fertilizer had been used, and in fact the local population reserves the use of animal manure primarily for fuel.

No official studies were made of the mineral composition, but it was assumed that interstratified montmorillonite, chlorite, illite, and attapulgite were the principal clay minerals.

Physical properties of the soils

The physical properties to be taken into consideration for irrigability classification included soil texture, permeability and susceptibility to wind erosion.

The moisture equivalent of soil samples taken from the project area was about 27·5 per cent and was taken to represent the field capacity of the soils. The value of about 200 mm available water capacity in a soil profile to a depth of 1 m was taken as the criterion for irrigability classification (Knappen, Tippets, Abett, McCarthy, 1952*a*, 1952*b*).

Land classification

Suitability of the soils in the project area for irrigation was classified as follows (Fig. 3):

— *Class 1*: excellent soils, which are uniform, deep, permeable and neutral with good water capacity and fertility, slopes of about 2 per cent or less, depths in excess of 1 m, and salinity at 0·25 per cent or less. Soils of this type cover 5 per cent of the project area.

— *Class 2*: good soils, with slightly rolling or hummocky slopes of 6–12 per cent; pH less than 8·5, depths greater than 75 cm, usable water capacity and fertility fair, salinity moderate (0·25–0·75 per cent). This soil, which covers 92 per cent of the project area, includes heavy clays and gravel in certain areas.

— *Class 3*: fair soils, with slopes of 6–12 per cent mottled clay or compact gravelly to stony subsoils, pH less than 9·0; salinity high (0·75–2·0 per cent) and depths exceeding 50 cm. In summer, ground water lies about 1 m below the surface. This soil covers 3 per cent of the project area.

On the basis of the above criteria most of the project area was included in Class 2 with some patches in Classes 1 or 3 (Fig. 3).

The preliminary conclusions were that proper drainage, if necessary at farm level, would check the salinity in the major part of the area.

Reclamation potential

The presence of shallow, highly saline ground water,

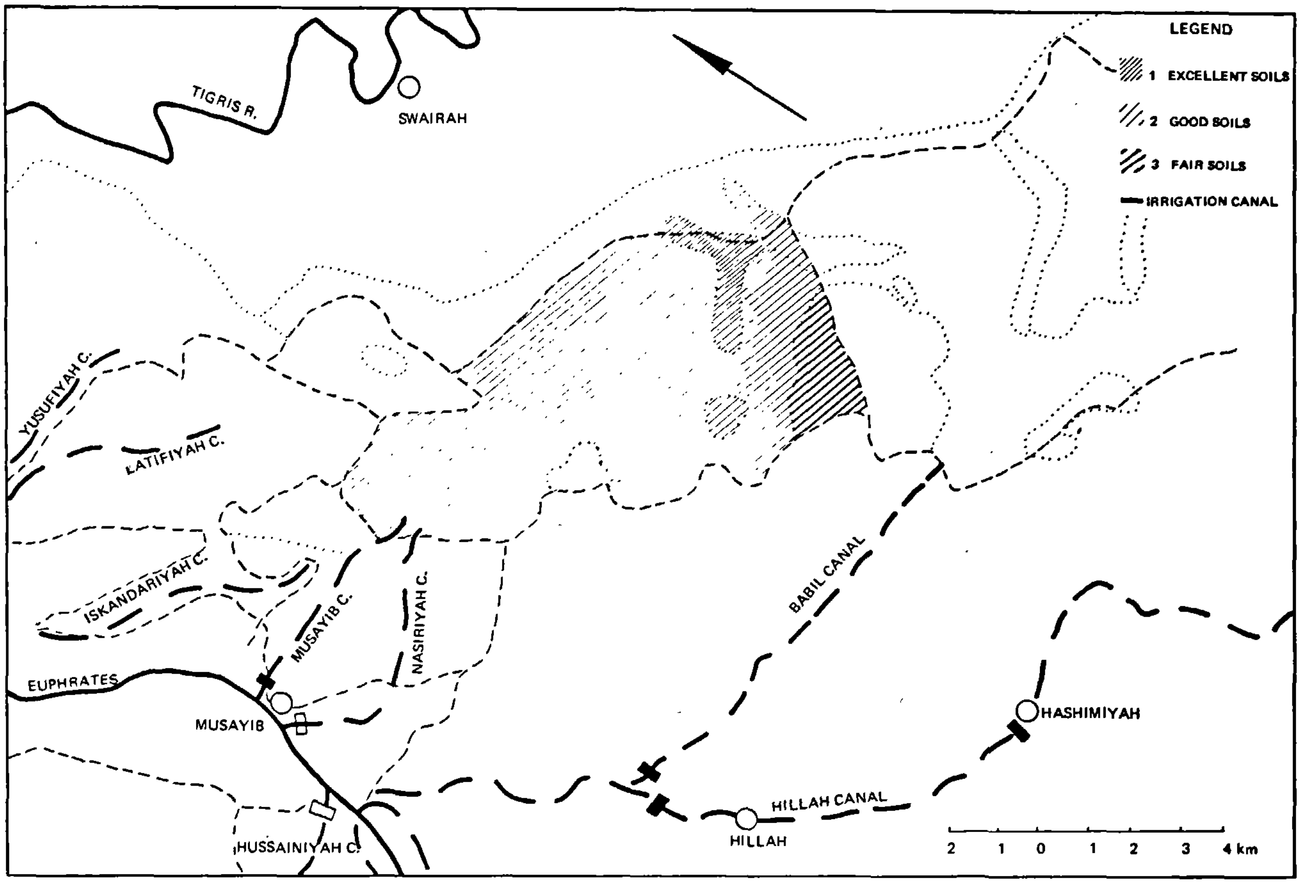


FIG. 3. Land classification map (after Knappen, Tippets, Abett, McCarthy, 1952*a*, 1952*b*)

particularly beneath soils in depressions, presented a potential danger for intensive irrigation without adequate drainage. Leaching to reduce soil salinity would be easier in the light, porous level soils than in the depression soils, where the downward movement of leaching water was impeded by poor structure and low porosity.

The reclamation process was planned in a way to allow the cultivation of a wide range of crops with high yields, provided that the land could be levelled for a uniform application of water, that adequate leaching could reduce the salt content of the root zone to acceptable levels, and that an effective drainage system could be established and maintained. Keeping in mind the above conditions, the original system of the project was thought sufficient to control the soil salinity.

Even before intensive irrigation began in the area in 1953, ground-water salinity was dangerously high (up to 4 per cent salt). This condition resulted from centuries of alternating cultivation and abandonment of the land surface by local tribes. During periods of cultivation, irrigation increased soil salinity. During the periods of abandonment which followed, natural leaching by rainfall drove surface salts to the ground water below. Over the years, as the process repeated itself, the level and salinity of local ground water gradually rose.

Surface water available for irrigation

Source and available quantities

The main canal off-take, i.e. the head regulation of the Greater Mussayeb Irrigation system, is located on the Euphrates, 10 km upstream from the Hindiya Barrage. Since the completion of the Habbaniyah storage reservoir upstream in 1956, the mean discharge available for irrigation during the dry season (July to December) has been about 400 m^3/s in the middle reaches of the river. In the initial design, however, it was assumed that in dry years the minimum discharge would not satisfy the peak requirements of an intensive cropping pattern. Therefore, as explained earlier, two alternative cropping patterns were envisaged, one for years of low or normal water supply, the other for years of high supply. Monthly water supplies to the project area in 1962–63 are shown in Table 8.

Canal capacity and control were designed to supply water to 21 055 ha under the *nirin* system and 62 625 ha under the intensive cropping system. The head capacity of the main canal was fixed at 40 m^3/s and could be increased to 60 m^3/s. The draw-off by the branches and canal losses were taken into consideration to compute section capacities. Lateral canal capacity was designed to accommodate 20·5

TABLE 8. The volume of water allocated to the Greater Mussayeb Project area (1962–63)

Month	Supply (m^3)	Quantity (m^3/ha)	Gross supply (cm water depth)
January	82944000	1000	10·0
February	69120000	820	8·2
March	100224000	1200	12·0
April	103680000	1240	12·4
May	107136000	1280	12·8
June	103680000	1240	12·4
July	107136000	1280	12·8
August	107136000	1280	12·8
September	103680000	1240	12·4
October	86400000	1040	10·4
November	86400000	1040	10·4
December	82944000	1000	10·0
TOTAL	1140480000	13660	136·6

litres/s per unit with a velocity not less than 0·20 m/s for full supply. With the branches for the settlement area operating on half-time rotation, the required capacities for a farm-unit of about 16·7 ha were calculated as follows:

At head of main canal	12·7 litres/s per unit
At head of branch canal	22·0 litres/s per unit
At head of lateral canal	20·5 litres/s per unit
At head of farmer's off-take	19·0 litres/s per unit

Quality of the irrigation water

The irrigation water for the project is taken from the Euphrates. It is water of a medium salinity with a low sodium hazard, and is therefore suitable for both irrigation and leaching. Observation of water in the Mussayeb canal revealed a negligible boron content and an electrical conductivity ranging from 0·4 in November to 1·3 mS/cm in July and August. Table 9 shows the chemical composition of the Euphrates as observed near Falluja and Mussayeb.

Silt load

Sediment carried by the Euphrates has not been studied systematically, but some data have been collected by the Irrigation Department. These data show that the river carried sediment throughout the year. No suspended-load measurements were avilable for periods near or above flood stage, but reports indicate that sediment carried during those periods is about 2 per cent.

With an average siltation rate of 1000 ppm throughout the year, and with the 1140480000 m^3 of water allocated to the project area, 1140480 m^3 of silt would be deposited in the project. This is equivalent to a layer of silt 1·4 mm thick.

Only part of this sediment is deposited in the canal and drainage system; the remainder is deposited on farm land. Although the total amount deposited on this land may seem insignificant, uneven distribution caused by the wild flooding system of irrigation for instance, may cause heavy silt accumulation in particular areas. In a very few years such areas may become unmanageable. Hence careful land levelling and a system of even water distribution are required.

Naturally, the heaviest sediment load is carried during the flood season, usually from the beginning of April to the end of June. In addition, periodic floods which rise rather quickly may carry an exceptionally heavy sediment load during the first two or three days of their duration.

Natural plant and animal life

Flora

Hardly a vestige of natural vegetation remains today throughout the lower Mesopotamian alluvial plain. As a result of overgrazing, the activities of fuel gatherers, and the area's agricultural history the perennial herbs and shrubs have been largely destroyed. The patches of vegetation which form thickets in abandoned wastelands are of secondary origin. Such low thickets consist of halophytic communities, mostly chenopods such as *Suaeda baccata, Nitraria retusa, Salsola longifolia,* and *Tamarix aphylla.* Thorny shrubs such as *Prosopis farcta* and *Alhagi mansorum* with *Citrullus colocynthis* are also very commonly found in the uncultivated areas. Next in distribution are the following halophytes: *Halocnemum strobilaceum, Aeluropus littoralis,* and *Cressa cretica.* The hygrophilous plants, such as *Phragmites communis, Typha angustata* and *Cyperus rotundus,* form widespread communities in canals, ditches and other wet places.

Fauna

Wild pigs, *Sus scrofa,* were commonly found in the thorny shrub thickets. The common wild deer *Gazella subgulturosa* and the spotted deer *Gazella gazella* were also very common. Wild rabbits, *Oryctolagus cuniculus* were also found abundantly. Among carnivores, foxes, *Vulpes vulpes,* jackals, *Canis aureus,* and wolves, *Canis lupus,* were found in great numbers; hyena, *Hyaena hyaena,* were also known to exist in the area.

TABLE 9. Chemical composition of irrigation water near Falluja and Mussayeb.

Site	EC[1] (mS/cm)				SAR[2]			Cations and anions (meq/l)										
	Dry season	Flood season	Average	pH	Dry season	Flood season	Average	Na	Ca	Mg	Cl	SO_4	HCO_3	CO_3	NO_3	K	P
Falluja	0·68	0·47	0·57	—	1·4	0·5	1·0	1·6	2·7	2·1	1·9	1·7	2·7	0·3	0·4	3·5	<0·1
Mussayeb	0·70	0·46	0·56	7·7–8·0	1·3	0·5	0·9	1·6	2·7	2·1	1·8	1·6	2·4	0·3	0·7	3·4	<0·1

1. EC = Electrical conductivity. 2. SAR = Sodium absorption rates = Na/[(Ca + Mg)/2].

Among the rodents, jerboas, *Alectaga cophratica* and *Jaculus jaculus*, and mice, *Mus musculus*, *Nesokia indica* and *Tatera indica*, were commonly found. The hedgehog, *Hemiechinus auritus*, occurred in the area. Skinks and lizards, *Albepharus branditii*, *Eumeces schueiderii*, *Chalchides ocellantus*, and *Acanthodactylus boskianus* were among the reptiles. Snakes included *Leptotyphlops macrorhynchus* and *Eryx jaculus*.

The following birds were commonly encountered: starling, *Sturnus vulgaris*, sparrow, *Passer domesticus*, black partridge, *Franolinus franolinus*, hawk, *Accipiter mirus*, hen harrier, *Circus cyaneus*, peregrine falcon, *Falco peregrinus*, black kite, *Milvus migrans*, wood pigeon, *Columba palumbus*, turtle dove, *Streptopelia turtur*, rock dove, *Columba livia*, hooded crow, *Corvus corone*, rook, *Corvus frugilegus*, and white stork, *Ciconia ciconia*.

Design and installation of the irrigation and drainage systems

The irrigation system

Before the initiation of the Greater Mussayeb Project, there was little or no cultivation in the area. On a few private lands, mainly in the south-west, farmers practised primitive cultivation with water supplied through old ditches from the Euphrates. Nomadic herdsmen, however, were more typical of the area's population. In 1952, when work on the project began, the number of local inhabitants was estimated at 1000.

In 1952 the development board decided that the new land settlement would be based on an intensive cultivation pattern. The consulting engineers proposed a cropping pattern which placed more emphasis on summer crops, with the *nirin* system to be maintained only in those areas where it was already practised. Under the *nirin* system a two-year rotation cycle was used and the land was equally divided. Half was cultivated with winter crops, mainly wheat and barley; the remaining half was left fallow throughout the second winter. A small area (10–15 per cent) was cropped in summer. The intensity of cropping under the *nirin* system was 60–65 per cent. As stated earlier, the consultants proposed two patterns under the intensive cropping system, one for years of low or normal water supply, the other for years of high water supply.

Although overall water losses are higher in summer than in winter, for the purpose of design the average loss was assumed to be 35 per cent of the discharge at the head-works throughout the year. Losses in the different canals and ditches were calculated according to canal length and discharge and estimated at: 12 per cent in the main canals; 6 per cent in branch canals (= 7 per cent of branch canal discharge); 7 per cent in lateral canals (= 8·5 per cent of lateral discharge); 10 per cent in farm ditches, waste, and subsoil drainage (= 13·5 per cent of farm supply).

When the design of the project was begun, farm sizes and land division had not been determined and the contour maps showing 0·5-m intervals proved to be inaccurate. The irrigable area was assumed to be 80 per cent of the gross area, and the main canal, about 50 km in length, had a planned capacity of 40 m^3/s. Its hydraulic features were designed according to the criteria shown in Table 10.

TABLE 10. Design criteria for the irrigation system[1]

Discharge (Q) (m^3/s)	Slope (%)	Bed width (m)	Depth (m)	V (m/s)
40	0·00009	21·05	2·45	0·68
37	0·00009	20·65	2·35	0·68
35	0·00010	19·65	2·32	0·66
34	0·00010	19·25	2·27	0·70
31	0·00010	18·65	2·22	0·67
28	0·00010	18·00	2·10	0·66
21	0·00010	15·25	2·00	0·61
18	0·00011	13·50	1·80	0·65

1. Manning number 'n' assumed to be 0·0225.

The branch and lateral canals were designed in the same manner as the main canal. Branch canal capacities ranged from 0·75 to 71 m^3/s. The lateral and sublateral canals matched the grid system taking into account the slope of the land. The laterals were spaced at 500 or 1000 m intervals. Their design was based on 20 litres/s per unit, and the turn-outs were based on 19 litres/s. Velocity in the laterals was designed to be no less than 0·20 m/s at full supply. In locations where the tail of the lateral was within reasonable distance of a main or branch drain an escape ditch was planned for the discharge of excess water.

The irrigation network consisted of a main canal, thirteen branch canals, seven parallels, and a large number of laterals. The total length of the canal system was 710 km and the system could be extended further for intensive cultivation. The complexity of this system called for a high degree of maintenance.

Wild flooding and meandering short furrows were commonly used to irrigate the private farms. Because of the rough topography and the lack of levelling practices, individual irrigation basins were kept small. This created an uneven distribution of water, a high percentage of wasted land, and excessive water application which generally reduced the yield–water ratio.

It appeared after some time that the adopted practice of border-strip irrigation led to an excessive application of water, generally as a result of poor land levelling, improper stream size and incorrect application time.

The structures on the main canal were all oversized to some extent in order to facilitate future enlargement. The head-works were designed for a maximum water supply of 60 m^3/s while the cross regulators and measuring devices were designed for a discharge corresponding to 50 m^3/s at the head.

Besides the head regulator, the flume bridges, and the cross regulators, the main irrigation structures were:

— *The off-take laterals.* The design of the laterals was based on the number of farm-units located on each lateral. In the same way the culverts supplying the laterals from branches and parallels were designed and classified with requirements of 20·5 litres/s per unit. Most of the culverts and all of the laterals were provided with gates to regulate water flow in accordance with the required discharge.

— *Farm turn-outs.* Since the system of water supply was based on equal supply to all units under all conditions, no regulating devices were required. The supply was regulated by rotations at the branch regulators. The head works, the off-take culverts and the turn-outs required adjustment for changes in the canal regime.

— *Drop structures.* Drop structures were located in the branch and lateral canals. For both, a typical design had been prepared as a clear overall weir with a stilling pool and cross-wall.

— *Escape structures.* The combination of the *nirin* and intensive cultivation systems in summer required a discharge of less than the full capacity during certain months. To operate the main canal and branches at a sufficient silt-carrying discharge, excess supply would be required. A number of structures were incorporated in the design to let this excess water escape into the drainage system.

The drainage system

The Greater Mussayeb Project was the first project in the country with a drainage system incorporated in the initial design. Construction of the canals and the drainage system took place simultaneously.

Reliable data on which to base the drainage system design were very scarce, and permeability values determined in the field were not consistent with those determined in the laboratory. The laboratory data on permeability (K) allowed the land area to be divided into the following four classes:

		Percentage of the area
— Class A	$K > 1$ cm/h	15
— Class B	$K = 0{\cdot}99–0{\cdot}5$ cm/h	40
— Class C	$K = 0{\cdot}49–0{\cdot}1$ cm/h	40
— Class D	$K < 0{\cdot}1$ cm/h	5

Since most of the values were low, it was thought that in classes B, C and D a more closely spaced field-drainage system would be required. To provide maximum drainage facilities within the project area, the smaller drains for class B, C and D areas were spaced at intervals of 333·3 m along the longer sides of the units. In class A areas, the intervals were 666·7 m. This arrangement allowed for an eventual installation of field drains within the units if later needed.

The completed project included a network of field collectors covering about 70 per cent of the gross arable area. They were spaced 330 m apart with lengths varying between 500 and 700 m. These field collectors led to open branch collectors connected with the northern and southern main drains. These two main drains formed the boundaries of the project area. From their confluence at the eastern extremity of the project, the drainage and escape water were discharged into an outfall.

The drainage network consisted of 170 km of main drains, 120 km of branch drains, 370 km of collector drains, and 1050 km of field collectors. Total length was 1710 km.

Average drain depth was 2 m for the main drains and 2·5 m for the collector drains, varying locally according to the topography and branch canal depths. Along one side of the collector drains a continuous road was provided to allow access for cleaning equipment. Bed slopes of the main drains and collectors varied according to the slope of the ground surface and ranged from 0·015 to 0·1 per cent. As a dragline was to be used for drain construction, the bed width was designed at 1 m with side slopes of 1:1.

Construction of the system began in 1953 and was completed towards the end of 1956. Construction costs amounted to about 5 million Iraqi dinars (calculated in 1956).[1]

During its initial stage, project operation depended on the population's progress in getting settled and becoming accustomed to the new practices of pasture and summer crop cultivation. According to plans, as long as the project was only partly operational, surplus water would be required to maintain commanding levels in the irrigation canals, resulting in considerable waste.

Road system and bridges

A number of communities and a proper connecting-road system were planned. The two main communities established during the execution of the project were Imam and Rashaid. Since no decision had been reached as to whether the farmers would live on their land or in small outlying villages, the number of roads and bridges was initially limited.

The main access road to the project, running along the main canal, adjoined the Baghdad–Hilla road. This access road was actually the embankment of the main canal and was unpaved. No secondary roads were planned at the start of the project, since no final decision concerning their construction or maintenance had been reached. However, access by truck to any plot was possible along the branch and lateral canal embankments or along the drain-maintenance roads.

Besides the bridges incorporated in the regulation structures, a number of road and foot bridges across the canals and laterals were planned. The location of these bridges was derived from a road and track pattern assumed on the basis of existing community locations. The design capacity of the road bridges was based on a live load of 20 tonnes; design of the foot bridges was based on a live load of 400 kg/m^2.

Two road bridges were constructed across the main canals, one at km 12·3 along the Baghdad–Hilla road, the other at km 34 near the Cutha site along the Suwairah–Cutha–Mahawil road. Two bridges across the north main drain, two across the south main drain, and one across the outfall drain were also included in the design.

The first stage of operation (1956–65)

Irrigation and drainage systems

Before describing the irrigation, drainage, and soil

1. One Iraqi dinar = U.S.$2.80.

conditions resulting from the first stage of operation of the project, it is worth quoting Nugteren's report (Nugteren, 1956) on the design of the GMP irrigation and drainage system to the Directorate of Irrigation in March, 1956:

> . . . since the designs for this project are nearly completed and the construction is proceeding well, it is hoped that the scheme can be put into operation within reasonable time. However, due to lack of time, a number of unknown factors existed during the whole or a part of the design stage which prevented very accurate engineering and which certainly will require adjustments in the field, although every effort has been made to reduce the extent of their effect. These factors are mainly:
> - no experimental data were available on water requirements of the proposed new crops;
> - the size of farm-units and the system of land division were decided upon when the design and construction had been partly carried out already;
> - no semi-detailed land classification was made available.
>
> If time allows, no design should be started unless these points have been studied.

Land distribution began during the construction of the irrigation and drainage system and continued until 1960. After less than four years of operation only 71·6 per cent of the units had been distributed. It was found that 11 per cent of the settlers were not actually living on the farms but farming their land as share-croppers. About another 3 per cent eventually left.

A survey in 1959–60 of the types and distribution ratios of crops showed more development in the upper and middle reaches than at the downstream end of the project. The plot area irrigated averaged 5·5 ha for winter crops and 3 ha for summer crops, so that each year 8·5 ha of each irrigable farm-unit was cultivated. The effective size of a farm-unit was 13·24 ha after decuction of the area allocated for roads, canals, farm houses, drains, etc., which means that 64 per cent of the area of each farm-unit was being exploited. However, for the entire project area this represented a total irrigated area of about 15 500 ha in the settlement part of the project, out of an area of 50 000 ha, or 31 per cent of the land originally designed for irrigation.

As technical staff and manpower were limited, this under-utilization of available land caused maintenance of certain portions of the irrigation and drainage network to be neglected. As a result, canals and drains were rapidly clogged by weeds and by water-borne and wind-blown silt. Other factors such as the lack of extension services, an inadequate technical infrastructure, and insufficient agricultural machinery also contributed to the initial failure of the project.

By the beginning of 1960, after only a few years of operation, much of the project's infrastructure was simply breaking down. In his report, Krishnamurthy (1960)[1] observed several symptoms of major deterioration.

First of all, water regulation was seriously impaired. The radial gates to the head regulator had been fitted in the wrong position, so that the heavy silt-laden water of the river's bottom layers was drawn into the canal system (instead of the clear surface water). This resulted in heavy silting in the leading canal above the head regulator, and in the main canal below. Discharge from the head regulator was thus also impaired, giving a water discharge below that of the design at full supply level.

Hardly any of the secondary regulators had been properly maintained. In many places gates were stuck, damaged or out of alignment, making water-supply to the adjoining farms extremely difficult to regulate. Off-takes were soon clogged with debris. In the branches and laterals conditions were worse. The gates of some cross regulators and drop-structures had been completely dislodged from their housing; others had been badly tampered with and roughly manipulated. Few of the regulators showed signs of greasing or oiling and all were in need of paint.

At the canal head-works, the river banks in the vicinity of the intake were to be protected by dry-stone pitching resting on a filter layer. It was noticed that this pitching, designed to act as a free draining material to keep the subsoil behind it well drained, was disturbed and overgrown with plants and shrubs. Plant roots clogged the interspaces, impairing drainage. It was likely that in the event of a high flood the stone pitching would collapse under the excessive pressure, since the subsoil would not be able sufficiently to discharge the collected water.

The canals had also undergone major deterioration. Along the main canal the bench-marks used for survey and restoration or construction work were missing or had been damaged. Those along the branches were in even worse condition. None of the channels, including the main canal, had distance marks.

The maintenance of laterals and sublaterals required silt and weed clearance, but this was either seldom or improperly done. During excavation (either manual or mechanical, depending on channel size) excavated material had been dumped haphazardly as spoil banks and had eventually slipped back into the channel through rain and wind erosion. This could be one of the reasons for local sand-dune formation. Too-frequent silt clearance, uncontrolled as to depth or width of cut, had noticeably affected channel characteristics, creating uneven canal beds and banks.

Originally, the main canal had been equipped with berms 7 m wide for protective purposes. Most of these, it was observed, had been greatly changed by silting and erosion, and in some places had almost disappeared completely. In the main canal, bank scouring and sand-bar formation were so extensive that the canal looked more like a river than an artificial channel. In the smaller canals where water flow was slower, deterioration was even more extensive.

Finally, siltation and weed growth had had disastrous effects on the escape and drainage systems, clogging the main escape structure. The secondary escapes had almost collapsed. Furthermore, blocked drainage was causing a rise in the water-table of irrigated sections, to a level very near the land surface. In the secondary and field drains, spaced 330 m apart, frequent pools of stagnant water occurred, and in two cases actual reversal of water flow was

1. K. V. Krishnamurthy, 1960, *The Greater Mussayeb project: a preliminary report on some operation problems.*

observed. In these cases the level of the water-table was noted as being 1·5–2·0 m below ground level. Had drainage been operating normally, this level would not have risen to within 2 m of the ground surface, and water current in the direction of the two main drains would have remained visible.

Changes in soil conditions

All the soils of the area had been classified as saline, their saturated extracts having a conductivity of more than 14 mS/cm. In the areas near the drainage canal, especially near the main drains, soil salinities fell below these limits, but on the whole salinity was fairly high—in some cases exceeding 20–30 mS/cm. In the vicinity of the irrigation canals, particularly along the banks of the main canal, the surface salinity was higher and deliquescent salt was widespread. Except at points farthest away from the main and secondary drains, salt crusts were rarely seen at the surface.

During the period from 1960 to 1964 leaching experiments confirmed that leaching the salts from the soils presented no difficulty provided that a sufficient quantity of water and an efficient drainage system were assured. In view of the high permeability of the soils it was believed that 20–40 days of leaching would be sufficient to reduce salinity to tolerable levels. Unfortunately, neither the supply of water nor the efficiency of the drainage system proved adequate. At the end of summer, the ground-water table, which varied between summer and winter by as much as 2 m, was 2–2·5 m below ground surface, except in the immediate vicinity of drains. From existing studies it appeared that the main salt present in the ground water was NaCl. Calcium and magnesium sulphates were also present. The frequent presence of salt incrustations, sometimes of marked thickness, noticed on the bottom of some apparently operating drains, indicated that discharge by the main drains was not operating efficiently at that time. Thus as a result of insufficient water application and inadequate drainage, the desired results of leaching were far from realized.

Changes in natural plant and animal life

Before the introduction of irrigation, the natural flora (mostly of secondary origin) and fauna of the GMP area existed in a balanced ecosystem typical of dry lands. The plant life, consisting mainly of thorny shrubs, served as primary producers as well as cover for many wild animals, such as wild pigs, hyenas, rabbits, foxes and wolves. The ecosystem's secondary producers and consumers were equally well balanced. Resources for the nomadic herdsmen of this largely uncultivated area lay in the edible plants (exhaustively used for fodder), woody shrubs (used for fuel), and natural game, including deer, rabbits, and wild pigs.

When irrigation was introduced, many of these balanced associations were disturbed, the following being the most obvious changes:

— When the irrigation and drainage canals were established many hydrophilous plants, including *Phragmites communis, Typha angustata,* and *Cyperus rotundus*, were observed growing along the canals and ditches. As the irrigation and drainage networks deteriorated during the early phases of operation, this plant growth increased, sometimes even blocking the canals.
— Increased salinity proved favourable to the growth of halophytes in abandoned farm lands. The pioneer and most widely spread species was *Suaeda baccata*. The most common associate of the halophytes in the deserted lands was the deep-rooted *Prosopis farcta*.
— A large variety of weeds appeared in the irrigated lands, and soon flourished in the absence of control measures.
— Wild pig and deer almost completely disappeared, and hunting consequently diminished in the area.
— Wolves and hyenas, killed by farmers to protect their livestock, decreased drastically in number.
— There was a relative increase in the number of foxes and rabbits.
— The number of rodents, in general, decreased.
— Fowl such as wild duck increased in numbers.
— The population of birds such as sparrows, pigeons, doves, and rooks greatly increased, while other birds such as black kites, hen harriers and partridges greatly decreased in number.
— Some wild birds such as falcons almost disappeared from the area.
— Reptiles, in general, decreased in number.
— Jerboas and hedgehogs showed a relative increase.

Human settlement

Settlement of the project area was to be effected by people from outside the immediate area. As construction proceeded and it became known that a new settlement project was to be established, increasing numbers were attracted to the area, mainly from nearby tribes. In 1954 the population was estimated at 3000 persons, most of whom had applied for an allotment. By 1956, when the farm-units were distributed, population had reached an estimated 5000–6000 inhabitants. During land distribution a number of units were taken up by absentee landlords and the farming on these units was carried out by tenant farmers and labourers.

Many settlers left as canal deterioration and increased salinity reduced productivity in the area. By 1960 an estimated 55 allottees had abandoned the settlement, and by 1964 only 1458 allottees remained. In addition, the number of units retained by outside landholders had dwindled to 347 and about 70 farm-units lay unutilized. By 1965 some 700 700 additional units had been distributed and the population had climbed to an estimated 14000–15000 persons. Population density and farm-family composition recorded for the period 1964–65 based on Imam and Rashayed district populations are shown in Table 11.

When land distribution began in 1956, the construction of twenty-three integrated villages, with complete community facilities, had been planned for the settlers. By 1959 two of the planned villages,

TABLE 11. Farm population and family composition in Imam and Rashayed districts in 1964–65

Farm population and family composition	Rashayed district	Imam district
Number of farms	385	155
Total population	2486	935
Average number of persons per farm	6·5	6·2
Adult population (over 14 years of age)	1293	448
Average number of adult persons per farm	3·4	3·0
Number of adult males	649	199
Number of adult females	644	249
Children and aged (inactive population)	1193	487
Inactive population as a percentage of total	48	52
Average number of inactive persons per farm	3·1	3·2

Imam with ninety-eight houses and Rashayed with seventy-seven houses, had been constructed. Each of the villages was provided with a primary-school building, a market, a coffee shop, a public bath house, a clinic, and a building for shops.

The houses were of masonry and consisted of two rooms each measuring 4 m^2 and a covered veranda, measuring 5·5 × 4 m. The veranda was closed at the back but left open at the front to allow for added construction; a condition of ownership was that construction be completed by the allottee himself. Thus minimum living space during the initial settlement period was provided, and each allottee would have the possibility of enlarging his house according to his family's needs and taste.

By this time, however, most settlers had already built mud houses on their own farm-units, and as these structures were naturally better adapted to the local life-style, most of the new constructions were left unoccupied.

This rejection of government housing can be explained by a number of local attitudes and customs. Chiefly cited among design drawbacks were:

— Lack of intimacy: Local traditions required that family life should be secluded in every respect. Thus all windows should have faced into the courtyard rather than outside and the courtyard should have been surrounded by high walls. Many settlers expressed fear of being robbed.
— The small size: Most family life is centred around the courtyard, and therefore its spaciousness is a prime requisite. Since the social life of men is quite separate from that of women, an additional separate room should have been provided for the head of the family to receive guests and carry on business. Additionally space should also have been provided for livestock, traditionally kept in an adjacent mud hut.
— The design was too modern for the very traditional population.
— The houses were too far from the farms.
— Completion of the houses involved costly materials.

Attitudes to modern agriculture

The lands were distributed mostly to pastoral nomads with few savings and very low standards of living. Most of the allottees had very limited experience in farming, and over 95 per cent were illiterate. A good number of allottees had no intention of becoming farmers, and some discouraged farmers soon abandoned their farms. Thus it was obvious that the farmer, with his poor financial and technical means, could not utilize the land satisfactorily.

For those who remained, agriculture became increasingly exploitative, on a semi-nomadic basis. Consequently fields were in general neglected and crops were often overgrown by weeds. In addition, idleness among the farmers became increasingly common, and much time was spent in the cafés located at the entrance to the project area. In fact, the farmer's lack of motivation to improve his situation was one of the area's main social problems. Social life, incentives, and adequate leadership did not exist.

Co-operatives

According to the agrarian law of 1958, each allottee was expected to join a multi-purpose agricultural co-operative society, providing credit, marketing and supply facilities. The isolation of the farmer's families on their own lands, however, did not help to develop the communal and co-operative spirit which the government had hoped for.

There are eleven districts in the Greater Mussayeb Project area, almost one for each branch of the canal, and a co-operative society was planned for each. By 1965 four co-operatives had been completed. During the first phase of operation the co-operatives had little impact on the farmer's life. Their main activity was that of supplying consumer goods to the farmers.

Education

Coming from the poorest section of the population, the allottees were almost all illiterate. However, they eagerly sent their children to school. Originally two primary schools were built—one in Imam and one in Rashayed. The schools were assiduously attended by the children, but hardly any teaching aids were available. The long distance from farm to school was a common obstacle to regular attendance. On the average, there were 100–120 pupils in each of the primary schools.

Health

Neither of the two health centres initially established in Imam and Rashayed was under a medical supervisor. Very little work was done in the field of preventive medicine, maternal and child care, environmental health, or health education. Preventive medicine was limited to smallpox vaccination. In both Imam and Rashayed there was a water-treatment plant, but chlorination never functioned properly. Further, no sewage removal facilities were provided. On the farm-units, water was taken directly from the field canal. Before the end of the first stage of operation the health centre in Imam was closed. In general, the out-patient clinics at Imam and Rashayed have not had any far-reaching effects on the health conditions of the population in the project area.

The project was chiefly plagued by tuberculosis and infectious childhood diseases, and infant and child mortality was extremely high. Malaria eradication was begun in 1957, and in 1960 there were no recorded cases of the disease.

A 1960 report on schistosomiasis revealed that on average the disease affected 29·5 per cent of the population (25·2 per cent females and 32·4 per cent males). The age distribution of the disease was as follows: 0–9 years, 32·7 per cent; 10–19 years, 51·1 per cent; 20 years or over, 23·2 per cent.

In spite of these findings, the authors of the report could never find the snail vector in the area of the project. It was concluded that, although schistosomiasis existed in the project area, as a residual of imported chronic diseases, it was not transmitted to fresh individuals, because of the lack of intermediate hosts. The most prevalent intestinal parasites encountered in the project area were hookworm and ascarids. A random survey indicated that 19·3 of the population were affected by hookworm and 33·1 per cent by ascarids.

There were also many cases of anaemia in the area, and the population in general was undernourished.

Agricultural economy

Cropping systems

According to the project plans, semi-intensive cultivation was to be practised initially and developed gradually into more intensive cultivation. Contrary to these plans, agriculture was practised on an extensive basis during the first years of operation. The settlers continued to cultivate their lands according to the traditional *nirin* system, leaving about half of the cultivable area fallow. Taking Rashayed and Imam districts as representative of the project area, it was found in 1964–65 that the net area for crop production averaged about 7·5 ha per farm-unit of 16·7 ha (Table 12).

TABLE 12. Cropping system in representative farm-units in the Greater Mussayeb Project (1964–65)

Crop	Hectares	Crop	Hectares
Winter crops		*Summer crops*	
Wheat	3–4·5	Cotton	0·25–0·5
Barley	1–2	Green gram	0·5–0·75
Alfalfa/Clover	0·25	Vegetables	0·5–1·25
Onion	0·25	Sesame	0·25–0·5
Horsebean	0·5–1		
		TOTAL	1·5–3
TOTAL	4–6·5	Average	2·25
Average	5·25	TOTAL CROP AREA	7·5

The inefficient drainage system during the early phase of operation did not allow proper leaching of the soil. In a few cases where drainage was efficient, the salt content was lower and the crops appeared almost satisfactory. In lands where the drainage system was operating poorly, the few surviving plants had a stunted development, and halophytic weeds invaded the land.

Wheat and barley were the two predominant crops. Production was limited to the needs of a subsistence economy and only a small part of the production was devoted to cash crops. Besides maintaining the *nirin* system of farming, farmers used unselected low-yield, indigenous varieties of seeds and did not apply fertilizers except on tomatoes and cucumbers.

In the absence of well-established figures, the following estimates reflect the average productivity during the early stage of operation:

Crop	*Yield (kg/ha)*	*Crop*	*Yield (kg/ha)*
Wheat	600–800	Cotton	500–600
Barley	720–880	Sesame	600–800
Beans	400–600	Berseem	4 cuttings

The uncropped land had a limited use as autumn and winter pasture and was then left completely fallow.

Machine operations were very superficial, affecting only the top 15–20 cm of soil; disc harrows were mainly used. Animals were sometimes used for ridging and light harrowing. Hoeing was rarely done; hand weeding was more frequent. Harvesting was done by hand and the farmers helped each other at that time. The threshing of cereals and leguminous crops was carried out by animals treading the cut plants.

The products required for farm purposes were stored in holes excavated in the ground. All crop residues were fed to livestock. Each family had a small vegetable plot to supply its own needs.

Afforestation

By 1964 three eucalyptus forests, each covering about 100 ha, had been planted by the government to provide raw materials for the paper industry. A few wind-breaks were also planted along the branch canals and drains. The seedlings used for the forest and the wind-breaks were mainly *Eucalyptus* and *Casuarina*. Some of the farmers managed to set up secondary wind-breaks with sesbania and poplar trees.

Livestock

Every farmer had, on average, two draught animals, a horse and a donkey. About two-thirds of the farmers raised one or two cows of the indigenous breed. Sheep of a local variety were also frequently raised.

Marketing of agricultural products

Production in the Greater Mussayeb Project was low, and the major portion, especially cereals, was consumed on the farm. The marketable surplus of cereals, fruit, and vegetables, including okra and egg plant, was small. The main cash crops—cotton, onions, cucumbers, tomatoes, and water-melons—were marketed occasionally. A few sheep and goats were also sold, but generally not more than between two and five.

From the marketing point of view, the Greater Mussayeb Project is favourably located and fairly well connected with outside markets. There were, however, no branch roads connecting the farms with the main canal road.

During the first phase of operation, the co-operative societies had very little impact on marketing, only in rare cases extending noticeable services. Most commonly the farmer carried his small marketable surplus to the nearby markets at the junction between the highway and the main canal road—about 23 km from the Greater Mussayeb Project Authority headquarters. In addition to Hilla, at a distance of 58 km, the small towns of Mahmudiya at a distance of 48 km and Yusifa, 63 km, provided market outlets for domestic animals and vegetables.

Per capita income

After a few years of operation, the farmers found it increasingly difficult to obtain a satisfactory return from their efforts. Production soon declined and the yield of grains dropped to the lowest level for irrigated farming in the Near East. Low productivity forced the farmers to depend increasingly on private loans from merchants outside the area. This form of exploitation complicated matters for the poor farmer and resulted in a continuous reduction of per capita income. During this stage, the average annual per capita income was as low as 25 ID.

Period of rehabilitation (1965–68)

The Greater Mussayeb Project Authority

The phase of rehabilitation and development of the project was initiated in 1965. At that time the government stepped in with the aim of reclaiming the soil and developing all aspects of irrigated farming. The Greater Mussayeb Authority was established and this semi-autonomous administration with multi-sectoral authority was given the task of rehabilitation.

The second phase coincided with the new five-year national economic plan for 1965–70, and a sum of 4 million ID was allocated for the Greater Mussayeb Project. Additional assistance was obtained from UNDP through FAO. During the period 1965–68 some progress was made on the construction of administrative buildings, housing, a mechanical workshop, and a main road running west to east through the project area. Drinking water and electric-power supply lines were also provided. Cleaning up of the silted irrigation and drainage networks, however, was largely omitted.

In 1965, in order to overcome the problems encountered during the initial stage of project implementation, the Greater Mussayeb Authority restated its objectives. Agricultural, economic, and social development of the Greater Mussayeb Project would be promoted through:

— land reclamation works for national agricultural development, including topographic, soil, ground-water, and socio-economic surveys, as well as land levelling and restoration of irrigation and drainage systems;
— improvement of the soil and the creation of a new productive system including leaching, fertilizer application, introduction of suitable crops and animals, mechanized services and the establishment of training centres and research programmes;
— the improvement of community standards, both materially through the construction of roads, housing, public services, drinking-water facilities, electrical networks and credit and marketing facilities, and socially through the promotion of greater community interest and responsibility.

It was recognized that salinity was the major problem in the project and that it had resulted from deterioration of the irrigation and drainage systems. The rehabilitation programme put great emphasis on the restoration of this network and on the improvement of agricultural and management practices. In relation to these aspects, a UNDP/FAO-assisted programme of action consisting of a reclamation and irrigation pilot project to cover a representative portion of the total Greater Mussayeb Project area was initiated in 1970, after five years of detailed investigation between 1965 and 1970.

Impact of irrigation on soil salinity

Studies carried out between 1965 and 1969 for the rehabilitation of the project indicated that approximately 66 per cent of the soils in the project area had been affected by salinity. Of these, 50 per cent were slightly to very strongly saline (4–25 mS/cm) and 16 per cent were severely affected (more than 25 mS/cm). Soil salinity was related to soil texture and topography. The salinity of light-textured levee soils, except for a surface crust, was low compared with that of fine-textured soils. In both units, soil salinity reflected the salinity of the ground water, both in intensity and chemical composition (Dougrameji *et al.*, 1970).

The relationship between ground-water salinity and soil salinization is shown in Figure 4, and the ratio of the percentage of salt in the water to the percentage of salt in the soil is shown in Table 13. (The dominant cation in the ground water was Na^+ and the dominant anion, Cl^-; overall salinity was high.) An increase in ground-water salinity corresponds to an increase in soil salinity. The ratio of ground-water salinity to soil salinity ranged from 2·0 in low-levee soils to 3·8 in high-levee soils. The most likely explanation for this high ratio lies in the history of the project.

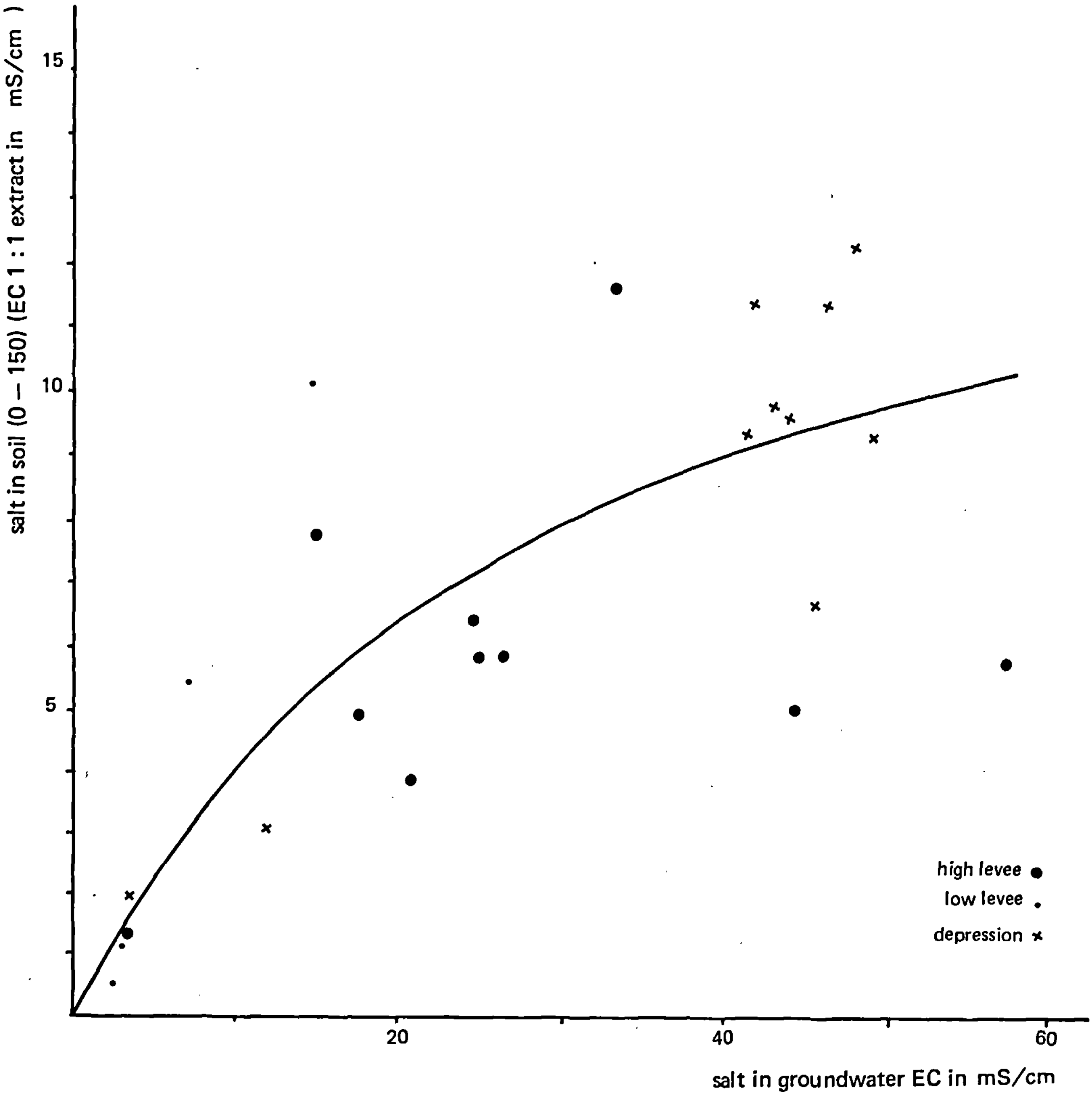


FIG. 4. Relation between ground-water salinity and soil salinization (EC = electrical conductivity)

A salinity survey of a representative pilot area (NEDECO, 1959) indicated that soil salinity varied from very low to very severe. The salinity classes observed are shown in Table 14.

Types of soil salinity varied from place to place. Shura salinity due to the presence of sodium salts in the soil layers, and Sabkha salinity caused by deliquescent salts at the surface, were commonly found. Puffed solonchaks occurred less widely, but could be found in the silted basin depression in the pilot area and on the high-lying irrigation levees that mark the courses of ancient canals.

Crop production

During the period 1965–68, low productivity persisted, although some improved crop varieties were used and application of fertilizers was slightly increased. Table 15 shows annual cultivated areas and average production in the GMP during this period. Average annual per capita income was estimated at 40 ID.

TABLE 13. Soil and water salinity data, and depth of ground water

Item	High levee (9 holes)	Low levee (3 holes)	Depression (10 holes)
Average salt in soil (%)			
0–30 cm	0·44	0·12	0·56
30–60 cm	0·46	0·13	0·67
60–90 cm	0·46	0·28	0·70
90–120 cm	0·46	0·31	0·75
120–150 cm	0·49	0·20	0·78
0–150 cm	0·46	0·19	0·69
Average salt in water (%)	1·73	0·38	2·33
Ratio salt in water (%) to salt in soil (%)	3·8	2·0	3·40
Average depth of ground water below surface (cm)	206	151	165

Population

Despite the fact that productivity declined and that many farmers abandoned their settlements, land distribution to new farmers continued until 1967. In 1968–69 an estimated 24000 people were living in the project area in 3054 families. The average number of persons in each family was about eight.

Education

Originally two primary schools existed in the area, one in Imam and one in Rashayed village. After 1965, more schools were established, and in 1968–69 there were seven primary schools and one intermediate school.

It should be noted that almost no farm girls attended school; the girls who did attend belonged mainly to families of project employees. Not even all the farm boys were sent to school. There were about 370 pupils for every 10000 inhabitants, compared with the national figure of 1158.

Illiteracy among farmers remained as high as 95 per cent, and there existed neither adult education nor any form of vocational training.

Health

During this period a main health centre was established in the administrative centre of the project. It was directed by a medical officer, assisted by a health official and two aides (one male and one female). The equipment of the centre was limited and there were no laboratory or X-ray facilities.

On the average, 80–100 patients came for consultation each day. The main cases were infantile infectious diseases, tonsillitis, enteritis, intestinal parasites, skin diseases and respiratory infections. Tuberculosis also remained a problem in the area.

TABLE 14. Salinity classification of soils in the Greater Mussayeb pilot project

Salinity class	EC (mS/cm)	Distribution (%)
Not saline to slightly saline	0–4	28·5
Slightly saline	4–8	30·0
Moderately saline to strongly saline	8–15	10·5
Very strongly saline	15–25	10·5
Severely saline	25–50	8·5
Extremely saline	50	8·5

TABLE 15. Average area cultivated annually and average production in the Greater Mussayeb Project

Product	Area (ha)	Farm yield (kg/ha)	Total yield (tonnes)
Wheat	11250	1200	13500
Barley	3750	1400	5250
Broad beans	500	800	400
Winter vegetables	500	—	—
Cotton	500	800	400
Green gram	2500	1000	2500
Onions	1250	6000	7500
Water-melons	750	3200	2500000
Summer vegetables	750	6000	4500
Ground-nuts	250	—	—
TOTAL	22000		

Period of new land reclamation and development (1968 to present)

After the visit of President Al-Bakr to the Greater Mussayeb Project in 1968, immediate remedial measures were taken. Clearing of the main canal began in 1968. By 1969 it was completely cleared to its original depth and design capacity, and the branch canals were also cleared. After restoring the irrigation and drainage networks, the GMP Authority undertook the important tasks of land reclamation and farm development. The main road connecting the project area with the Hilla–Baghdad highway was paved in 1969. From 1969 to 1974, about 1500 out of a total of about 3000 farm-units were developed and additional data were collected for effective land reclamation and the selection of suitable cropping patterns. These included the classification of the soils according to their suitability for specific cropping patterns, taking into account their texture, salinity and response to reclamation practices.

After these new cropping patterns were established, more detailed calculations than in the past were to be made of the irrigation requirements, by using more modern formulae to estimate the consumptive water uses of the crops, or by determining these uses experimentally *in situ*. These determinations required further collection of agro-climatological data.

A proper drainage system design was drawn up using the knowledge of such soil-physical properties as the permeability (K) and the depth (D) of the layer through which the flow of ground water towards the drains principally takes place. Flow rates in the drains were determined by the amount of water needed to control salinity in the soil.

Additional data collected

Solar radiation and potential evapotranspiration

In the early 1960s a network of sunshine recorders had been established, and the stations at Baghdad and Nasiriyah were representative of conditions in the project. Daily average total global radiation varies from about 1·92 kW/m^2 in the peak of summer to about 0·58 kW/m^2 during the coldest part of winter (Table 16).

Potential evapotranspiration determined by the Penman formula is shown in Table 17.

Soil units

The soils of the Greater Mussayeb Project area are of recent origin, and since there is little profile development, the depth of the solum was taken arbitrarily as 2 m, or the depth of the water-table where the water-table was less than 2 m deep. Classification of soil type was based on the texture of the surface soil (40 cm), the subsoil (120 cm) and the substratum (120–200 cm), the textures being grouped as follows:

- fine-textured soils (clay, silty clay, sandy clay);
- medium-textured soils (clay loam, silty clay loam, sandy clay loam, silty loam and loam);
- coarse-textured soils (sandy loam, loamy sand, sand).

The soils are generally light greyish brown in colour and highly stratified, especially in the subsoil and substratum, as a result of continuous flood and irrigation deposition. Textures of the various strata range from fine sand to clay, with silt loam and silty clay loam predominating in the surface soil.

Soil structure, even in the finer textures, is weak and unstable. Although the aggregates may become very hard when dry, they disperse rapidly when moistened. Silt and carbonate content are high. The presence of soluble salts, particularly with high exchangeable Na, tends to create this unstable structure. Eight physiographically based soil units have been identified in the project area (Fig. 5) and are described below.

1. *Irrigation levee soils.* Located along rivers and old irrigation canals and closely related to major irrigation systems of the past and present, these soils are topographically higher (2–3 m) than the river basins. Weak angular blocky in structure, the soil is generally coarse to medium in texture, both at the surface and in the subsoil; sometimes texture becomes fine in the subsoil. Average profile characteristics are:

pH	ESP[1] (%)	CEC[2] (%)	Gypsum (%)	Carbonate (%)	OM[3] (%)
7·0–8·9	1·1–64·2	6·6–31·4	0·2–4·3	20·1–33·5	0·18–1·4

1. ESP = exchangeable sodium percentage.
2. CEC = cation exchange capacity.
3. OM = organic matter.

2. *Silted river-basin soils.* Most of the soils of this extensive unit are located in areas adjacent to the north and south main collectors. They were formed above the original river basin by the deposition of irrigation sediments during some thousands of years of irrigation. The texture is medium to fine at the surface and in the subsoil and substratum. The structure is weak-to-medium angular and sub-angular blocky. Average profile characteristics are:

pH	ESP (%)	CEC (%)	Gypsum (%)	Carbonate (%)	OM (%)
7·6–8·1	2·4–35·5	8·0–34·6	0·2–4·3	22·1–35·4	0·2–1·5

3. *River-crevasse soils.* This soil, found in small areas near the main Mussayeb and older irrigation canals, was formed as a result of breakage of river banks, erosion of the soil, and deposition of river sediments. The surface and subsoil texture is therefore coarse to medium. Structure ranges from structureless in coarse textured soils to weak sub-angular blocky in medium-textured soils. Average profile characteristics are:

pH	ESP (%)	CEC (%)	Gypsum (%)	Carbonate (%)	OM (%)
7·5–7·9	3·0–27·6	6·8–33·0	$<$0·2	17·3–28·9	0·9–1·5

TABLE 16. Mean monthly total radiation (in kW/m^2 per day)

Station	January	February	March	April	May	June	July	August	September	October	November	December
Baghdad	0·78	0·99	1·30	1·49	1·73	1·93	1·89	1·75	1·50	1·11	0·82	0·69
Nasiriyah	1·08	1·25	1·49	1·73	1·73	1·79	1·84	1·86	1·72	1·43	1·00	0·89

TABLE 17. Mean monthly potential evapotranspiration (in mm)

Station	January	February	March	April	May	June	July	August	September	October	November	December
Baghdad	47·6	74·6	125·7	170·9	235·1	294·9	304·7	269·1	197·8	137·6	72·1	42·3
Habbaniyah	43·0	73·0	125·0	170·0	235·0	298·0	329·0	276·0	194·0	133·0	61·0	44·0
Diwaniya	38·0	60·0	106·0	152·0	200·0	291·0	311·0	265·0	197·0	131·0	66·0	40·0

FIG. 5. Soil unit map of the Greater Mussayeb Project

4. *Basin depression soils.* Covering a small area in the lower topographic position along the southern drain, this soil is a transitional form between basin and depression soils. Its texture is fine and the soil is characterized by wide deep cracks. Salinity is low due to the proximity of the main drain.

5. *Old river-bed soils.* Located in the centre of the project area, these soils are formed by the sediments of an old river-bed. Surface and subsoil texture is medium to coarse, and structure is weak sub-angular blocky. Average profile characteristics are:

pH	ESP (%)	CEC (%)	Gypsum (%)	Carbonate (%)	OM (%)
7·6–8·2	16·2–39·4	16·1–17·5	<0·2	24·8–28·8	0·4

6. *Silted 'hour'*[1] *soils.* These soils are formed by the accumulation of river sediment on 'hour' soils. At a depth of 70–120 cm, the soil is characterized by a bluish-green or black colour resulting from iron reduction and organic matter. Shells are also found in these soils. Texture is fine at the surface and variable in the subsoil. Structure is weakly developed blocky and sub-angular blocky. Average profile characteristics are:

pH	ESP (%)	CEC (%)	Gypsum (%)	Carbonate (%)	OM (%)
7·6–7·8	3·4–6·5	16·3–29·4	<0·2	31·0–35·2	0·8–1·0

7. *Levelled-dune soils.* Covering large areas throughout the project, these soils were formed as a result of dune levelling by farmers who then used the soil for cultivation. The texture varies in the substratum and is medium to coarse at the surface. Structure is weak and ranges from platey to sub-angular blocky in fine-textured soils. Average profile characteristics are:

pH	ESP (%)	CEC (%)	Gypsum (%)	Carbonate (%)	OM (%)
7·2–8·6	2·7–29·1	6·5–32·0	0·04–0·2	18·5–31·6	0·03–0·8

8. *Dunes.* These are distributed in different parts of the project and extend beyond the lower end of the south drain. They are mostly clay-silt dunes, and the parent material is transported by wind over the entire project area. Many of the silted basin depressions are covered by this material in a layer of variable thickness; the material also constitutes part of the sediments in the irrigation canals. The texture of these clay-silt dunes ranges from clay loam to sandy clay loam. The material is slightly saline and contains a high percentage of carbonates (30·5–31·5 per cent). The soil characteristics are similar to those found along irrigation canal embankments.

1. 'Hour' = local name for a shallow lake in the upper deltaic reaches of the Mesopotamian Plain.

Taking the UNDP/FAO pilot project as representative of the entire project area, the approximate percentage distribution of the main soil units is as follows:

- high-irrigation-levee soils: 28 per cent;
- low-irrigation-levee soils: 24 per cent;
- silted river basin soils: 41 per cent;
- silted 'hour' soils: 1·5 per cent;
- river-crevasse soils: 1 per cent;
- levelled sand-dune soils: 1·5 per cent;
- dunes and tells: 2 per cent.

Soil salinity

Further studies carried out (Dougrameji and Kaul, 1972) in a 1500 ha sample area located between km 27 and km 32 in the northwestern part of the project, and stretching from the Greater Mussayeb Main Irrigation Canal to the North Main Drain, revealed that 65·5 per cent of all the soils studied were moderately to strongly saline and 44·5 per cent were non-saline to slightly saline.

In the entire project area, the seepage from the irrigation canals and resulting high water-tables had caused serious salinization of the soils adjacent to the canals, and extremely saline soils were formed in a relatively short period of time, especially where no interceptor drain existed or where lands had been abandoned. Exchangeable sodium decreased from the light-textured levee soils to the fine-textured basin soils, with a corresponding increase in calcium and magnesium. In most soils high salinity was associated with high exchangeable sodium.

A soil-salinity map based on the standards for salinity set by the United States Department of Agriculture was prepared by the State Organization of Soil and Land Reclamation (SOSLAR) in 1974. The map classifies soil salinity into four main classes and two subclasses. The main classes are: very slightly saline, slightly saline, moderately saline, and highly saline. A simplified version of the detailed map produced by SOSLAR is shown in Figure 6.

Hydro-physical properties of the soils

A review of the initial investigations carried out in the project for the design of the irrigation and drainage systems clearly showed that these studies were not sufficient. Apart from a few scattered permeability measurements and consumptive-water-use values, no initial studies were made of the hydro-physical properties of the soils. These properties provide a more constant and reliable soil index than the highly variable salinity values, which reflect the conditions at the time of measurement only. Not until 1968, at the beginning of the rehabilitation stage, was emphasis finally given to the hydro-physical properties of the soil in the project area (Saif and Al-Jawher, 1974). These included permeability, soil-moisture characteristics, porosity and infiltration rates.

Permeability. Hydraulic conductivity measurements using the auger-hole method were conducted in 948 locations and at depths of 2·5 and 3·5 m. These

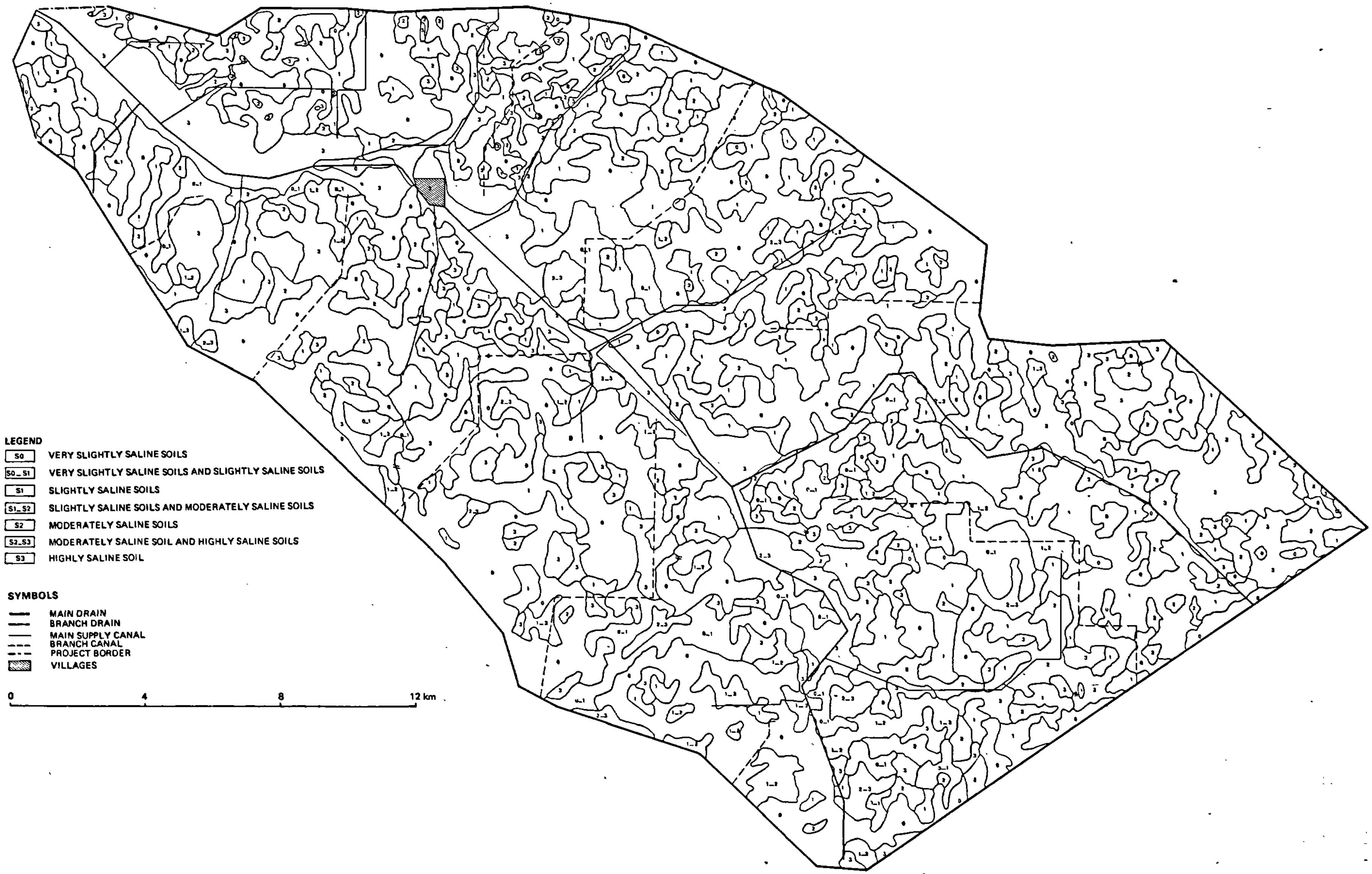


Fig. 6. Soil-salinity map of the Greater Mussayeb Project

measurements revealed quite a variety of permeability values, but a dominant value of 1·2 m/d was adopted. Simultaneously, a more detailed study (Dougrameji *et al.*, 1970) was completed, and hydraulic conductivity, soil texture and soil-moisture characteristics were studied in three soil units, namely high-levee, low-levee and silted-river-basin soils.

The levee-soil profiles consist mainly of medium-textured irrigation deposits 3 m deep, with an average permeability of 1 m/d; the overlying clay had a permeability of 0·4 m/d. The river-basin profiles consist of medium- to fine-textured irrigation deposits 2·8 m deep, with an average permeability of 0·6 m/d. Permeability in the overlying clay was 0·4 m/d.

In certain localities the deeper clay layers proved to be more permeable than the overlying medium-textured soils. This could be attributed to better structure. Compact clay layers, greyish to blackish in colour, form the silted river-basin sediments. These layers contained mollusc shells, and gypsum was commonly present. It is generally considered that deposition took place mainly under anaerobic conditions. The clay layers underlying the levee deposits are more brownish in colour, with gypsum commonly present.

Occasionally, when holes were dug in the basin soils, it was noticed that there was an abrupt rise in water-table well beyond the first wet layer. This meant that, locally, an impervious to semi-pervious layer at a depth of 1–2 m was preventing the ground water from rising to the surface. In one auger hole the water-table rose from a depth below 190 cm (the depth of the first wet layer) to a depth of 106 cm in a single day. Table 18 shows the relationship between permeability and texture as encountered in the respective soil units. The fine-textured soils are shown to be of moderate-to-low permeability, the medium-textured soils are moderately permeable, and the coarse-textured soils are moderately to highly permeable.

Soil-moisture characteristics. In general, the moisture characteristics of a soil are related to its texture. The heavy-textured clay soils have high moisture percentages, as is the case with the basin soils. These soils contain over 60 per cent moisture at saturation, an average of 40 per cent at field capacity, and over 20 per cent at wilting point. The percentage of moisture in medium-textured high-levee soils is 50 per cent at saturation, 25 per cent at field capacity, and about 13 per cent at wilting point. The percentage of available moisture for each soil-texture class has been summarized in Table 19.

The moisture contents at field capacity and at permanent wilting were found gradually to increase as the soil became finer. The increase at field capacity, however, was not equalled by the increase at the permanent wilting point. The maximum available moisture is shown to be found in medium- and moderately fine-textured soils rather than in fine-textured soils. The calculations of the available moisture on a volumetric basis show the same trend as on a weight basis. Apart from texture, many other factors influence the water-holding capacity and the variation in moisture content.

TABLE 18. Relationship between soil texture and permeability

	Texture classification		
	Fine-textured soils (clay, silty clay)	Medium-textured soils (sandy loam to silty clay loam)	Coarse-textured soils (loamy sand and sand)
Permeability (m/d)	0·4	0·4–1·6	1·6

Porosity. The rate of downward movement of the process of drainage is determined by the size and shape of the soil's pores. Capillary and total porosity increase with fineness in texture, but for the non-capillary porosity the trend was not constant. The ratio of capillary to non-capillary porosity ranged from less than unity in coarse-textured soils to 1·2 in medium-textured soils and 1·5 in fine-textured soils. The effective (drainable) porosity was estimated at about 8–10 per cent.

Infiltration rate. Infiltration rates of different soil units were measured, using a double-ring infiltrometer, in thirty-seven locations. These data revealed that a moderately slow infiltration rate with a value of 0·5–2·0 cm/h was dominant (twenty-one locations). A moderate infiltration rate with a value of 2·0–6·3 cm/h was found in seven locations. Finally, a low infiltration rate with a value of 0·1–0·5 cm/h was encountered in seven locations.

Soil microbiology

Studies carried out since 1960 on the microbiological population and activity in the central Mesopotamian Plain indicate high counts of non-symbiotic nitrogen-fixing bacteria and lower counts of symbiotic nitrogen-fixing bacteria. Also, the nitrifiers and sulphate-reducing bacteria were low, but actinomycetes counts were high (Yousef *et al.*, 1976).

Several reasons for the difference in microbiological activities were suggested, including low organic matter and nitrogen content of the soil, type and degree of salinity, soil and air temperature, cropping pattern, soil texture and moisture content.

Potential land-use capability

From the soil-survey data, it was possible to evaluate the soil conditions, to delineate the areas which needed leaching and reclamation, and to define drainability classes for the different soil units. A potential land-use-capability classification map for the project was prepared on the basis of factors affecting or limiting the land use (Fig. 7). Texture (T), topography (t) such as *tells*, high lands and sand dunes (C) were considered to be permanent factors, while soil salinity and water-logging were considered as only temporary problems. It was assumed that all soil-reclamation activity would be completed before cultivation could be resumed.

On the basis of the above-mentioned criteria, the soils of the project were divided into the following four classes:

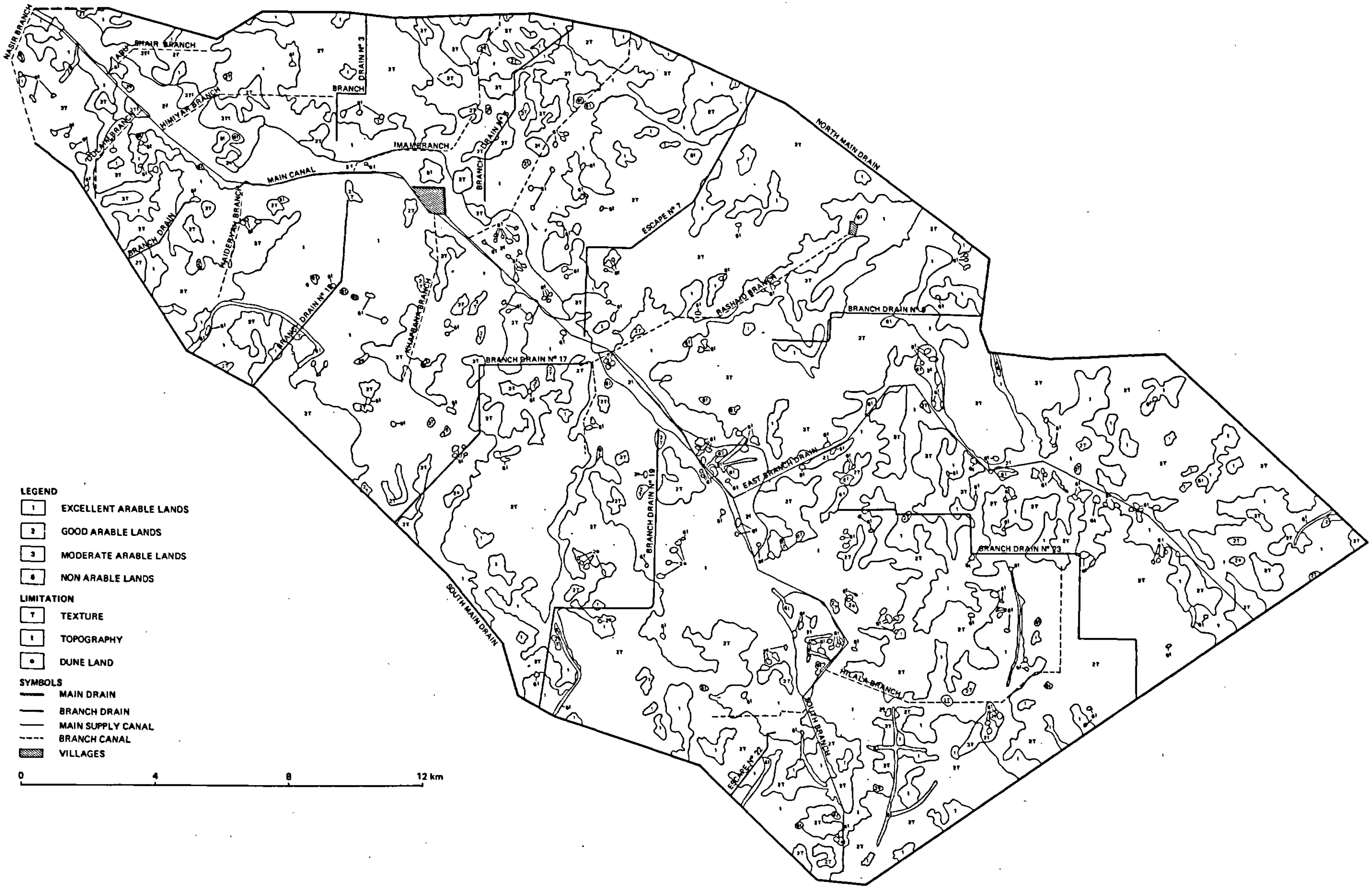


FIG. 7. Potential land-use capability classification of the Greater Mussayeb Project

TABLE 19. Soil properties and moisture retentions of textural classes of Greater Mussayeb Project soils

Textural class	Number of samples	Mechanical composition			Bulk density (g/cm³)	Moisture weight (%) at				Available moisture		Porosity		Ratio: Capillary porosity/ Non-capillary porosity
		Sand (%)	Silt (%)	Clay (%)		0 atm	0·6 atm	1·3 atm	15 atm	Wt (%)	Vol. (%)	Capil-lary (%)	Non-capil-lary (%)	
Sand	2	92·80	6·00	1·20	1·44	44·03	16·95	7·21	4·16	3·05	4·39	14·47	29·56	0·49
Loamy sand	1	85·35	8·20	6·45	1·40	45·55	21·40	9·47	4·63	4·84	6·78	21·91	23·59	0·93
Sandy loam	9	57·97	33·93	8·10	1·36	48·68	32·48	19·78	10·03	9·75	13·28	23·63	25·08	0·94
Loam	23	38·68	41·99	19·33	1·17	50·30	35·90	24·94	11·59	13·35	15·48	25·14	25·70	0·98
Silt loam	1	31·50	51·00	17·50	1·27	52·54	37·94	29·11	14·90	14·21	18·05	27·52	23·90	1·15
Silt								23·77	10·07					
Sandy clay loam								17·23	7·83					
Clay loam	2	25·88	40·32	33·80	1·25	53·39	39·21	31·11	17·14	13·97	17·36	29·65	22·67	1·31
Silty clay loam	8	17·90	45·61	36·48	1·25	54·05	40·64	33·05	17·56	15·49	19·30	32·08	21·02	1·52
Silty clay	2	15·45	41·75	42·80	1·23	55·33	41·93	33·90	20·55	13·35	16·42	31·51	22·50	1·40
Clay	42	19·00	31·85	49·15	1·17	55·87	42·46	34·41	21·18	13·23	15·48	32·44	22·85	1·42

1. *Excellent arable lands* (1). These soils are the most suitable for cultivation, after land-levelling and/or soil reclamation. These lands are characterized by a medium-to-coarse texture (loamy sand, sandy loam) at the surface and subsurface. They are suitable for all crops, vegetables, and trees.
2. *Good arable lands* (2):
   - good arable land (2T): the texture of this soil, which is fine in all three layers, is a limiting factor for utilization;
   - good arable land—dune lands (2C): the presence of sand dunes limits the utilization of this land; good management and agricultural practices are necessities;
   - good arable land—high topography (2t): these are medium- to coarse-textured soils (sandy loam or loamy sand). The high topography is a negative factor in the use of these lands; to be successful, irrigation should be supplied by pump.
3. *Moderately arable lands* (3Tf). The texture and topography of these soils plays an important role in their utilization. Characterized by fine-textured soils in one or all three layers, these lands must be irrigated by pump.
4. *None-arable lands* (6t). This category includes *tells*, and the higher sand dunes.

Aquifer properties

Data on aquifer properties were compiled from observations (Hassan and Van der Sluijs, 1970) carried out on shallow water wells located between Baghdad and Hilla. Out of twenty-eight wells examined, only twelve were of a depth greater than 13·5 m. In four, gravels were found in the bottom section. Three wells showed marked lithological changes at a depth of 12–13 m, and two became predominantly sandy at a depth of 15 m. Others exhibited a sequence of silt and clay over the entire drilled section of 40 m.

The boreholes drilled in 1955 (NEDECO, 1959) near the collector-drain pumping station showed a sequence of fine sand, silty clay, and clay over the entire section, except where layers of sand and gravel, about 1 m thick, appeared at depths between 9 and 11 m.

The log of the pumping well (Amer and Malik, 1973) shows that the greater part of the aquifer in the Hilla region has a texture of sandy clay loam to sandy loam. A clay layer of 2 m thick was encountered at a depth of 21 m and another, 7 m thick, at a depth of 123·0 m.

The average transmissivity (KD) around the test well was calculated at 600 m^2/d and the storage capacity was $1{\cdot}5 \times 10\,m^3$. The drawdown within a radius of 100 m was very low when water was pumped at a discharge rate ranging from 9·25 to 10·0 litres/s (the average constant value was 9·8 litres/s, i.e. 846 m^3/d).

The average depth of water-table was from 150 to 200 cm but rose under irrigation to within 100 cm of the surface.

In the study area (Dougrameji *et al.*, 1970) the ground water was found to follow roughly the same topographical contours shown in the two crosssections (Fig. 8).

Crop water requirements

Climatological data were collected in the project area during the period between 1972 and 1974 in order to compute potential evaporation from open-water wet soils, and short-grass cover (Hani and Pike, 1974). The total open-water evaporation (EO) amounted to 2500 m/y, and potential evaporation from a short green cover (ETP) was 2000 mm/y. Daily evapotranspiration rates (ETP) varied from 2·5 mm in winter to 9·0 mm during the peak summer months (Table 20). These data indicate that optimum cropping intensity would be in the order of 125 per cent, and any further increase in intensity would result in decreasing economic returns per water unit.

Crop water requirements (Hani and Pike, 1974) were computed with the aid of the potential evapotranspiration (ETP) values obtained from Penman's formula. Monthly factors were used for each crop-growing season. The figures thus obtained give low coefficients in the early and late growing season and coefficients in excess of unity during the peak growing season. Additional information was gained from a

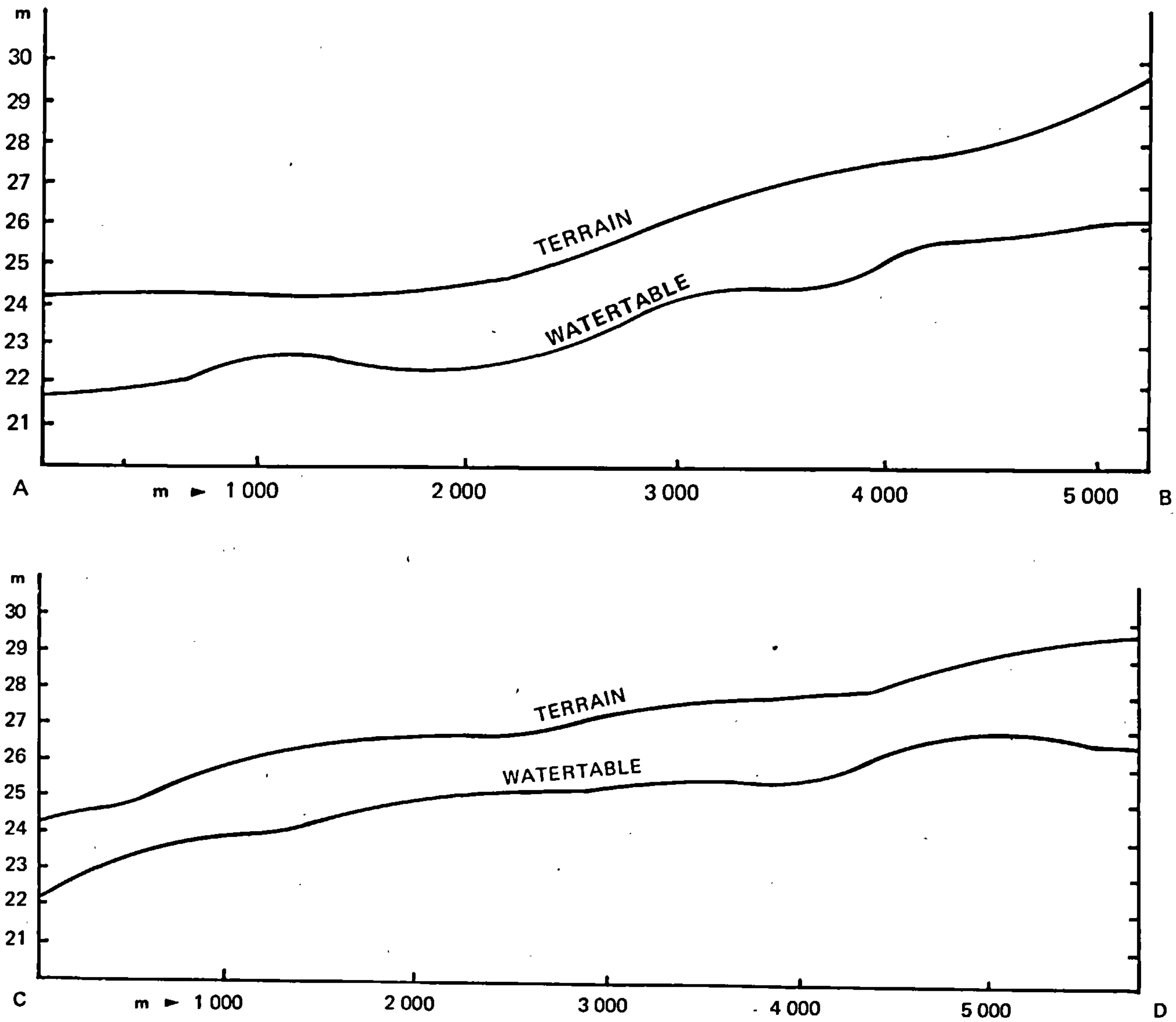


FIG. 8. Cross-section between main irrigation canal and main north drainage canal of the Greater Mussayeb Project

series of four lysimeters and field experiments using the soil-moisture depletion method (Table 21). The results indicate that the applications which provide an optimum yield/water ratio are in some cases less than the potential evapotranspiration. For potatoes optimum yield was obtained at 0·4 ETP, for wheat optimum yield was at 0·7 ETP. Optimum yields for cotton and maize were obtained at water-use rates higher than the computed ETP (1·04–1·1 ETP). This shows the significant effect of crop height on the amount of water used by the crop during the extreme evaporative conditions of summer. Thus crop physiological factors cause wide variation in water use among different crops under similar climatic conditions.

Irrigation water requirements

As described above, irrigation requirements were determined from consumptive use data for different cropping patterns and intensities. Assuming an overall irrigation efficiency of 50 per cent, the total water demand was evaluated at $793 \times 10^6 m^3/yr$. This is equivalent to an average water depth of 1·7 m over a net irrigable area of 46750 ha. Peak requirements occur in August and September and in March, when the total discharge at the head regulator reaches $40 m^3/s$. Minimum demands occur in December and May, when the head discharge is reduced to $23 m^3/s$. However, in order to preserve canal efficiency and silt control, the main canal discharge must not be allowed to fall below 75 per cent of its full capacity. This will require a total allocation of $886·4 \times 10^6 m^3/yr$ of river water to the project, which represents a 30 per cent decrease in the original total annual allocation of $1140 \times 10^6 m^3$ made to the project in 1962–63. At the present time field-application efficiency is about 40 per cent, but this efficiency can be raised to 60–70 per cent through proper land-levelling and the adoption of effective farm-irrigation methods.

TABLE 20. Meteorological data and evaporation rate from free water surface (Greater Mussayeb Project, 1972–74) (Hani and Pike, 1974)

Year/ month	Meterological data					Evaporation rate (mm/d)			Pan co-efficient E/E_0
	Mean air temperature (°C)	Relative humidity (%)	Dew point (°C)	Relative sunshine intensity (g . cal/cm^2 per day)	Wind speed (km/h)	Class A Pan E_0	Penman E	Sunken pan	
1972									
June	32·1	26·3	10·4	661·0	8·9	14·4	10·7	—	0·775
July	33·0	27·7	12·8	633·0	12·0	17·6	11·3	—	0·644
August	34·5	29·2	13·8	599·0	8·6	16·4	10·8	—	0·663
September	30·5	31·3	11·3	544·2	6·7	12·4	8·8	—	0·709
October	26·0	35·4	9·4	413·1	5·6	7·5	5·0	—	0·664
November	16·6	40·8	2·4	307·3	5·7	5·0	3·0	—	0·618
December	6·5	66·2	3·0	254·0	4·7	2·1	1·6	—	0·735
1973									
January	8·6	60·7	1·1	282·9	6·5	2·8	2·3	—	0·862
February	14·1	60·8	6·5	337·0	6·3	3·5	2·7	—	0·790
March	16·2	51·4	6·0	541·4	7·4	5·9	5·2	—	0·886
April	20·7	39·5	6·4	613·5	7·9	8·2	7·1	—	0·877
May	27·0	26·6	5·8	675·6	6·8	12·1	8·8	—	0·727
June	30·6	25·1	7·6	711·1	11·1	16·7	10·9	—	0·656
July	33·6	19·0	6·5	731·0	11·5	17·2	11·7	—	0·698
August	34·7	19·6	7·4	656·3	10·6	18·6	10·7	—	0·577
September	29·2	24·6	7·7	563·7	6·6	11·0	7·5	—	0·700
October	25·2	31·3	7·0	426·6	5·5	7·6	5·2	—	0·691
November	14·4	38·7	0·5	327·5	7·1	3·3	3·1	2·7	0·915
December	10·2	58·5	0·3	272·4	6·2	2·2	1·9	1·9	0·900
1974									
January	8·2	62·5	1·4	285·0	7·1	1·8	1·6	1·2	0·889
February	11·4	60·2	1·7	376·9	7·4	3·6	2·7	2·6	0·742
March	14·5	62·8	8·0	400·0	6·0	4·7	3·5	3·4	0·728
April	19·3	49·0	·6	683·5	8·6	7·7	6·5	5·6	0·835
May	27·2	39·6	14·2	710·1	7·0	10·5	8·5	8·3	0·821
June	31·9	36·5	15·1	748·7	8·8	15·0	10·2	10·4	0·688
July	33·2	37·6	16·8	721·0	9·0	14·8	9·9	10·6	0·677
August	31·8	42·0	17·3	680·3	24·7	12·2	9·1	9·7	0·750

TABLE 21. Net crop and soil water requirements of some crops in the Greater Mussayeb Project

Crop/ year	Water required (mm) in												Total (mm)
	January	February	March	April	May	June	July	August	September	October	November	December	
Wheat	71	68	120	99	3	—	—	—	—	64	68	68	561
Cotton	—	96	53	120	182	303	363	144	3	—	—	—	1264
Alfalfa	39	54	137	181	290	339	346	299	191	135	104	83	2198
Maize	—	—	—	—	—	—	—	43	220	260	140	—	663

TABLE 22. Chemical analysis of irrigation water from the main canal at different times

Date	EC (mS/cm)	Soluble cations and anions meq/l							
		pH	Ca	Mg	Na	Cl	SO_4	CO_3	HCO_3	NO_3
26 October 1972	0·98	8·1	2·4	3·0	2·00	3·5	1·65	0·20	2·20	0·32
27 November 1972	0·81	8·1	2·6	3·2	0·77	3·5	0·79	—	3·34	0·71
4 December 1972	0·84	8·1	2·6	2·8	0·74	3·3	0·56	—	3·40	0·97
4 January 1973	0·98	7·8	2·2	2·8	0·78	3·6	1·00	—	3·12	0·65
19 February 1973	0·94	8·0	2·4	3·6	0·93	4·2	0·07	0·18	2·54	0·65
25 September 1973	1·14	7·9	2·8	3·0	1·21	5·0	1·30	0·32	1·68	—
16 October 1973	1·22	7·6	3·0	3·2	0·66	6·0	2·43	0·12	1·60	0·32
14 November 1973	1·09	7·4	3·4	2·6	0·37	4·0	0·25	—	3·20	0·65
4 March 1974	1·18	7·9	3·9	3·1	0·98	6·0	3·00	—	3·00	0·97
14 May 1974	1·39	8·2	4·8	4·1	1·38	6·3	3·70	—	2·48	0·97
4 June 1974	1·35	8·5	1·6	3·2	1·52	5·5	2·00	0·40	1·90	—
16 September 1974	0·74	7·8	2·6	2·4	2·08	3·5	0·20	0·16	2·12	0·48

Irrigation water quality

The quality of irrigation water is suitable for agriculture. The water can be classified according to the USDA system as Class 2 with respect of salinity and Class 1 with respect to exchangeable sodium. Table 22 shows chemical properties of the irrigation water taken from the main canal during the period 1972–74.

Drainage criteria

Field studies (Dougrameji *et al.*, 1970) showed that the farm losses for which the drainage system was responsible in a high-levee soil amounted in July to 4·2, 3·2 and 2·1 mm/d with summer cropping intensities of 100 per cent, 75 per cent and 50 per cent respectively. The leaching requirements for the same soils were 2·6 mm/d under 100 per cent cropping intensity, compared to 5·7 mm/d for basin soils (Table 23). It was further demonstrated that in the case of a high-levee soil the field losses are equal to the leaching requirement, whereas basin soils need extra water to meet the leaching requirement. The calculated drain spacings for various cropping intensities given in Table 23 show that the original drain design with field drains spaced 333 m apart is insufficient to meet drainage demands under intensive irrigation.

The studies of Amer and Fakhri (1972) on high-levee soils were in agreement with the previous studies (Dougrameji *et al.*, 1970) and arrived at an average daily discharge per metre length of drain during leaching of 2·66 mm^3/d. The corresponding average drainage rate was 17·7 mm/d. The natural ground-water discharge was estimated at 4 mm/d. Canal seepage in the area was estimated at 0·0005 litre/(s . metre length). The percentage of water to be removed by the drains, or drainage requirement, was 37·5 per cent of the irrigation requirement for leaching such soil. The water-table was calculated to remain on average not less than 2·25 m below the surface. The existing drain spacing of 200 m was found satisfactory under leaching conditions, while under normal irrigation spacing was found to be equal to 120 m when tile drains of 10 cm inside diameter were used. With tile drains of 15 cm diameter a spacing of 150 m would be satisfactory. For diameters greater than 15 cm or for open drains, the spacing should not be greater than 150 m.

Transmissivity (*KD*) was determined by using the steady-state concept (Amer and Malik, 1973). An average value of 17·2 m^2/d was found, which is lower than the values previously reported for similar soils.

Soil reclamation

The reclamation of salt-affected soils in the project required, besides leaching and drainage, additional land-levelling to obtain a higher irrigation efficiency. Even after reopening the existing drains and constructing additional ones, fallow plots between or adjacent to irrigated fields would be liable to resalinization. One of the best ways to avoid this is to practise intensive cropping, with over-irrigation throughout the year. In case not enough water is available, full-intensity cropping should be practised at least during one season, i.e. in winter or spring. In addition, during the initial stage of rehabilitation special salt-tolerant crops are to be grown.

The amount of water required for reclamation (leaching) is directly proportional to the quantity of water needed to compensate for evapotranspiration. The drain discharge will also be related to the consumptive use of crops and will be greatly dependent on the cropping pattern and the cropping intensity. But the varying leaching requirements pose a problem in the planning of a drainage scheme. If planned according to the maximum summer needs, the system will have an over-capacity during the winter and will be expensive to construct; if planned according to the winter needs, the ground water may rise to a non-permissible depth during the summer.

Furthermore, proper leaching is only possible when the lands are adequately levelled.

On the basis of studies in a pilot area NEDECO (1959) suggested guidelines for leaching (Table 24).

Amer and Fakhri (1972) carried out research on drainage and leaching criteria on 500 ha of the Himair district. This area consists of high-levee soils varying in texture from a sandy clay loam to a silty clay loam. Soil permeability was found to be 1·8 m/day for the first 3 m and 0·65 m/day for the rest of the profile down to a depth of 6 m below the soil surface. Water was applied continuously for 27 days with an average discharge of 30·5 litres/s and with a water depth of 11·0 cm above the soil surface.

The average electrical conductivity of the drainage water was 15·4 mS/cm before leaching,

TABLE 23. Maximum calculated drain discharge values (mm/d) and drain spacing (m) in July

Cropping intensity	Maximum drain discharge in July (mm/d)		Drain spacing (m)	
	High levee	Basin	High levee	Basin
100% winter + 100% summer	4·2	5·7	65	50
100% winter + 75% summer	3·2	4·3	85	65
100% winter + 50% summer	2·1	2·9	115	85
100% winter + 25% summer	1·1	1·5	185	150

TABLE 24. Water depths and number of days required for leaching according to salinity and drain spacing in the pilot area (NEDECO, 1959)

Area (ha)	EC (mS/cm)	Approx. number of farm-units	Number of days required for leaching		Water depth needed for leaching (cm)
			L[1] = 300 m	L[1] = 150 m	
1981	0–4	120	None	None	None
2085	4–8	126	25–26	7·5–18·5	25–60
740	8–15	45	60–80	18·5–24·5	60–80
740	15–25	45	80–100	24·5–30·0	80–100
834	25–50	50	100–125	30·0–38·0	100–125
591	>50	36	>125	>38·0	>125

1. L = drain spacing.

TABLE 25. Salinity distribution by depth before and after 27 days of leaching (continuous leaching)

Depth (cm)	EC (mS/cm)	
	Before leaching	After 27 days of leaching
0–30	48·06	2·63
30–60	18·55	1·60
60–90	11·23	2·27

TABLE 26. Salinity distribution by depth before and after 12 days and 24 days of leaching (non-continuous leaching)

Depth (cm)	EC (mS/cm)		
	Before leaching	After 12 days	After 24 days of leaching
0–30	29·34	7·39	2·4
30–60	11·80	9·10	1·8

21·4 mS/cm during leaching, and 20·0 mS/cm after leaching. The average ground-water conductivity of 16·6 mS/cm increased by 8·4 per cent during leaching. Salts were removed at the rate of 2200 kg/d/ha. The leaching requirements were found to be 33 per cent. The volume of irrigation water required to obtain a more favourable salinity level was equal to 1000 mm/month. The leaching coefficient was found to be 0·41.

During this study, the salinity, which reached 50 mS/cm in the top of this type of soil, could be lowered to 2 mS/cm by continuous leaching for a period of 27 days with an average water depth above the soil surface of 11·5 cm (Tables 25 and 26). When the salinity level in the top layer was 25 mS/cm or less, continuous leaching with the same average depth of water for a period of 15 days was sufficient. Table 27 shows average salinity data for large areas which were leached in the Hillala and Himair districts.

TABLE 27. Average salinity of surface soil before and after leaching in the Hillala and Himair districts (mean values in brackets)

Location	Units	Salinity (mS/cm)		Time required (days)
		Before leaching	After leaching	
Hillala	36	16·4–52·4	1·2–4·6	15–25
		(26·9)	(2·6)	(21)
Himair	4	6·7–10·7	1·5–2·7	
		(8·5)	(2·1)	(21)

TABLE 28. Areas of land reclaimed between 1969 and 1973

Year	Area reclaimed (ha)	
	State farms	Farmers' farms
1968	250	37·5
1969	400	37·0
1970	505	450·0
1971	1050	3912·0
1972	1625	9937·5
1973	3000	10662·5
1974		5000·0 projected
1975		5000·0 projected

Reclamation of saline soils on a large scale began in 1970 and by 1974 approximately 18000 ha or 34 per cent of the total area of strongly salt-affected land was reclaimed, at an average rate of 4500 ha/yr. At present the process is continuing at the same rate. Table 28 shows the amounts of land reclaimed annually since 1969.

Reclamation of the areas involved the following treatments:

- — land-levelling to allow even water distribution;
- — installation of drains made of clay pipes lying from 100 to 150 m apart;
- — leaching the soil for periods varying from one week for salinity levels of 8 to 16 S/cm up to more than a month for salinity levels over 25 S/cm.

Modifications of the irrigation and drainage network

Irrigation system

The Greater Mussayeb Irrigation network now consists of a main canal 49·5 km in length, twenty-two branch and parallel canals of a total length of 106·58 km, lateral canals totalling 473·34 km in length, and sublaterals totalling 114·20 km. There are in total thirty-two regulating structures and three pumping stations (UNDP/FAO, 1976*a*).

Remedial measures proposed in 1960 to keep silt from interfering with the intake of the main canal consisted of the construction of the following:

- — a 45-m deflector wall into the river upstream of the intake;
- — a 50-m curved divide wall from the downstream end of the regulator upstream into the river to divert clearer surface water into the forebay and to allow bottom water to pass through submerged orifices in the wall;
- — a super-elevated sill, 50 m in length, curved in profile and raised at its downstream end to provide for a more evenly distributed flow pattern prior to entry.

These recommendations are being tested in a model before a final decision is taken on the intake design. The main canal extends southeastwards for a distance of nearly 50 km before dividing into two main branches: an eastern branch extending 17 km, and a southern branch 16 km in length. In 1967 the canal capacity had fallen to 40 per cent of its design capacity, but in 1969 the canal was restored to its original capacity of 40 m^3/s.

Between 1972 and 1974 the flow in the Euphrates reached its lowest discharge because of upstream developments in Syria and Turkey, and irrigation water was partly drawn from Lake Habbaniyah. The result of this decreased water supply was a lowering of the silt content in the main canal from a maximum of 4000 ppm to less than 500 ppm. This decrease caused scouring in the canal and over a two-year period (August 1972–74) the bed level below the head regulator was lowered by 0·75 m, increasing the discharge capacity to its design maximum of 40 m^3/s.

Continuous silting of the main canal in the past had caused the cross-section to adopt a new equilibrium condition with a wider, shallower bed. During redesign of the main canal, all parameters except the depth were fixed. Maintenance of this depth is imperative for future sediment control. To restore the canal to full capacity, it is proposed to re-profile the bed by excavating some 8000 m^3 of earth.

Measurements in the four main branches showed a reduction in capacity from 67 per cent to 20 per cent. Silt entry was found to be 30 per cent higher in the branches than in the main canal.

It is planned to restore all branches to their original capacities or to the capacity required to meet the needs of modified cropping patterns and intensities. All sublaterals are also in need of renovation. Provisions have therefore been made to refill and compact all existing laterals and re-excavate them to the designed cross-sections.

Half the existing structures are presently in need of repair; gates are jammed or broken and gears and linings have become worn or inoperative from excessive silting. Additional new structures on the main and branch canals are essential for an efficient operation of the canal after renovation.

The silt load entering the GMP canal is estimated at an average 2760 t/d. Its efficient elimination will decide the success or failure of the project. Remedial measures can only be realized through the creation of an efficient operations and maintenance organization; the present organization is underfinanced and understaffed.

Drainage system

Although 1910 km of drainage pipes have been cleared by the project authority since 1970, the system still suffers from inadequate maintenance and from frequent blockages caused by wind-blown sand, sedimentation and reed growth.

Over a period of two years, detailed studies were made to determine the drainage requirements to maintain the ground-water table below the critical depth, assuming a cropping intensity between 125 per cent and 170–200 per cent. The investigations concluded that, given a field application efficiency of 60–65 per cent, the average drainage rate required for a cropping intensity of 125 per cent would be 1·85 mm/d, while the required rate for a cropping intensity of 170–200 per cent would be 3·15–3·20 mm/d. Taking into consideration the future cropping intensities, an average drainage rate of 2 mm/d must be provided. Depending on soil conditions, the minimum permissible water-table depth, shortly after irrigation, should not be less than 90–150 cm.

The present drainage system, even if properly maintained, is inadequate to provide efficient drainage at a rate both compatible with the physical requirements of the crops and necessary for the elimination of excess water and salinity from the project area. Any intensification of the present open-drainage network would further complicate the present maintenance problem, involving higher costs and loss of land.

Vertical drainage

Vertical drainage was tested by drilling a 130-m well of 12·4 cm diameter, and test pumping. The results showed that one tube-well per 10 ha would be required to keep the water-table at a permissible depth. However, as the salinity of the pumped water prohibited its re-use for irrigation, this costly system proved uneconomical (Amer and Malik, 1973).

Tile drainage

The installation of a subsurface drainage network appears to be the most economic means of providing adequate drainage for the project. Low in cost, the installation of tile drains will save up to 12 per cent of the arable land presently occupied by open drains. Changing over to this system requires the installation of 7858 km of 10-cm field tile drains with flushing outlets and manholes, and 775 km of 15–30 cm closed collector-pipe drains. This system would serve a net irrigable area of 38750 ha, 88 per cent of this area having a cropping intensity of 125 per cent, the remaining 12 per cent of the area (mainly State farms) having a cropping intensity of 170 per cent. The depth of the drains would be 1·8–2·0 m below the surface and the spacing would vary according to soil permeability.

Evolution of the organizational structures

Administration

In 1956–57 the project started with a small administrative unit placed under the Department of Irrigation of the Development Board and divided into two sections: irrigation affairs with one civil engineer and three surveyors, and agricultural and co-operative affairs with a section head, two extension officers and four co-operative supervisors.

The tasks of the administration were limited to the provision of water requirements and the planting of forests, wind-breaks, and new orchards (principally date palm and grapes).

In 1965, when the rehabilitation stage began, the Greater Mussayeb Project Authority, a semi-autonomous administration with increased cross-sectoral authority, was established. The Authority's Board of Directors is composed of personnel from closely associated ministries and representatives of the project farm population. Its chairman is the Director-General of the project.

The number of officials and employees working in the project in 1968 is shown in Table 29. In 1973–74, fifty-five of the project's staff members had a university degree or higher education; 150 staff members had high-school-level education; and about 1 000 were skilled or unskilled workers.

Agricultural research and extension service

Little agricultural research was done in the project area prior to 1960. Afterwards, a certain amount of

TABLE 29. Number of officials and employees in the Greater Mussayeb Project in 1968[1]

Department	Officials (professional and semi-professional)	Permanent employees
Administration and finance	26	8
Supplies	8	1
Agriculture	18	—
Engineering	11	21
Agricultural co-operatives	22	12
Mechanics	4	46
TOTAL	89	88

1. An additional 260 workers were engaged for various types of manual labour.

research was carried out on the effect of fertilizers, but it was not until 1972, when UNDP/FAO teams began trial experiments in the pilot project area, that Technical Notes were prepared on irrigation and drainage, agronomy and horticulture, and livestock and farm management. From 1972 to 1975 some forty-six of these Technical Notes were prepared. Until very recently the administration of the Greater Mussayeb Project never had extension officers in sufficient numbers, nor adequate organizational structures to provide an effective extension service to the farmers. No research or demonstrations were done to supplement farm operations. In 1969 Dr D. Al-Hardan, former Director-General of the Greater Mussayeb Project Authority, made the following statement:

> Extension service is included as a section under the branch of the agriculture co-operation Directorate. In effect, agricultural extension has a secondary character and it has not been the object of comprehensive development. On the village level, offices are almost non-existent. The existing agricultural division was not designed for carrying out an extension programme. It deals chiefly with regulations and procedures, instead of agricultural extension. The agricultural co-operation division does not perform extension activities, except by occasional and rare farm visits by extension field technicians.

This lack of an effective extension service has undoubtedly contributed to many of the Greater Mussayeb Project's failures and has impeded the project's overall development. A case in point is the farmers' tendency to fall back, even recently, on their former practice of *nirin*-system irrigation. It is necessary, therefore, for the government to give greater priority to this service. In particular, the practice of eroding the ranks of extension-service personnel to meet *ad hoc* needs of other project sections should be discontinued.

Evolution of the legal structure and system of land tenure

Initial land distribution and early settlement

The first land distribution was made in 1956–57, when 1189 farm-units each of 66·66 donums (16·67 ha) were allotted in accordance with law No. 51, 1950. The Miri-Sirf (State land) development authority managed this programme. According to this law, the allottees were required to be farmers and to live on the farm; re-leasing or selling units to third persons was none the less allowed. The allottee was required to farm ten years on the unit to become the owner.

A second group of distributions was made in accordance with the Agrarian Reform law No. 30, 1958. According to this law the allottee was required:
- to be a farmer;
- to live on the farm;
- to have a family;
- to build a house on the farm;
- to establish an orchard;
- not to lease or sell the unit, nor to share-crop;
- to become a member of the co-operative.

The allottees would receive their title-deeds in exchange for payment of the fixed value of the land over a period of forty years. The second law was issued to eliminate the defects of the first. Unfortunately the operation of both laws was unsatisfactory. As mentioned earlier, about 33 per cent of the land was originally distributed to non-farmers living outside the project area, and most of the lands belonging to these absentee land-owners was sold illegally.

Later amendment

In 1965 the Ministry of Agrarian Reform issued law No. 121 concerning the distribution of land to tenants on annual contracts. The last amendment of the land-reform law was issued in 1970 (law No. 117). This law stipulates land maxima for a farming family as follows:
- 15 ha of less-fertile land irrigated by means other than gravity;
- 10 ha of fertile land irrigated by means other than gravity;
- 10 ha of less-fertile land irrigated by gravity;
- 15 ha of fertile land irrigated by gravity.

Thus the following land-tenure patterns exist:
- settlement under the Miri-Sirf law No. 51 of 1950;
- settlement under the Agrarian Reform law No. 30 of 1958;
- contracts according to the Ministry of Agriculture and Agrarian reform law No. 121 of 1965;
- contracts according to the Ministry of Agriculture and Agrarian Reform law No. 116 of 1970;
- purchase from original settlers;
- share-cropping under contract with legal settlers;
- squatting on vacant government lands or on lands abandoned by original settlers.

Farmers who obtained rights on land by any of the last three means are illegal occupants.

Farm size

Although each farm-unit was originally designed to cover an area of 66·66 donums (16·67 ha), considerable variations in size, ranging from 9·4 to 32 ha, occur. One explanation for larger-than-standard units is that some settlers had obtained titles to more than one unit, i.e. in the name of sons or near relatives. Other reasons include illegal purchases, squatting, etc. Smaller units resulted from illegal sales of parts of the allotted land, subleasing, etc.

TABLE 30. Frequency distribution of the net area of cropland per unit

Class intervals (ha)	Frequency	Percentage of total
8·75–11·24	9	9·47
11·25–13·74	22	23·16
13·75–16·24	37	38·95
16·25–18·74	21	22·10
18·75–21·24	3	3·16
21·25 and larger	3	3·16

Table 30 shows the frequency distribution of various farm-unit sizes in a sampled area (the computed mean was 59·57 donums, i.e. 14·89 ha).

A recent sample survey showed that 5·6 per cent of the settlers hold titles to their land under either the Miri-Sirf law (1950) or the land-reform law (1958); 24 per cent farm their lands on annual contracts; the rest (18·4 per cent) are illegal occupants.

Impact of land tenure on land use

In agriculture, land use is influenced by the pattern of the land-tenure system—a fact clearly applicable to the Greater Mussayeb Project. Farmers who hold titles under the Miri-Sirf or the land-reform law, for example, have the greatest security of tenure and therefore the security and incentive necessary for long-term planning and decision-making. Decisions involving investment in land and water development or the application of modern agricultural techniques assume a certain degree of stability. Consequently, among farmers with little security of tenure, land development has fallen behind. This is the excuse given for farmers under annual contracts—even though these contracts are almost automatically renewed—and, to a greater degree, for occupants farming illegally. In the early 1970s a sample survey showed that 48 per cent of the farmers under annual contract grew no alfalfa and 58 per cent had no orchard. Among illegal occupants these figures rose to 71 and 79 per cent respectively.

Pattern of land use

The broad pattern of land use in the Greater Mussayeb Project in 1972 is shown in Table 31.

TABLE 31. Broad pattern of land use in the Greater Mussayeb Project in 1972

Land use	Area (ha)	Percentage of total
Distributed to settlers	50750	60·64
Allocated for afforestation	15500	18·52
Privately owned	10900	13·02
Unfarmed land	6636	7·82
TOTAL	83786	100·00

Economy

Budget allocation

The budget allocated to the Greater Mussayeb Project over the years 1965 to 1974 is shown in Table 32.

Allocation of land to crops

From 1969 to 1974 only about half of the farm-units were reclaimed and developed. Cropping, therefore, differs between the reclaimed and unreclaimed units. Table 33 shows the areas of land allocated to various crops during the winter season of 1975–76, while the areas fertilized and the amount of fertilizer used are shown in Table 34.

Land allocation on reclaimed farm-units

Average land allocation per farm-unit on reclaimed lands is shown in Table 35 (Sumanovac, 1972), which accounts for eight principal crops—the modal number on a typical farm-unit. The basic data presented in this table, however, are somewhat over-simplified; a more realistic representation is therefore provided in Table 37, where land allocation for a wider variety of crops is taken into account. This new pattern was obtained by analysing farm-management survey data which considered the relative frequency as well as the magnitude of the cropped areas (UNDP/FAO, 1976*b*).

TABLE 32. Economic operation plan for the Greater Mussayeb Project, 1965–66 and 1973–74

Year	Money allocated (× 1000 ID)[1]	Constant expenditure (× 1000 ID)[1]		Running expenditure (salaries, fuel, maintenance) (× 1000 ID)[1]	Total expenditure (× 1000 ID)[1]	Expenditure (%)
		Equipment	Building			
1965–66	580	—	—	3	—	—
1966–67	750	2	—	3	5	7
1967–68	661	118	53	13	184	28
1968–69	1088	1	124	6	131	12
1969–70	420	120	35	14	169	35
1970–71	800	378	50	15	443	55
1971–72	1240	657	112	156	925	75
1972–73	700	335	120	245	700	100
1973–74	944	212	469	263	944	100

1. 1 ID = U.S.$2·80.

TABLE 33. The area cultivated in winter season of 1975–76 in the Greater Mussayeb Project with different crops (Yousef, 1976c)

Crop	Area cultivated (ha)	
	Co-operative farms	State farms
Wheat	11609·5	2500·0
Barley	6207·5	125·0
Beans	1039·2	25·0
Alfalfa	418·0	625·0
Clover	145·5	12·5
Vegetables	1137·0	12·5
Onions	886·5	—
Sugar beet	—	5000·0

TABLE 34. The areas fertilized and type and amount used in the Greater Mussayeb Project (Yousef, 1976c)

Crop	Areas fertilized (ha)	Quantity of fertilizer (tonnes)	
		Ammonium sulphate	Urea
Wheat	14109·5	2025	4065
Barley	125·0	2025	4065
Beans	25·0	2025	4065
Clover	12·5	2025	4065
Vegetables	1149·5	2025	4065
Onions	886·5	2025	4065
Sugar beet	4300·0	2025	4065

Land allocation on unreclaimed farm-units

On many of the unreclaimed farm-units the land has not been levelled, leaving scattered high spots that cannot be farmed. In particular, the unreclaimed units have to be fallowed annually. In these circumstances the *nirin* system is widely practised, and since the degree of salinity differs from one farm-unit to another, the cropping intensity and choice of crops varies accordingly.

Table 36 gives the basic land-allocation data for a typical unreclaimed unit, and on this basis a computed pattern of land allocation is shown in Table 38. This new pattern was obtained by analysing farm-management survey data, where the magnitude and relative frequency were considered.

Tables 35–38 show that wheat and barley, the two predominant winter crops, account for the greatest allocation of land. On unreclaimed farms, barley receives a much higher land allocation than on the reclaimed units, as this crop is more salt-tolerant than wheat. The total number of crops grown annually ranges from 3 to 11, but the modal number is 8 on both reclaimed and unreclaimed farm-units.

TABLE 35. Land allocation to farm enterprises on a typical reclaimed farm-unit

Enterprise	Land allocation (ha)	Percentage of uncropped land
Wheat	5·77	38·73
Barley	1·60	10·71
Onions	0·82	5·51
Tomatoes	0·32	2·15
Cucumber	0·74	4·92
Cotton	0·49	1·27
Maize	0·84	5·62
Green gram	0·63	4·20
Gross cropped land	11·19	75·11
Area double-cropped	1·02	6·87
Net cropped land	10·16	68·24
Current fallow	4·73	31·76
Net cropland	14·89	100·00

TABLE 36. Land allocation to farm enterprises on a typical unreclaimed farm-unit

Enterprise	Land allocation (ha)	Percentage of uncropped land
Wheat	3·11	20·92
Barley	2·20	14·81
Broad beans	0·36	2·43
Tomatoes	0·24	1·61
Cucumbers	0·26	1·75
Cotton	0·16	1·12
Green gram	0·13	0·85
Sesame	0·14	0·96
Gross cropped land	6·62	44·45
Area double-cropped	0·00	0·00
Net cropped land	6·62	44·75
Current fallow	8·27	55·55
Net cropland	14·89	100·00

TABLE 37. Average allocation of land to farm enterprises per farm-unit (reclaimed)

Enterprise	Land allocation (ha)	Percentage of net cropland	Relative frequency of allocation
Wheat	4·965	33·34	1·00
Barley	1·372	9·22	0·77
Berseem	0·340	2·28	0·39
Broad beans	0·545	3·66	0·39
Marrows	0·038	0·25	0·19
Onions	0·705	4·73	0·81
Tomatoes	0·275	1·85	0·77
Cucumbers	0·630	4·23	0·90
Cotton	0·420	2·82	0·58
Ground-nuts	0·047	0·32	0·04
Maize	0·700	4·85	0·45
Aubergines	0·070	0·49	0·32
Potatoes	0·0075	0·05	0·32
Water-melons	0·015	0·10	0·32
Green gram	0·537	3·61	0·41
Cowpeas	0·0025	0·02	0·32
Sesame	0·0075	0·05	0·32
Okra	0·025	0·17	0·64
Alfalfa	0·090	0·59	0·32
Orchards	0·370	2·48	0·48
Gross cropped land	11·185	75·11	—
Current fallow	4·755	31·75	—
Gross cropland	15·915	106·87	—
Area double-cropped	1·022	6·87	—
Net cropland	14·890	100·00	—
Net cropped land	10·162	68·24	—

TABLE 38. Average allocation of land to farm enterprises per farm-unit (unreclaimed)

Enterprise	Land allocation (ha)	Percentage of net cropland	Relative frequency of allocation
Wheat	2·955	19·84	0·96
Barley	2·092	14·05	0·86
Broad beans	0·345	2·32	0·47
Onions	0·025	0·17	0·08
Tomatoes	0·227	1·53	0·84
Cucumbers	0·245	1·64	0·91
Berseem	0·0025	0·02	0·01
Alfalfa	0·065	0·44	0·24
Cotton	0·160	1·07	0·34
Grain sorghum	0·675	0·45	0·05
Sesame	0·135	0·91	0·39
Green gram	0·120	0·81	0·32
Cowpeas	0·0475	0·32	0·03
Water-melons	0·0125	0·08	0·02
Sweet melons	—	—	0·01
Okra	0·0025	0·01	0·02
Ground-nuts	—	—	0·01
Aubergines	0·0025	0·02	0·01
Maize	0·020	0·12	0·02
Orchards	0·095	0·64	0·20
Gross cropped land	6·620	(44·45)	—
Current fallow	8·272	55·55	—
Gross cropland	14·892	100·00	—
Area double-cropped	—	0·00	—
Net cropland	14·892	100·00	—
Net cropped land	6·620	44·45	—

TABLE 39. Cropping intensities on reclaimed farming units (%)

Years after reclamation	1	2	3	4	5	6	7
Cropping intensity	115	115	95	80	70	65	60

TABLE 40. Average crop yields on reclaimed and unreclaimed farm-units (kg/ha)

Crop	Reclaimed	Unreclaimed
Wheat	1320	980
Barley	1132	740
Onions	5940	—
Tomatoes	8512	8512
Cucumbers	4472	4472
Cotton	1368	1120
Maize (cobs)	1260	—
Green gram	700	600
Sesame	—	4600
Broadbeans		
Green pods	—	1400
Dry beans	—	600

TABLE 41. Wheat (Mexipak) production on the Greater Mussayeb Project State farm (1969–73)

	1969	1970	1971	1972	1973
Area cultivated (ha)	37·5	145	159	140	245
Total production (*t*)	45·0	235	325	376	727
Average yield (kg/ha)					
Hamiar	1200·0	1612	2060	2664	5720
Rashayed	—	—	—	—	2732

Cropping intensity

On the basis of the available data, the average cropping intensity on the unreclaimed farm-units is calculated at 45·5 per cent. On reclaimed units, a cropping intensity of about 115 per cent was introduced and sustained through the supervision and assistance of land-reclamation teams for a period of about two years. At the end of this period, farmers were expected to maintain this level without supervision. In fact this initiation period has proven too brief, and many farmers have reverted to their traditional methods, in particular that of uncontrolled flood irrigation. As a result, much of the initial efforts are being nullified. Table 39 shows the actual and projected decline in cropping intensity.

Other reasons can be cited for this reduction in cropping intensity on reclaimed farm-units. Maintenance of the irrigation and drainage networks in the Greater Mussayeb Project remains neglected because of lack of proper organization, manpower, and equipment. Consequently, irrigation and drainage channels are still silting up. The lack of an efficient extension service and of an adequate farm credit system are other factors.

Crop yields

Although present yields in the Greater Mussayeb Project remain low, many farmers on reclaimed units are now using fertilizers, chemicals for plant-protection, and improved varieties of seeds. Yields exceeding 1000 kg/donum (4 t/ha) of wheat have been reported by several farmers. Table 40 shows crop yields on reclaimed and unreclaimed farms and Table 41 wheat yields on the Greater Mussayeb Project State farm.

Fruit trees

Survey data showed that tree crops have not yet become very popular among the farmers of the Greater Mussayeb Project. Some fruit-bearing trees may be seen occasionally, but in many cases these are in poor condition. The average land allocated to the trees by the farmers who have established an orchard is 0·37 ha on reclaimed farm-units and 0·095 ha on the unreclaimed units. The modal number of trees in an orchard is four. In a typical orchard the combination is date, pomegranate, apricot and grape.

Livestock and animal health

A 1976 survey indicates the following livestock population in the project area:

Sheep	*Cows*	*Poultry*		*Camels*	*Horses*
		Co-operative	*Private*		
60000	18000	20000	100000	5000	600000

On the government farm the livestock population is as follows: sheep, 10000; cows, 1400.

TABLE 42. Average number of head of livestock per farm-unit in the Greater Mussayeb Project area

Enterprise	Livestock per farm-unit	
	Reclaimed	Unreclaimed
Cattle	(88·50) relative frequency	(91·50)
Cows	3·09	3·57
Calves	2·29	1·98
Sheep	(54·00) relative frequency	(62·50)
Ewes	13·19	9·00
Lambs	6·04	3·89
Poultry	(88·50) relative frequency	(90·00)
Cocks	2·90	1·80
Hens	14·92	8·58
Chicks	11·51	12·43

A livestock centre was established by the project authority in 1970, and a milk-collecting centre, which sends its milk to the State Dairy Factory in Baghdad, also operates in the area.

One of the obvious shortcomings in the field of livestock production is the inadequacy of animal-health control. Ticks have invaded the area and theileriosis is prevalent in both cattle and sheep. Babiosis in cattle, and helminths, including liver fluke, also occur. Authray and clostridal infection in sheep and foot-and-mouth disease in cattle are common. Until very recently, animal-health control was non-existent. There is no dipping policy, and no quarantine measures were taken during outbreaks of foot-and-mouth disease. Although a veterinary clinic with two veterinary doctors, two assistants, and two health officers has recently been established, annual mortality remains high: cows, 5 per cent; young stock, 7 per cent; ewes, 13 per cent; lambs, 12 per cent.

TABLE 43. Estimated present farm income from a typical reclaimed farm-unit and a typical unreclaimed farm unit

Enterprise	Land allocation in donums[1]/ animal units	Gross receipt (ID)	Cash expenses (ID)	Returns over cash expenses (ID)	Other expenses (ID)	Returns to labour and management (ID)	Labour bill (ID)	Farm income (ID)
Reclaimed farm-unit								
Wheat	23·07	295·388	123·770	171·618	49·531	122·087	18·941	103·146
Barley	6·38	90·526	28·002	62·524	12·313	50·211	14·442	35·789
Onions	3·28	131·512	42·066	89·446	13·028	76·418	78·166	−1·748
Tomatoes	1·28	94·731	33·971	60·760	4·858	55·902	48·054	7·848
Cucumbers	2·93	169·295	54·061	115·234	8·345	106·889	88·170	18·719
Cotton	1·95	48·683	6·782	41·901	6·486	35·415	31·535	3·880
Maize	3·35	42·210	13·296	28·914	7·591	21·333	15·457	5·866
Green gram	2·50	22·687	3·245	19·442	5·907	13·535	7·810	5·725
Cow-calf	3·00	139·431	112·386	26·955	7·284	19·671	66·630	−46·959
Sheep	13·00	85·371	49·465	35·906	3·796	32·110	26·442	5·668
TOTAL A		1119·834	467·044	652·700	119·139	533·561	395·647	137·934
Add[2]					+17·184			
TOTAL B		1119·834	467·044	652·700	136·323	516·377	395·647	120·750
Subtract[3]					−105·105		−356·064	
TOTAL C		1119·834	467·044	652·700	31·218	621·482	39·583	581·919
Unreclaimed farm-unit								
Wheat	12·46	133·197	47·535	85·662	26·228	59·434	9·319	50·115
Barley (hand-harvested)	4·41	40·885	7·369	33·516	8·383	25·133	15·153	9·980
Barley (combine-harvested)	4·41	40·885	14·915	25·970	8·476	17·494	6·289	11·205
Broad beans	1·45	25·266	6·125	19·141	2·000	17·141	6·875	10·266
Tomatoes	0·96	71·049	25·476	45·571	3·643	41·923	36·039	5·889
Cucumbers	1·04	60·191	19·189	41·002	2·962	38·040	31·295	6·745
Cotton	0·67	13·132	0·766	12·366	2·181	10·185	9·328	0·857
Green gram	0·51	3·978	0·662	3·316	1·205	2·111	1·462	0·649
Sesame	0·57	6·583	0·586	5·997	1·102	4·895	1·337	3·558
Cow-calf		185·788	149·648	35·940	9·712	26·228	58·840	−62·612
Sheep	9·00	59·103	34·245	24·858	2·628	22·230	18·306	3·924
TOTAL A		640·057	306·516	333·339	68·520	264·814	194·243	40·576
Add[2]					+11·095			
TOTAL B		640·057	306·516	333·339	79·615	253·724	194·243	29·481
Subtract[3]					−60·657		−194·243	
TOTAL C		640·057	306·516	333·339	18·958	314·381	—	314·381

1. One donum = 0·25 ha.
2. Add interest on fixed capital and adjust interest on borrowed annual capital.
3. Subtract interest on fixed and annual equity capital, cost of land use and irrigation water, and wages due to family labour.

Although the primary occupation of the project's population appears to be arable-crop farming, survey data collected in 1972 show that about 97 per cent of the farmers also raise livestock. Cattle, sheep, and poultry are the principal livestock, but goats, horses, and donkeys are also commonly found. A modal combination consists of four cows, three calves, ten ewes, six lambs, twenty-eight fowl, and a donkey. The average number of head of different livestock per farm-unit is shown in Table 42.

Farm income

A comparison of the estimated farm income from typical reclaimed and unreclaimed units is shown in Table 43.

Population

Density and family composition

In 1972 the population of the area was estimated at 32000 inhabitants. An average farm family consists of nine members. Besides his own family, a farmer may have adult brothers or aged parents living with him in his farm home. Sometimes more distant relatives such as uncles, aunts, nephews and nieces are also counted among his family. A sample of ninety-five farmer families revealed the size distribution shown in Table 44. For the purpose of analysis, farm family members were classified according to age and sex, as shown in Table 45 (UNDP/FAO, 1976*b*).

TABLE 44. Frequency distribution of sampled farm families by number of family members

Class intervals	Frequency of farm families	
	Number	Percentage
1–4 members	9	9·47
5–8 members	38	4·000
9–12 members	33	37·74
13–16 members	11	11·58
17–20 members	4	4·21
TOTAL	95	100·00

TABLE 45. Distribution of average numbers per farm family by age and sex groups

Age group	Male		Female		Total	
	Number	(%)	Number	(%)	Number	(%)
Over 55 years	0·33	(7·54)	0·20	(4·12)	0·53	(5·73)
18–55 years	1·76	(40·18)	2·15	(44·24)	3·91	(42·32)
12–17	0·69	(15·75)	0·89	(18·31)	1·58	(17·10)
5–11 years	0·98	(22·37)	0·96	(19·75)	1·94	(21·00)
Under 5 years	0·62	(14·16)	0·66	(13·58)	1·28	(13·85)
TOTAL	4·38	(100·00)	4·86	(100·00)	9·24	(100·00)

Farm labour

On average, five out of nine family members—two males and three females—actually participate in farm labour. Of these, about 50 per cent are between the ages of 18 and 55. In this age group about 67 per cent of both males and females are employed in on-farm jobs; 33 per cent of the males worked off the farms. It was noted that 97 per cent of the girls between the ages of 12 and 17 work on the farm as opposed to 65 per cent of the boys in the same age group. This is due to the fact that at this age boys attend school or are employed in off-farm jobs.

About 73 per cent of the male members above the age of 55 perform light work on the farm; 27 per cent are too old to do any work.

Development of the educational system

In 1968–69 there were seven primary schools (one for girls only) and one intermediate school in the area. At present there are twenty-eight primary schools in the area, in addition to three girls' schools. A secondary school, located in the central area near the administration, has also been established.

Health

While the two small clinics in Imam and Rashayed villages, each with one health officer, have remained almost unchanged, an additional larger clinic has been developed in the central area. There are three male physicians, one woman doctor, and one dentist in this clinic. There are also four male and two female nurses, together with a pharmacist, ten or so assistant health officers, and about the same number of helpers. A new hospital with thirty-two beds is about to be opened in the same location.

Development of other occupations

Although no agricultural industry exists in the area, many non-agricultural occupations have developed with the considerable growth in local population. In the proximity of the headquarters of the project the population numbers about 5000, consisting mainly of staff and project workers. This area has developed into a semi-urban centre, following the establishment of numerous services, including a barber, a baker, repair shop, furniture and general store, as well as markets for engineering materials and vegetables.

The centre has a full electric power (220 V) and a drinking-water supply. Besides many primary schools, the centre has the project's only mixed high school. Many families have television sets, radios and refrigerators.

The most evident trace of modernization is the growth in the number of motor vehicles. In recent years the Greater Mussayeb Project authorities have issued about 150 driving licences. Presently operating in the project area are sixty taxis, eighteen buses, 120 pick-ups, and twenty trucks. These vehicles are used mostly for transporting people and goods from the producing farms to the project's main market or to the surrounding marketing centres at Hilla, Swaira, Mussayeb, Mahamedia, etc.

Conclusions

In the preceding sections it has been shown that there exists a strong relationship between over-irrigation, soil salinity, crop production, and the general welfare of the settler population on an irrigation project. The effect of salinity is not a gradual decline of productivity, but rather a catastrophic breakdown of the intensive agricultural system and a sudden return to the low productivity of the traditional fallow system. An effort has been made to visualize the liability of various parts of the Greater Mussayeb Project to desertification through waterlogging and soil salinization. The results of this effort are shown in Figure 9, the map of natural vulnerability of the landscape to desertification. In this map a distinction has been made between areas subject to various degrees of hazard and areas undergoing actual loss of fertility. Soil conditions prevailing in this part of the Mesopotamian Plain are such that irreversible loss of soil productivity as a result of salinity and waterlogging is not very likely, as practically all soil types can be more or less readily reclaimed. However, for the optimum growth of a variety of crops, the problems of soil fertility must still be solved after the process of reclamation is completed.

A number of other lessons can be learned from the Mussayeb experience. On a technical level it has been demonstrated that proper design of an irrigation and drainage network requires a more thorough understanding of the water requirements of the crops to be grown and of the physical and chemical properties of the local soil types. More co-ordinated and detailed advance research is of great importance, particularly in arid and semi-arid areas such as this. Studies of the consumptive uses of the predominant crops carried out under controlled conditions could lead to a more practical knowledge of water uses as a function of crops and a simple set of climatic factors, and might reduce the need for more lengthy field experiments later on. Concerning drainage, it should be especially noted that experience acquired elsewhere on the spacing of tile drains and the composition and thickness of drain envelopes is not necessarily directly applicable to soils of arid and semi-arid regions, where different clay mineralogy and a generalized lack of organic matter may considerably affect the soil structure. Further research should therefore be carried out to find out under which conditions drains operate best in soils subject to low rainfall and high temperatures, and to calculate the expected economical operating life.

In general one cannot overstress the importance of carrying out pilot projects before undertaking full-scale project operations whenever techniques introduced from elsewhere may encounter differing local conditions.

More difficult and urgent than the technical matters, however, are the sociological problems. The adoption of a system which relies on the combined presence of special managerial skills, a well-organized administration, teams of engineers, researchers, economists, technicians, and social workers, and—last but not least—a farmer population receptive to new methods and advice, often means a revolutionary change in life-style for technical personnel as well as for the farmer population. Both groups are required to live for protracted periods on new agricultural settlement areas, often cut off from their social and cultural roots and without apparent professional, material, or spiritual compensation. The authors of this study believe that the factors which thus motivate staff members and settlers alike are too little understood.

Concerning the farmer population in particular, it appears beyond question that a more intensive cultivation of reclaimed areas requires a continuing education of the farmer. The establishment of extension services able to explain to the farmer, in his own language, the advantages of alternative methods of land use and to train him in the use of equipment, seeds, fertilizers, and pesticides is of particular importance. It is equally evident that efforts in these fields are unlikely to lead to satisfactory results if they are not backed up by a satisfactory credit and marketing system. A comprehensive study of the social conditions and constraints related to the implantation of modern agricultural schemes in areas with predominantly traditional farming populations might therefore contribute to solving a number of outstanding problems.

Finally, closer attention to certain economic aspects is also desirable. In Mussayeb for instance, it proved highly important to determine the size of the unit to be allocated to the individual farmer, taking into account his needs and his capacity to cultivate under intensive conditions. The establishment of an adequate credit system advancing to the farmer the funds necessary for the purchase of fertilizers, pesticides and equipment necessary for the successful implementation of intensive agriculture also deserves continued attention.

Data available thus far show that where the worst problems could be overcome the standard of living of the settlement population has significantly improved and the contribution of the project to the national economy has greatly increased.

Bibliography

AL-BARAZI, N. K. 1963. *The geography of agriculture in irrigated areas of the middle Euphrates valley.* Baghdad, Al-Ani. 2 vols.

AL-HARDAN, D. 1971. *Greater Mussayeb project development.* Ministry of Agrarian Reform (Iraq).

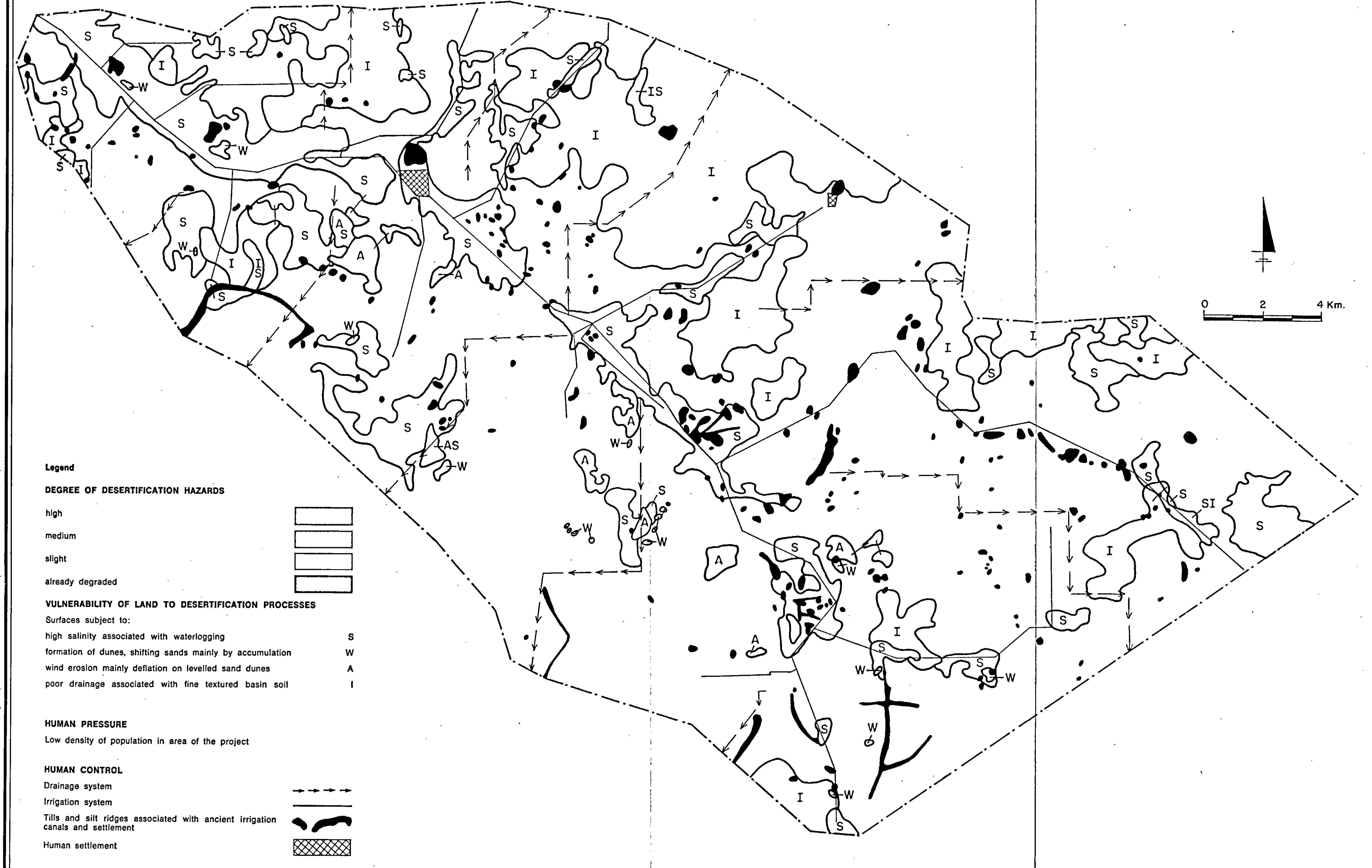
——. 1974. (*Greater Mussayeb project: annual report.*) Baghdad, Ministry of Agrarian Reform. (In Arabic.)

ALI, H. M. 1955. *Land reclamation and settlement in Iraq.* Baghdad, The Baghdad Printing Press.

AL-KHALISI, A. n.d. (Summary of the National Development Plant (1976–1980) in agriculture.) (In Arabic.)

AL-RAWI, A. H.; AL-KHAFAJI, A.: THIJEEL, A. A.; KNIBBE, M. 1971. *Morphology and salinity of soils in two areas of the Greater Mussayeb project.* Abu Ghraib, Institute for Applied

FIG. 9. Synoptic map of desertification hazards, the Greater Mussayeb Project, Iraq



Research on Natural Resources (IARNR). 21 p. (Technical Note 32.)

——; HARDAN, A.; TOMA, G. S. 1975. The mineralogical composition, occurrence and distribution of clay minerals in the Lower Mesopotamia Plain sediment. *Second Scientific Conference, Baghdad.*

AMER, M. H. 1972. *Drainage criteria and salinity study for a high levee soil in the Greater Mussayeb project.* UNDP/FAO Project IRQ/530. 56 p. (Technical Note 3.)

——; FAKHRI, W. A. 1972. *Leaching investigations for the salt affected high levee soils of the Greater Mussayeb project.* UNDP/FAO. 16 p.

——; MALIK, M. B. 1973. *Feasibility of vertical drainage at Hillala area in the Greater Mussayeb project.* UNDP/FAO Project IRQ/530. (Technical Note 11.)

BLANEY, H. F.; CRIDDLE, W. D. 1950. *Determining water requirements in irrigated areas from climatological data.* Washington, United States Department of Agriculture, Soil Conservation Service. (Technical Publication 96.)

BURINGH, P. 1958. *Soil survey of the Hilla-Kifl drainage project, Hilla section.* Baghdad, Ministry of Agriculture, Directorate General of Agricultural Research.

COUMBARAS, A.; CARRIE, R. 1969. *Preliminary report on the public health aspects of the Greater Mussayeb area project.* Geneva, WHO.

DOUGRAMAJI, J. S.; HAWA, A. I.; ISHAQ, A.; HASSAN, H. A.; AL-RAWI, J. Z.; AART, VAN A.; UBELL, K. 1970. *Hydrological and soil physical conditions in a pilot area in the Greater Mussayeb project.* Abu-Ghraib, Institute for Applied Research on Natural Resources (IARNR). 23 p. (Technical Report 17.)

——; KAUL, R. N. 1972. Sand dune reclamation in Iraq. Present status and future prospects. *Ann. Arid Zone,* vol. 2, nos. 3 and 4.

HANI, M. D.; DIDWANIA, B. L. 1974. *Water supply distribution, operation and maintenance of the irrigation branches, laterals and sub-laterals of the Greater Mussayeb project.* UNDP/FAO Project IRQ/530. (Technical Note 45.)

——; PIKE, J. G. 1974. *Evapotranspiration in the Greater Mussayeb project.* UNDP/FAO Project IRQ/530. (Technical Note 46.)

HANNA, A.; TALABINI, K. 1971. Quality of the irrigation water in Iraq. In: *Salinity Seminar Baghdad: Report of Regional Seminar on Methods of Amelioration of Saline and Waterlogged Soils, Baghdad, 5–14 December 1970.* Rome, FAO. 254 p.

HASSAN, H. A.; VAN DER SLUIJS, A. A. 1970. *Compilation of hydrological data from the area between Baghdad and Hilla anticipating more detailed research in the Greater Mussayeb project.* Abu-Ghraib, Institute for Applied Research on Natural Resources (IARNR). 8 p. (Technical Report 10.)

HEKKET, H. 1972. *Sedimentation in the irrigation system of the Greater Mussayeb project.* UNDP/FAO Project IRQ/530. (Technical Note 9.)

INTERNATIONAL LAND DEVELOPMENT CONSULTANTS N.V. 1969. *Report on the drainage and desalinization of the pilot area in the Greater Mussayeb project.* Arnhem.

IRAQ, REPUBLIC OF. 1965. *Law no. 121 promulgating the Greater Mussayeb project.* Baghdad.

ITALCONSULT GREATER MUSSAYEB AREA. 1964. *Socio-economic development programme.*

KNAPPEN, TIPPETS, ABETT, MCCARTHY (consultants). 1952*a*. *Report on the rehabilitation of the Hilla canal system.* Baghdad, Government of Iraq, Development Board.

—— 1952*b*. *Report on the development of the Tigris and Euphrates river systems.* Baghdad, Government of Iraq, Development Board.

MALIK, E. M. 1974. *Maintenance manual for irrigation works.* UNDP/FAO Project IRQ/530. (Technical Note 40.)

MITRA, A. K.; TALIB, M. 1973. *Production and production requirements: cost and expected returns for small grains, forage crops and livestock enterprises in the Greater Mussayeb project area.* UNDP/FAO.

NEDECO. 1959. *Hilla–Diwaniya drainage study.* Baghdad, Ministry of Agriculture (Iraq); The Hague, NEDECO.

NUGTEREN, J. 1956. *Report on the design of the Greater Mussayeb project.* Baghdad, Government Press (Iraq).

POURTAUBORDE, J. E. 1955. *Note on land and water use on the Greater Mussayeb extension and irrigation project.* Rome, FAO. (Mission Report.)

SAIF, H. T.; AL-JAWHER, T. A. 1974. (*Semi-detailed soil survey and hydrological investigation of the Greater Mussayeb project.*) Baghdad, State Organization for Soil and Land Reclamation. (In Arabic.)

SUMANOVAC, P. 1972. *Farm management studies and machinery requirements.* UNDP/FAO Project IRQ/530. (Technical Note 13.)

UNITED NATIONS DEVELOPMENT PROGRAMME (UNDP)/FOOD AND AGRICULTURE ORGANIZATION (FAO). 1973. *Report of special committee on co-operatives.* UNDP/FAO Project IRQ/530. (Technical Note 19.)

——; ——. 1976*a*. *Pilot project in soil reclamation and irrigation farming development in the Greater Mussayeb area: Phase II, Iraq.* UNDP/FAO Project IRQ/530. (Project Findings and Recommendations.)

——; ——. 1976*b*. *An economic appraisal of farm management and cropping patterns, based on the work of A. K. Mitra.* Rome, FAO. 107 p. (AG:DP/IRQ/530.)

——; UNESCO. 1975. *Contributions on natural resources research.* Paris, Unesco. 286 p. (Institute for Applied Research on Natural Resources, Final Technical Report.)

YOUSEF, A. N. 1976*a*. (*Annual report of the Directorate General of Irrigation for the period 1949–1954.*) Baghdad, Ministry of Irrigation. (In Arabic.)

——. 1976*b*. (*Greater Mussayeb Project and present status of housing.*) Baghdad, Ministry of Housing and Works, Directorate of Housing, Studies and Statistics Section. (In Arabic.)

——. 1976*c*. (*Accomplishments during the period 1968–1974.*) Baghdad, Annual Report of the Ministry of Agriculture and Agrarian Reform. (In Arabic.)

——; AL-BAQUARI, M. S.; AL-AZAWI, S. K.; HAMDI, A. 1976. *Population of* Azobacter *spp. in certain Iraqi soils.* Abu-Ghraib, Institute for Applied Research on Natural Resources (IARNR). 19 p. (Technical Bulletin 87.)

FIG. 9. Synoptic map of desertification hazards, the Greater Mussayeb Project, Iraq

6 Desertification in the Mona Reclamation Experimental Project, Pakistan

Case study presented by the Government of Pakistan

Acknowledgements

Unesco would like to express its thanks to the Planning and Co-ordination Cell of the Irrigation, Drainage and Flood Control Research Council of Pakistan, which was responsible for the preparation of this case study. The text was written by a working group composed of S. Hamid, M. A. Qayyum, C. Ata-ur-Rehman, H. Ali Chaudry, S. M. H. Zaidi, G. Haider, M. Anis Ahmad, S. B. Hasan and M. A. R. Farooqi.

Assistance was provided by the following institutions in Pakistan: the Pakistan Water and Power Development Authority; the Irrigation and Power Department, Government of the Punjab; the University of Agriculture, Lyallpur; the Punjab Land Records Office; the Agricultural Census Organization; the Population Census Organization; the Pakistan Meteorological Department; and the Library of the Government College, Lahore.

Unesco also wishes to thank A. Majeed and K. H. Jafri of the Planning and Co-ordination Cell and K. Dettmann for their valuable contributions.

UNDP, FAO and WMO also collaborated in this study.

Introduction

History of irrigation in Pakistan

Irrigation has been practised in Pakistan from the earliest times. In recorded history, river-flow irrigation can be traced as far back as the eighteenth century, when the Arab conquerors differentiated between the irrigated and non-irrigated lands for the purpose of levying land taxes. The oldest form of river-flow irrigation is the *sailaba* or 'overflow' system, which is still practised on a substantial scale within the active flood-plains along the rivers. This form of irrigation, though most primitive, has made an important contribution to the agricultural economy. Its inherent advantages of maintaining soils relatively salt-free and high in fertility result from the periodic flooding of the riverine areas.

The next stage in the development of irrigation was the use of inundation canals, which drew water during the summer, when the rivers rose above the levels of their inlets and irrigated lands which otherwise would not have received water by natural flooding. The inundation canals are, however, uncontrolled and cannot exploit low river-flows. This irrigation activity was limited to relatively narrow strips of land along the rivers. The supply channels were inefficient, depending on uncertain river-flows and tending to silt up rapidly. They were also dangerous because of disastrous breaches to which they were subject in the flood season. In spite of these shortcomings, the inundation canals did provide a limited source of irrigation. The system was subsequently improved during the Mogul period with semi-controlled structures extending the period during which water could be diverted from the rivers, and with small perennial canals irrigating parks and gardens further inland.

The most spectacular achievement in the utilization of river water in the Indus Plains took place from about the middle of the nineteenth century, with the development of an intricate system of water control and distribution which has led to one of the largest irrigation systems in the world. A permanent barrage was constructed in 1859 on the River Ravi, a tributary of the Indus. This made it possible to divert water from the river at all stages of flow the whole year round. Following this successful attempt, several barrages have been constructed at strategic points across the River Indus and its main tributaries. At present there is a system of link canals and 70–75 per cent of the natural river-flows are being utilized.

All the old inundation-canal systems which suffered from the fluctuating river levels have since been abandoned or converted to receive controlled supplies.

The present irrigation network comprises some 62 230 km of conveyance channels (canals, branches, distributaries and minors) in forty-two principal canal systems which have more than 78 000 watercourses (farm channels). In addition, some 600 km of very large link canals have been constructed. There are now seventeen barrages and canal diversion works in the Indus River system. The combined diversion capacity of the main canals system is nearly 7 000 m^3/s, with individual capacities up to 440 m^3/s. The diversions are generally limited in the high-flow season (summer) by the available water supply.

The gross area commanded by the irrigation system within the Indus Plains totals about 13·4 million ha, of which about 133 million ha are classed as cultivable. Some 8·9 million ha of this area receive a perennial supply, while the remainder receives non-perennial supplies, usually from mid-April to mid-October. At present about 123×10^{12} m^3 of river-flows are diverted, out of which about $71{\cdot}5 \times 10^{12}$ m^3 are available at the heads of watercourses.

Drainage

Prior to the advent of canal irrigation in the Indus Plains, run-off from monsoon storms found its way to natural channels and eventually entered the rivers. When the canals were constructed they intercepted run-off and increased flood hazards. Surface drainage works, therefore, became necessary to protect the agricultural lands from the effects of excess storm-water run-off and flooding. At present, there exists a large network of surface drains in the irrigated areas of the Upper Indus Plains and to a lesser extent in the Lower Indus Plains.

The existing surface drains suffer from several problems, the major one being the inadequate maintenance facilities. During winter, the flow in the drains decreases considerably, so that a fungus layer appears on the surface of the water and obstructs its flow. Very often weeds also grow in the bed and along the sides of drains.

Continued seepage from conveyance channels in the absence of an efficient drainage system resulted in a gradual rise of the water-table, creating waterlogging and soil salinization problems. Large-scale efforts to control and eradicate this problem were started by the government in 1958, under the Salinity Control and Reclamation Projects (SCARPs) Programme. This work has been assigned to the Water and Power Development Authority (WAPDA). For subsurface drainage in the affected areas, vertical drainage has been provided in the plains in those areas where tube-wells are feasible. In other areas, horizontal drainage projects have been proposed. So far, about 11 000 tube-wells have been installed in the public sector under the above programme. In addition, some 146 000 tube-wells of relatively smaller capacity in the private sector are also indirectly providing subsurface drainage.

Waterlogging and salinity

Prior to the introduction of the present system of canal irrigation in Pakistan, the water-table depths over most of the area were from 24·4 to 27·4 m. As the extensive network of canals and watercourses was unlined, large quantities of water diverted from the rivers were lost in seepage. Over the years, this continuous seepage raised the water-table from varying depths almost to the ground surface, causing waterlogging and widespread soil salinization. The soil salinization was also due to salts in the irrigation water, which under existing irrigation practices tends to remain within the soil profile with a general movement towards the surface.

Thus both waterlogging and salinity have now become widespread throughout the areas commanded by the irrigation canals. The severity of the problem, however, varies from place to place and from field to field (Appendix III gives an idea of the severity and extent of waterlogging and salinity). In areas where Salinity Control and Reclamation Projects have been implemented and also where subsurface drainage is taking place through large-scale ground-water development by means of private tube-wells, the water-table has fallen, but the reclamation of saline soils is slow.

Project planning and implementation

The Water and Power Development Authority has formulated two regional plans, for the northern and southern zones respectively (Figs. 2 and 3). Detailed planning of seven Salinity Control and Reclamation Projects covering a total area of 4·79 million ha in the northern zone has been completed. Of these, four projects involving the installation of 6 844 fresh ground-water tube-wells, 560 saline ground-water tubewells, and construction and remodelling of 845 km of surface drains have been approved.

In the southern zone the planning of eight Salinity Control and Reclamation Projects with a total area of 3·6 million ha has been completed. Of these, three projects have so far been approved and taken up for implementation. These projects cover an area of 0·70 million ha and involve the construction of 1381 fresh ground-water tube-wells, 379 saline ground-water tube-wells, 1 437 km of surface drains and ten pumping stations.

In North-Western Frontier Province, besides the completion of sixteen dug wells and 1 430 m of tile drains in Peshawar City, twenty-eight tube-wells have been installed and placed in operation.

In Baluchistan, construction work has been started on the Hair Din Surface Drainage Scheme which, on completion, will provide drainage facilities to an area of 29 950 ha.

To date, the results of the Salinity Control and Reclamation Projects are promising, particularly with respect to drainage aspects, in spite of the problems of corrosion and encrustation in tube-wells. In Salinity Control and Reclamation Project No. 1, which has been in operation for the past fourteen years, the water-table is now between 3 and 7 m below the ground surface and the problem of waterlogging has thus been eliminated. Reclamation of about 45 per cent of the saline area has also been achieved. However, the improvement of saline sodic or sodic soils has been very slow. As a result of land drainage, the reclamation of many salt-affected areas, the availability of increased irrigation supplies through ground-water pumping by tube-wells, the introduction of the use of fertilizers, good-quality seeds, better agronomic practices, etc., cropping intensitites have gradually increased and the crop yields have improved. Consequently, the gross value of the agricultural produce in the project area (crops and livestock) has increased two and a half times since the project was initiated.

Ground-water pumping, however, has created some problems. Monitoring studies have indicated that in some places the deterioration in ground-water quality is greater than had been anticipated at the time of planning. This deterioration in water quality has been attributed to varying changes in ground-water environment owing to extensive ground-water exploitation.

The case-study area

The Mona Reclamation Experimental Project (MREP) is located in the north central part of the Chaj Doab,[1] 48 km north-east of Sargodha, 145 km north of Lyallpur and 241 km north-west of Lahore. A major portion of the study area is situated in the Bhalwal Tehsil of Sargodha district, and about 10 per cent of it lies in the Phalia Tehsil of Gujrat district. It is about 40 km long and 13 km wide and is bounded on the east by the Lower Jhelum Canal (LJC) Main Line, and on the north and south by its Shahpur Branch and Northern Branch respectively. No significant boundary line demarcates the case-study area on its western side. Most of the area lies in the abandoned flood-plain of the Jhelum River; the rest is a part of the ancient alluvial plain. The total area of the project is about 44500 ha, and the cultivable area is about 41300 ha. There are eight-three villages in the area, of which forty-five lie completely within the project boundaries and the rest are situated partly inside and partly outside the boundaries.

The study area was originally a part of the Shahpur district, consisting chiefly of the Bar or central portion of the Chaj Doab in the Punjab. This district, with boundary changes, is now known as Sargodha district. Very little is known about the early history of the study area, but the mounds of ruins scattered over its surface suggest that it might have been cultivated and densely populated in the past. This view is supported by the writings of the Greek historians of Alexander's time, who describe the region as being densely populated. Historical records and architectural remains of comparatively recent age show that the area was prosperous even during the Mogul Emperor Akbar's time. The town of Bhera, which is adjacent to the study area, has an ancient history. The city flourished during the fifteenth century and brick buildings with beautiful wood carvings still stand denoting the prosperity of that period. The study area is now inhabited mostly by agriculturists. It has also produced excellent soldiers for the armed forces.

1. Chaj Doab is the area lying between the rivers Jhelum and Chenab.

Development of irrigation

Prior to the development of the canal system, cultivation in this area depended on rainfall, well irrigation and natural inundation from the river. Wheat, millet, cotton, sorghum and gram respectively occupied 46, 21, 8, 6 and 4 per cent of the total cropped area. According to the records available, the depth of the water-table in the area varied from 6 m to 20 m below the surface, increasing with distance from the river.

Inundation-canal irrigation was introduced in the case-study area in 1860 when the Macnabbwah Canal was excavated. Construction of the Raniwah Canal in Bhera Tehsil followed in 1870. The present form of canal irrigation (weir-controlled irrigation) was first introduced in 1901, with the partial completion and opening of the Lower Jhelum Canal, the construction of which began in 1897. This canal, which takes off from Rasul Barrage on River Jhelum, has a capacity at its head of 150 m^3/s and commands a gross area of 0·6 million ha. Approximately 31500 ha of the case-study area are commanded by the main line and northern branch of the lower Jhelum Canal and receive perennial canal-irrigation supplies. The 8100 ha commanded by the Shapur branch receive non-perennial supplies, during summer. A few shallow wells irrigate a small part of the remaining uncommanded area.

The area receiving perennial irrigation supplies is divided into regular squares and killas (1 killa = 0·445 ha) so as to simplify the planning of networks, the distribution of water and the management of land. This is not the case with land commanded by the Shahpur branch; previously this area was served only by inundation canals from the Jhelum River, and it was only recently incorporated in the Lower Jhelum Canal system.

Within the canal-commanded area are patches of land of 20–400 ha, which are 0·33 or 0·66 m higher than the surrounding land and therefore cannot presently be irrigated from the canal system; some of these have been dry farmed in the past.

Three periods have been identified for the purpose of analysing environmental changes consequent to irrigation activities in the case study area:

- *The pre-irrigation period, i.e. the period before 1901.* In that year irrigation supplies were made available in the area from the weir-controlled Lower Jhelum Canal, and planned settlement started.
- *The irrigation period, i.e. the period before the pre-rehabilitation project.* Between 1901 and 1965 irrigation activity was at its height, but lack of attention to drainage during this period resulted in waterlogging and salinization of the area, leading to desertification.
- *The irrigation period, i.e. the period after the post-rehabilitation project.* After 1965, large-scale rehabilitation measures including the Mona Reclamation Experimental Project were launched to control waterlogging and salinization.

The introduction of canal irrigation brought about a number of significant changes in the area. Large, hummocky, previously uncultivated plains of thorn scrub were brought under cultivation. Statistics indicate that in Sargodha district, the irrigated area increased from about 22 260 ha in 1900–1 to 73 250 ha in 1902–3. Irrigation brought overall prosperity, and most of the nomadic people whose livelihood depended on the land started settling. Many new villages were founded by grantees of wasteland and colonized largely by immigrants from the neighbouring Khushab area and elsewhere. During this period, work on the settlements began taking shape. Agricultural prosperity was significant in parts of the case study area where irrigation through inundation canals was introduced. This increased agricultural activity led to a decrease in the native fauna and flora.

Waterlogging and salinity

Before the introduction of weir-controlled irrigation, the water-table was 6–18 m deep over most of the area, and fairly stable. As soon as canal irrigation was introduced, ground-water levels began to rise. The deep percolation of water from the canal system and from irrigated lands became a new source of recharge, which was greater than the rate at which water could be discharged from the aquifer. In the early 1960s, 90 per cent of the area was affected by high water-tables and a little over 19 per cent by salinity in varying degrees; the major portion of the saline area was affected by waterlogging also. This situation affected the agricultural productivity of the area and necessitated the adoption of rehabilitation measures and implementation of the project within the overall context of the Salinity Control and Reclamation Programme for controlling and eradicating waterlogging and salinity in the irrigated areas of the Indus Plains.

The reclamation project in the case study area comprises 138 deep tube-wells of 0·6–11 m^3/s capacity, each designed to provide subsurface drainage and supplementary water supplies for irrigation and reclamation activities. This project has been selected as an experimental scheme for monitoring all aspects of irrigation—tube-wells, ground-water levels and quality, soils, agricultural, socio-economic conditions—and for research on soil reclamation and water management. This area was chosen as it had the advantage of not being in an advanced stage of deterioration and that results were expected to be available in a shorter period of time.

Objectives of the Mona Reclamation Experimental Project

The main objective of the Mona Reclamation Experimental Project is to collect operation research information adaptable to areas being developed under Salinity Control and Reclamation Projects. The studies conducted over the last ten years have shown the relative economic feasibility of various methods of soil reclamation and have helped in setting up water-quality criteria for agricultural production on various soils. In addition, valuable data have also been collected on irrigation practices, water management, land-levelling and the rehabilitation of watercourses.

The Mona Reclamation Experimental Project has been selected as the case-study area as conditions therein are generally representative of the conditions found in the waterlogged and salinized areas of the Northern Indus Plains. The soils are representative of the major soil series found in the Plains. The area is served by both perennial and non-perennial canals and also includes areas not irrigated by canal works (uncommanded). It is an experimental reclamation scheme from which data have been available in a systematic form and on a continuous basis since its inception. Prior to the adoption of improvement measures, the water-table was quite high and a considerable area was salt-affected to varying degrees. The ground-water quality in the area also is quite variable, being very good to very poor. The area has a representative cropping pattern, and socio-economic conditions are similar to those of the other irrigated areas where drainage and reclamation projects have been implemented. The availability of bench-mark data for future use through a comprehensive socio-economic survey was another consideration in selecting this project as the case-study area.

Conditions in the pre-irrigation period

Physical features

Climate

The available recorded information shows that the average annual rainfall in the area was in the order of 380–280 mm in summer and 100 mm in winter. Rainfall varied from year to year and from place to place. For example, at Bhera in 1891–92 total annual rainfall only amounted to 130 mm, while in the following year it rose to 610 mm. In March 1888 only 13 mm of rainfall were recorded in Bhera, while only 16 km away at Miani, rainfall reached nearly 610 mm. In summer, the average maximum temperature was 38°C; the minimum was about 29°C. In winter, the maximum temperature was around 15°C and the minimum was 4°C. The area was less exposed to wind as compared with most parts of the Punjab; however, in dry, hot weather, dust storms were frequent, generally from the direction of the sandy Thal area.

Soils and geomorphology

The soils were inherently fertile, of high potential productivity, and well suited to irrigated farming. The calcium carbonate content of the soils was high, and the sodium content generally low. Although the soils had a relatively low organic-matter, available nitrogen and phosphate content, they were productive when irrigated. The low ratio of sodium to calcium kept the soils sufficiently open to permit a moderately free downward movement of percolating

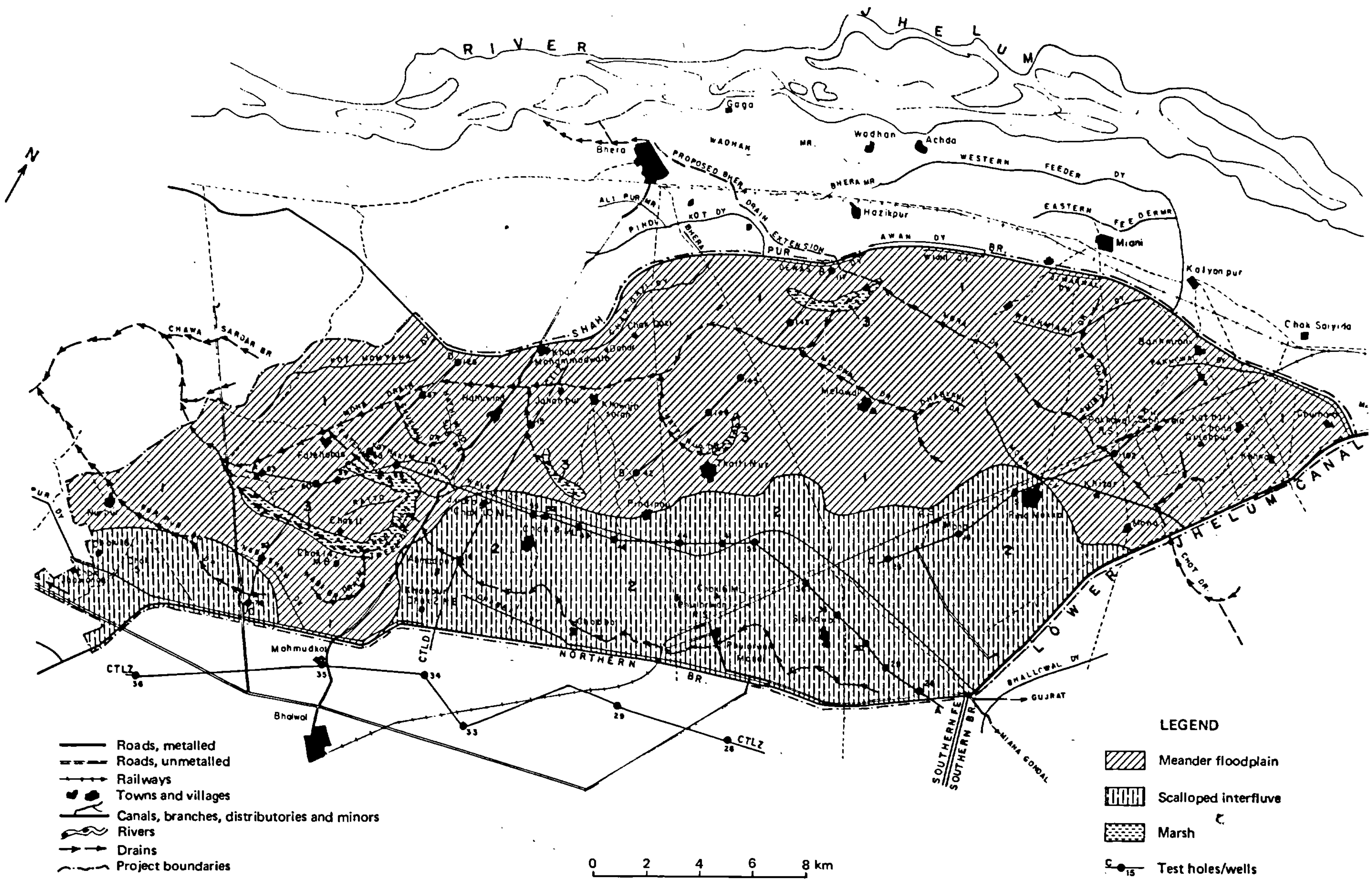


FIG. 1. Physiography and location of test-holes/wells

water, and was thus favourable to the reclamation of salinized lands through leaching.

The study area lies within an alluvial plain formed mainly by the Jhelum River. The relief is generally level with an average slope of 0·02 per cent in a southwestern direction. There were some prominent depression areas, and a few patches showed varying degrees of surface relief. The elevation of these areas, situated in the northeastern and southwestern extremities of the area, ranged from about 191 m to 198 m above sea-level.

Two major land-forms, the meander floodplain and the scalloped interfluve, were recognized in the area (Fig. 1) and constituted 60 and 40 per cent of the area respectively. The plain contained the oldest materials of the Doab (land between two rivers) and at its northern boundary there were prominent alluvial bluffs.

Ground water

Prior to the irrigation period, the water-table was in dynamic equilibrium and fluctuated with seasonal variations in recharge; there was no long-term trend. The depth of the water-table immediately prior to canal irrigation was in the range of 6–18 m, deepening as distance from the river increased (Fig. 2). Groundwater movement was from north to south, away from the river, which was the main source of recharge.

Flora and fauna

The characteristic trees and shrubs were *van* (*Salvadora oleoides*), *kari* (*Capparis aphylla*), *jand* (*Prosopis cineraria*), *malla* (*Zizyphus nummularia*), *kikkar* (*Acacia arabica*), *tahli* (*Dalbergia sissoo*), *ukah* or *koah* (*Tamarix articulata*), *ber* (*Zizyphus jujuba*), *lasura* (*Cordia myxa*); the *tut* or mulberry (*Morus alba*), *sohanjna* (*Pterygo sperma*) and *shirih* (*Albizzia lebbek*) were largely grown on cultivated lands. Shrubs and plants like *lie* (*Tamarix gallica*) or *pilchi* (*T. dioica*), *akk* (*Calotropis procera*) camel-thorn or *jawaha* (*Alhagi maurorum*), *harmal* (*Peganum harmala*) and *bhakkhra* (*Tribulus alatus*) were also common. *Khar* or *sajji* (*Salsola griffithsii*) and *lana* and *lani* (*Salsola* spp.) were found in barren salty soils, and *nar* (reeds) in moist places. The commonest grasses were *khabbal* (*Cynodon dactylon*), *dub* (*Eragrostis cyposuroides*), *chhembar* (*Eleusine flagellifera*), *sawak* (*Panicum colonum*), *palwah* (*Andropogon annulatum*), *dhaman* (*Pennisetum cenchroides*), the *dabbh* (*Poa cynorsuroides*), the *kana* (*Saccharum munja*), and *kah* (*S. sponteneum*).

It is reported that in the pre-irrigation period, tigers were present in Sargodha district, but none have been seen since 1897. Among other wild animals, leopards and hyenas were occasionally seen or heard, whereas wolves, foxes, wild cats, mongoose, hedgehogs, rats, mice, badgers (*bijju*), hare, ravine-deer, pigs and porcupines were frequently seen. For

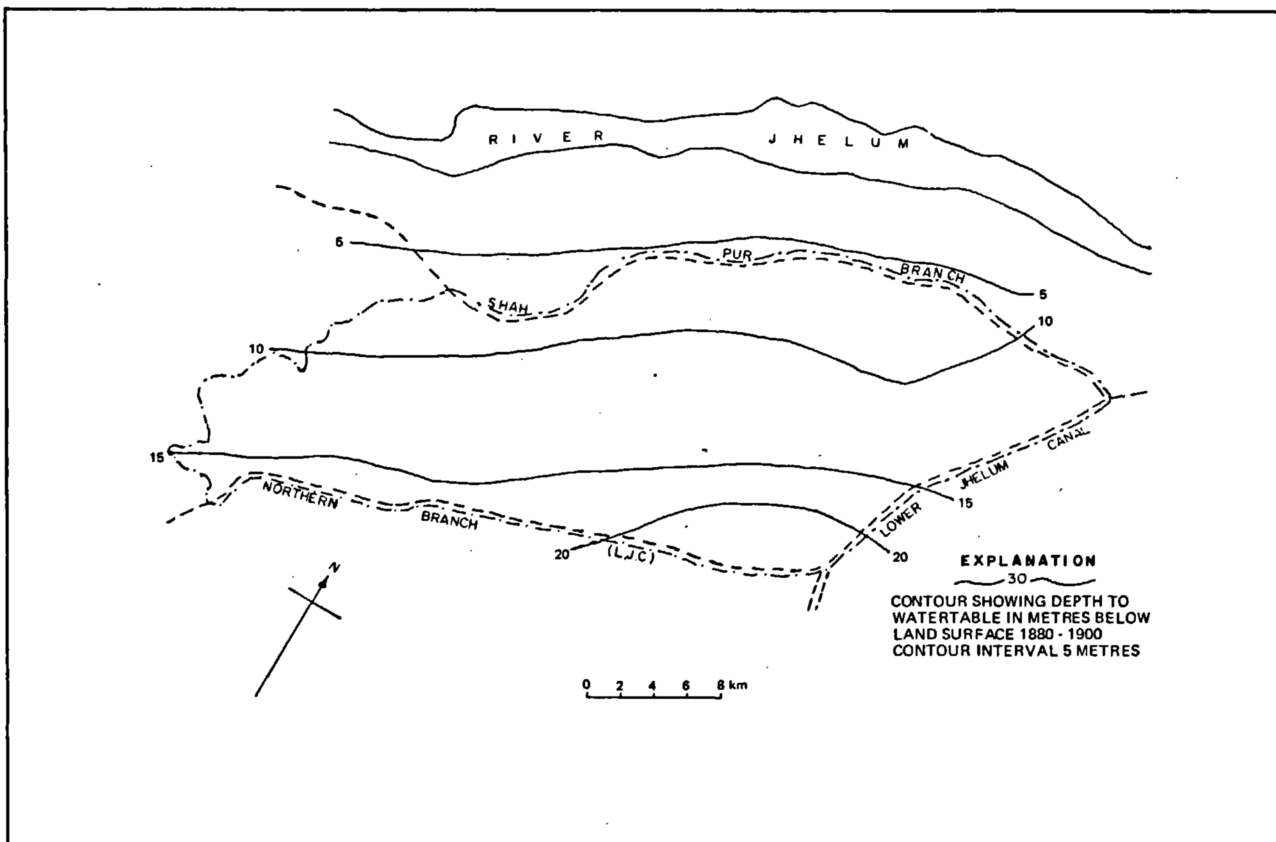


FIG. 2. Map showing the approximate depth to the water-table below land surface in the pre-irrigation period (1880–1900)

the hunter there were mountain-sheep or oorial, which was similar to moufflon of Corsica. However, the numbers of these animals, which were subject to hunting, rapidly decreased at the end of the nineteenth century.

Among the birds, bustard (*tog*), flocks of imperial, painted and pallas sandgrouse, quail (*batera*) and grey partridges (*titar*), ducks of many kinds, geese, blue-coated demoiselle cranes (*kunj*) and numerous other aquatic birds, sometimes together with snipe and bittern, were common. Crows and kites were ubiquitous and hawks used to fetch high prices for sporting purposes. In cultivated tracts, parrots were noticed and golden orioles were occasionally seen in the trees. Blue jays and scarlet woodpeckers were common. Immense flocks of rosy pastors (*tilliar*), the hereditary enemy of the locust, used to visit the district in hot weather.

Among reptiles, venomous snakes like cobra or *phaniar* (*Naja tripudians*), the *karait* or *sangchur* (*Bungarus coeruleus*) and the *phissi* or *khapra* (*Echis carinata*) were common. Locusts, generally coming from the south-west, sometimes invaded the area in destructive numbers. In 1891 numerous flights of locusts, recognized as *Acridium peregrinum*, invaded the area. Another flock of locusts recognized as *Paecilocera picta* visited the area in 1893. A type of cricket (*toka*) of the genus *Gryllodes*, and an acridian of the genus *Chrotogonus*, often caused great damage to sprouting summer crops.

Population

The population of the study area during this period is not known. However, according to the available information in the contiguous area the density of population was 21 inhabitants/km^2 in 1891, and increased to 69/km^2 in 1911.

The occupational activities of the population of Sargodha district, according to the 1891 census, are given in Table 1.

Social and family structure

The men of the pastoral tribes led a comparatively lazy life and the demands on their labour were practically limited to drawing water for cattle and milking the cows. Men of the agricultural population were more or less employed in some form of husbandry all year round.

TABLE 1. Occupations of the population of Sargodha district, 1891

Occupation	Percentage of total population
Government	1·9
Pastoralism and agriculture	53·8
Domestic service	5·3
Preparation and supply of goods	25·3
Commerce and transport	5·1
Professional	2·6
Various and independent	6·0

The families in the area have always been patriarchal,[1] patrilocal[2] and patrilineal.[3] Most of the decisions in the family were taken by the elder of the family. Early marriages and exchange cross-marriages (locally called *watta satta*) were also practised. In the early periods bride-price was also paid in some cases, and divorces were rare. Nearly 80 per cent of the people between the ages of 30 and 40 were married. The average age at which a rural male married was over 21 years. Marriages and other social ceremonies were important occasions for display for the villagers, and huge sums of money were spent on festivities, even if it meant taking money on loan.

The Punjab has always been regarded as the land of villages. In the past each village had its distinct boundary and acted as a separate socio-economic unit. In fact, inter-village communication was so low that every village was a little estate, self-sufficient within its own environment, resisting all outside influences. This remained the situation until the introduction of the canal-irrigation system.

In the villages of the study area, as was the practice all over the country, land-ownership, revenue, irrigation and other records were kept on a village basis. The majority of cultivators within the village kept close contact with each other, thus forming a unique communication system through the village *dera* (the common sitting place for men), and the *tanoor* (village bakery) where women gathered for routine gossip and news. The village thus formed a cohesive social unit. Every village had the following structure: a headman, a watchman, a number of land-owners, artisans who served the agriculturists, and also certain priestly castes.

The joint family was the recognized family unit, but many people considered that living in nuclear families carried fewer problems. Generally, the people were socially conservative and social mobility was restricted.

Women were generally regarded as inferior in status. However, a woman as a mother, wife, or sister had a significant influence on the day-to-day running of household affairs. High value was placed on sons as they ensured the continuity of the family, economically and socially. A woman who gave birth to many sons enjoyed high social prestige. The tragedy of the woman was not biological, it was rather sociological and ideological. There were a number of customs, taboos, beliefs, prejudices, superstitions, myths, rituals and institutions which made women socially inferior to men. Studies have shown that in farm operations women assisted their menfolk. Usually they looked after the domestic animals and also worked in the fields during the harvesting, threshing, winnowing and gleaning of the wheat in addition to engaging in household chores. Public opinion was generally against providing education to women.

The food of the common people was simple, consisting generally of cereals, vegetables, milk and

1. The head of the family is a male who makes decisions for the entire family.
2. A married son brings his wife to live with his parents in his own community.
3. The lineage of children is drawn from the male side of the parents.

its by-products. During the hot weather it consisted of bread made from wheat flour, with buttermilk, pickles or *gur* (locally made sugar), while in cold weather, millet or maize bread were taken with the same accompaniments. The people had their regular meals twice a day, at about 10 a.m. and then after sunset. In the hot weather, in addition to the regular meals, the remains of the previous day's food were used with buttermilk, which was taken to the men working in the fields about an hour after sunrise; parched grain was taken in the afternoon.

Education

During the days of British occupation, the whole educational system was geared to meet colonial needs and requirements for law and order. The primary objectives of education were therefore to provide men for clerical jobs in different administrative departments and to westernize the people by impressing upon them the superiority of western culture and knowledge.

There were two high schools at Bhera, one maintained by the Municipal Committee and the other an unaided Anglo-Sanskrit school. There was only one girl's school at Bhera. There were two primary schools in the case-study area, one at Hazoorpur and the other a Zemindari school at Chawa. The first high school was established in the area in 1890. Literacy in Sargodha district in 1894 was 3·3 per cent among males and less than 0·5 per cent among females.

Agricultural economy

Agriculture

Before the introduction of the Lower Jhelum Canal, the cultivation in Sargodha district was mostly rain-fed (*barani*) or irrigated from dug wells, and in some parts from river overflows (*sailaba*) or from inundation canals. The main food crops were wheat, bajra, jowar and grams, while the cash crop was mostly cotton. Crops like sugar-cane, maize, tobacco or poppy were minor, and an insignificant proportion of the land was allotted to them. Fruit and vegetables were also grown, generally with well irrigation. The average yields of crops in Bhera Tehsil are given in Table 2.

Table 3 gives an indication of the cropping pattern prevalent during the pre-irrigation period in Sargodha district. The total cropped area was approximately 205 600 ha.

As can be seen from this table, wheat and bajra (millet) were then the important crops.

Normally, 15–20 per cent of the cultivated area was left fallow throughout the year and about 60 per cent was put under *rabi* (winter) crops and 20–25 per cent under *kharif* (summer) crops. This meant that a large area was put under wheat year after year, with an occasional change to oil-seeds followed by cotton or fodder, succeeded after a fallow by cotton.

In the pre-irrigation period, the farmers did not have much marketable surplus to sell, and therefore a market structure had not developed.

TABLE 2. Average yield of crops in Bhera Tehsil (kg/ha)

Crop	*Barani* crops	Irrigated from wells	Under *sailaba* and canal inundation
Wheat	550	1100	735
Barley	550	1100	735
Grams	735	735	735
Bajra (millets)	365	920	645
Jowar (sorghum)	365	550	460
Cotton	365	550	365
Maize	—	1100	735
Rice	—	1100	1100
Sugar-cane	—	1840	—

TABLE 3. Cropping pattern during the pre-irrigation period in Sargodha district

Crop	Percentage total crop	Crop	Percentage total crop
Wheat	42	Jowar (sorghum)	7
Cotton	6	Pulses	3
Oil-seeds	4	Barley	3
Grams	5	Other cereals	2
Bajra (millets)	18	Miscellaneous	10

TABLE 4. Livestock statistics of Sargodha district in 1893

Animals	Number (thousands)	Animals	Number (thousands)
Bulls and bullocks	111	Sheep	193
Cows	124	Goats	115
Male buffaloes	15	Horses and ponies	8
Cow buffaloes	35	Mules and donkeys	21
Calves and young buffaloes	72	Camels	13

Livestock

In the pre-irrigation period, cows, buffaloes, camels, sheep, goats and horses were the most important livestock in the area. The district of Sargodha used to be one of the best areas in the country for breeding horses and ponies. The milch animals of that period were low yielders; on the average, a cow gave 2·5–3·5 kg of milk/d. The livestock position in the Sargodha district in 1893 is given in Table 4.

Large numbers of cattle died annually through disease. No preventive measures were adopted by the people to save their livestock from contagious diseases and outbreaks of rinderpest and foot-and-mouth disease were of almost annual recurrence.

Conditions in the irrigation period before the rehabilitation project (1901–65)

The canal irrigation system

The case-study area is served by a part of the Lower Jhelum Canal (LJC) system which takes off from the

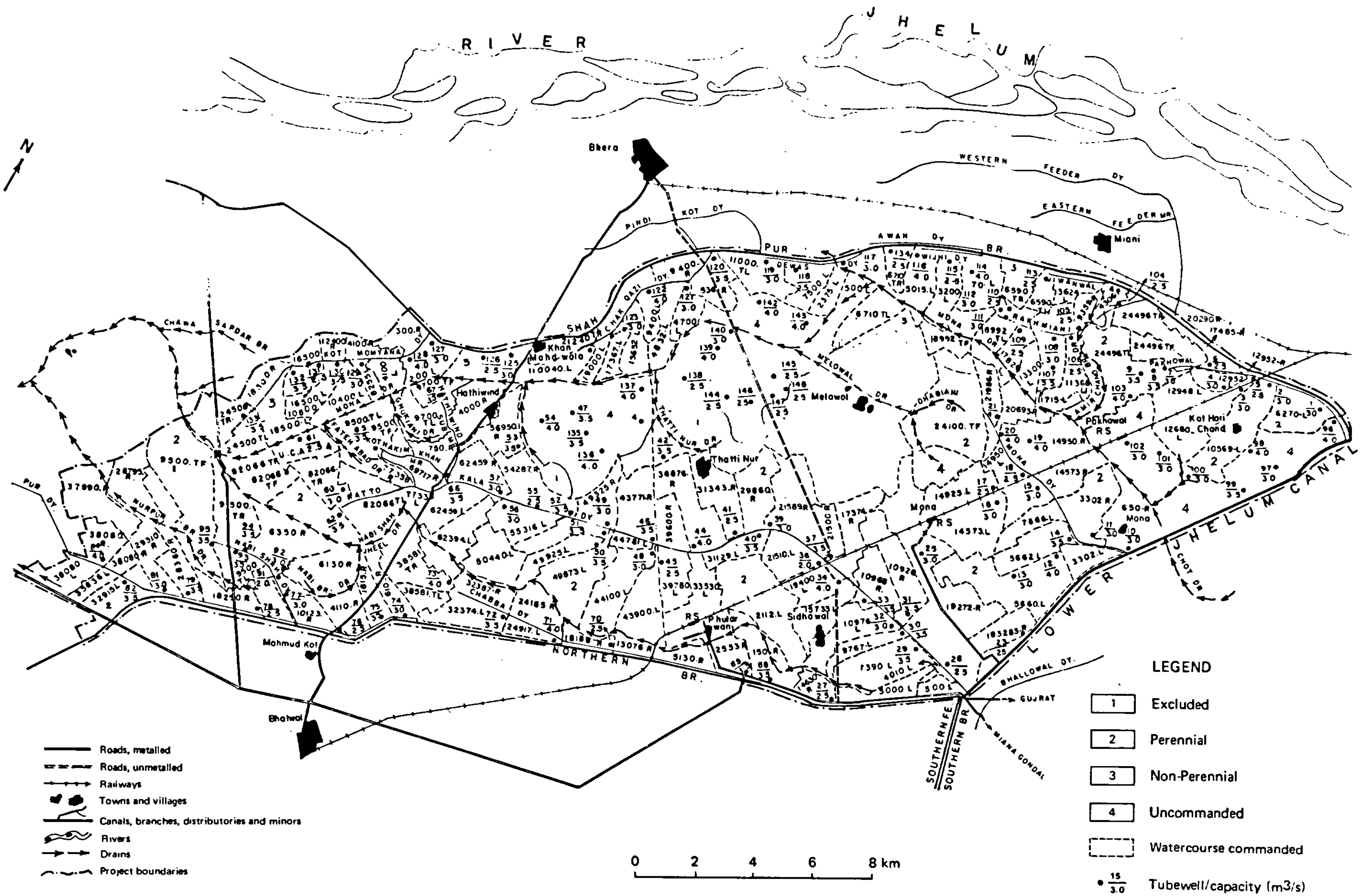


FIG. 3. Irrigation commands

left bank of the Jhelum River below the Rasul Barrage constructed in 1901. The construction of the LJC was begun in 1897 and the canal was opened in 1903. It was originally planned to irrigate some 242 816 ha of land, and this objective was attained by 1908–9. The LJC now has a capacity of 149·5 m^3/s at its head and commands a total gross area of 647 511 ha, with a cultivable commanded area of 607 042 ha. The canal commands a greater part of the Sargodha and Jhang districts lying between the Jhelum and Chenab Rivers. The irrigated tract extends to the confluence of the two rivers, the Chenab and the Jhelum. The development of the whole system as it now exists took place between 1897 and about 1919.

In the case-study area, approximately 31 566 ha are commanded by the main line and northern branch of the LJC, and receive perennial canal-irrigation supplies. The 8 094 ha commanded by the Shahpur Branch Canal receive *kharif* (summer) supplies only. The remaining 5 665 ha are not commanded by gravity irrigation systems and are at present largely irrigated by tube-wells and open-wells, etc. The various irrigation commands are given in Figure 3.

The case-study area is served by a network of seven distributaries off-taking from the Lower Jhelum Canal–Main Line, and its Northern Branch and Shahpur Branch. The authorized full supply (AFS) of these distributaries and other relevant information is given in Appendix IV. Except for a small amount of discharge through the Fatehpur Distributary, all canal inflow in the distributaries is used within the area. The annual average perennial diversion during the period 1960–65 from the Main Line and Northern Branch of the Lower Jhelum Canal was ($169 \times 10^6\ m^3$), commanding a cultivable area of 25 110 ha, and the non-perennial supply from the Shahpur Branch for the same period was of the order of $34 \times 10^6\ m^3$, commanding a cultivable area of 6 680 ha.

The water from the outlets is conveyed in ditches called 'watercourses'. Generally the supply from the outlets in a watercourse is of the order of 0·03–0·08 m^3/s depending upon the size of the area to be irrigated from the particular outlet. The watercourses branch off into field channels as they run through the farm land to deliver water to the farmers' individual holdings. Usually these watercourses consist of earthen channels.

Each outlet of the canal system that delivers water to a watercourse serves a land area known locally as *chak*, which varies in size from 120–160 ha to 400–600 ha, the average being a little more than 280 ha. There are about 233 outlets under the canal and tube-well systems in the case-study area. The *chakbandi*[1] registers, and *chakbandi* maps for the outlets, are maintained by the Irrigation Department. They provide data for full discharges of outlets serving watercourses, including the normal maximum discharge of each outlet, the gross area served, the cultivable commanded area, the *ghair mumkin* area (area occupied by villages, roads, etc.), the net irrigable area, and the exact point where each watercourse leaves the distributary. The *chakbandi* maps are drawn to a large scale of 1:630 000 or 1:950 000. Individual maps show details of part or all of the lands served by a distributary of the canal system, covering about 3–15 outlets. The features of most maps include land-surface contours at 30-cm intervals for all squares,[2] positions of watercourses and uncommanded areas such as roads and villages.

Water distribution to the farmers at the outlet level is made through a system called *warabandi.* Each farmer gets his share of water for fixed periods in each week or ten-day period as may be the prevalent practice. His period of use in a week or ten days is in direct proportion to his farm area. The farmer diverts water to his field by making a cut in the watercourse at the beginning of his landholding. When his stipulated time is over, he closes the earthen cut and allows the water to flow downstream to the area of the next farmer. This practice suffers from the inherent defect that a farmer is obliged to turn water on his field whether he needs it or not, while at critical times of crop requirement he may have to wait his turn. However, this is unavoidable, because the river flows are variable from time to time and have to be used as the supply becomes available. Since the construction of the Mangla Dam on the River Jhelum, partial regulation of river water has been achieved and variations are now less marked.

The flow in the irrigation channel is dependent upon the variable flows available from the rivers. There are times when acute shortage occurs owing to deficient supply in the rivers. When this occurs all irrigation canals cannot be supplied with water according to their full design capacity. In such circumstances canals are run with partial supplies, and in rotation. The distribution system of outlets is designated so that each outlet draws its proportional share, and water is carried to the tail end of the channel. Shortages are thus proportionally distributed throughout the system. The outlets designed with the above objective in view are called adjustable proportionate modules. These have been developed to provide an equitable distribution of available supplies.

The irrigation canals in the area have been constructed with raised earthen banks to maintain water-surface levels higher than the surrounding lands—a necessity for gravity flow. The raised banks are subject to attack by rain, windstorms, etc. During heavy rains the banks are eroded, necessitating annual maintenance. Turfing on bank slopes is designed to minimize gullying and dirt tracks are maintained along all the channels to facilitate inspection. Trees are usually planted along the canal banks for aesthetic purposes as well as for timber.

Apart from the embankments of the extensive canal system, the principal maintenance problem is the flow section, which in earthen channels is subject to erosion and wash-aways owing to the movement of silty water with varying quantities of silt load. Periodic desilting of the irrigation channel is carried

1. The water-distribution scheme of a *chak.*

2. The area receiving perennial irrigation is divided into regular squares (each square covering ten hectares) and *killas* with the result that distribution of water and management of land is easy. This is not the case with land under Shahpur Branch command. Previously this area was served only by inundation canals from the Jhelum River. The Shahpur Branch was only recently incorporated in the Lower Jhelum Canal.

out using manual labour. When the hydraulic regime is sufficiently disturbed by appreciable silt deposits, to avoid heavy expenditure on silt clearance, the outlets are redesigned to conform to the raised water levels in the channel caused by raised bed levels. The method ensures equitable distribution of canal supplies to the tail end of the channel.

The drainage system

The case-study area is provided with a network of surface drains for handling storm run-off, but there are few data available on the development of the drainage network. In the entire project area of approximately 492 km^2 there is a total of 129 km of main and branch drains and 29 km of tributary drains, i.e. about 0·32 linear km of drains/km^2 of catchment. This compares favourably with the figure of not less than 0·25 km/km^2 recommended for the Chaj Doab. The Mona Drain is the main drain, running from east to west, bisecting the area and forming the irrigation boundary between the Shahpur and the Northern Branches. It has a flow capacity of 1·0 m^3/s and originates at the eastern end of the study area, where it intersects the Chot Drain.

Except for the past few years, no data on the discharge of the drains are available. In 1956 the Irrigation Department installed a gauging station on the Mona Drain at the point of outflow from the area, and in 1960 another gauging station was installed near the point where the drain enters the area. The 1960 station measures practically all the surface run-off water inflow to the project area from adjacent areas upslope, while the 1956 station records most of the surface run-off outflow from the area. Drain discharge data from these stations are given in Table 5.

Layout of villages

After the introduction of the Lower Jhelum Canal, the character of the countryside completely changed. The number of villages of each size increased considerably, showing that population increase has been evenly distributed over all sizes of villages. The number of inhabited villages and towns in Sarghoda district increased from 706 in the pre-irrigation period to 1066 in 1911. It may be noted that many of the villages were very large estates or townships and that their population was not often concentrated in one village, much of it being in hamlets situated at some distance from the parent village. There was nothing very distinctive about the arrangement of the houses in most of the old towns and villages. The dwellings were clustered together in a haphazard manner and the only principles of town planning were those which relegated the lowest grades of workers to the outskirts of the towns and grouped the other non-landowners around the homestead of the particular proprietors under whose patronage they carried on their trades or labour. In villages, the courtyards were generally spacious, in comparison with the smallness of the buildings and the narrowness of the streets.

The development of the villages continued over a period of time. In the case-study area before the rehabilitation measures there were eighty-three villages. Of these, forty-five villages lie completely within the boundaries of the study area, while the remainder are partially inside. Each village in the case-study area has a unique socio-economic character and is the smallest unit in the administrative organization.

TABLE 5. Measured annual inflow and outflow from the Mona Drain (in million m^3)

Year	Inflow at station established in 1960	Outflow at station established in 1956
1960–61	18·01	31·70
1961–62	7·03	31·08
1962–63	7·03	34·66
1963–64	6·54	27·75
1964–65	4·69	35·03
1965–66	7·40	28·37

Land tenure and size of holdings

In 1917, in Sargodha district 39 per cent of the cultivation was done by owners or grantees themselves, 2·3 per cent by occupancy tenants[1] and 58 per cent by tenants-at-will; the remaining 0·7 per cent were the squatters (without title). The land-tenure system, which was highly biased in favour of the landlords, had persisted for many generations. The development of agriculture was directly linked with the facilities available for irrigation.

In 1965–66, in the case-study area, there existed three land-tenure systems: owner-operators, owner-cum-tenants and tenants. Under the system of owner-operators, or peasant-proprietorship, farm land was cultivated by the owner himself. The owner-operators were natives, settlers, or refugees. The natives were the original inhabitants of the area, and had held right of ownership to the land since ancient times. Their forefathers held large pieces of land, which had been subdivided continuously among the heirs for many generations. The settlers were given title to the land at the advent of canal irrigation in the area, and a holding of two squares was granted to each of them, with the condition that a mare would be maintained on the holding for the supply of horses to the cavalry. The settler holdings has also been reduced in size owing to subdivision, sale or purchase of land and these holdings were no longer of uniform size. The owner-operators were an important class of cultivators of the area, as they constituted 42 per cent of the total cultivators and operated 43 per cent of the farm area. Nearly 56 per cent of them were concentrated in the perennial areas, 12 per cent in the non-perennial irrigation areas, and the remainder within the uncommanded areas. On the whole, more than half of these cultivators had landholdings below the subsistence level (Table 22).

Studies have revealed that very few cultivators liked to be tenants when they had land of their own. Though as many as 50 per cent of the owner-cultivators held operational units below the subsistence

1. Farmer with title to possession of the land.

TABLE 6. Areas of land held by different colonists in Sargodha district, 1917

Class of colonist	Area allotted (ha)	Class of colonist	Area allotted (ha)
Horse-breeders		*Arboriculturists*	
Peasants		Nurserymen	883
Cavalry	11709	Planters	507
Others	67085		
Nazrana-paying		*Other colonists*	
Stud-farms	2733		
Cavalry	2802	Peasants	28286
Others	6214	*Nazrana*-paying	17182

level, they did not like having additional land on rent. Again only about 20 per cent of the cultivators were owner-cum-tenants, operating about 17 per cent of the total farm area. As many as 37 per cent of the cultivators in the case-study area were tenants, a landless class depending directly on leased land for their livelihood. They operated 40 per cent of the farm area.

A number of colonists were occupancy tenants and others had expectation of obtaining that status. The colonists were considered as a distinct body of men formed of various classes. The areas held by each class in 1917 in Sargodha district are given in Table 6.

The most important were the horse-breeders, who were required to keep a branded mare in good condition for every unit of grant and to give the Army Remount Department the first refusal of the progeny. The difference between the peasants and the *nazrana*-paying[1] colonists was that the former could keep only one mare within a two-square unit of grant, on which they were required to reside, while the latter could keep two or more mares on 15 ha and reside elsewhere. In all horse-breeding grants, succession was according to the rule of primogeniture. The arboriculture colonists held their lands on twenty-year leases subject to resumption in the event of previous death or breach of conditions. Nurserymen ordinarily received ten *killas* (more than four and a half hectares), three of which were required to be set aside and maintained as a nursery for saplings. A tree planter ordinarily received one square and was required to plant not less than two miles of roadside avenue with *shisham* (*Dalbergia sissoo*) or *kikar* (*Acacia arabica*) trees. He was also bound to maintain the avenue in good condition.

The other colonists had no special conditions of service except in the case of recipients of grants of four squares or more, where if a peasant died before acquiring occupancy right, all his rights were extinguished. Another difference between peasants and *nazrana*-payers was that the unit of grant for the former was one square and for the latter two or more squares and whereas the former obtained occupancy rights on entry, the latter became similarly entitled only if still surviving after five years from the commencement of the tenancy. These two classes of grantees were subdivided as shown below:

Class of grantee	*Area allotted (ha)*
Infantry grantees	12112
Civil grantees	9409
Janglis (locals)	24207

The infantry grantees were prisoners, while the civil grantees were a miscellaneous collection, largely non-agriculturists and non-residential. The *Janglis* were the old denizens of the Bar; they were not farmers. In addition to the occupancy tenants and Lower Jhelum Colonists there were a certain number of other persons holding government land. These were:

- holders of land on long leases under the rules of 1897;
- holders of land on annual leases; and
- a leasee who accepted a grant in exchange for land.

Physical environment

Climate

There are no recording stations in the case-study area from which long-term systematic climatic data are available. The nearest stations—Sargodha, Miani and Bhalwal—are all outside the project boundary. A weather station at Phularwan was established within the study area in 1969–70. For this report, the data from Sargodha have been utilized to determine the rainfall pattern. The mean annual rainfall there is 378 mm and varies from less than 5 mm in November to 114 mm in July and is concentrated mostly in the monsoon months (Fig. 4). According to the published data of the Meteorological Department for the years 1931–60, the mean monthly maximum temperatures at Sargodha varied from 19°C in January to 42°C in June and the minimum from 5° to 28°C (Fig. 5). The annual extremes range from −3°C to 48°C on the basis of unpublished data for the period 1957–74. The average normal relative humidity varies from 34 per cent in June to 73 per cent in January (Fig. 6). The daily sunshine intensity in kW/m^2 is not available; however, mean monthly solar radiation varies from 4 mm/d equivalent evaporation[2] in December to 8·9 mm/d in May. The wind velocity recorded at the Sargodha station by an anemometer at 16·7 m above ground level varies from a minimum of 0·5 km/h in December to a maximum of 12 km/h in July (Fig. 7). The average annual evaporation at Sargodha is 2360 mm.

Soils

The major differentiating factor among the soils in the area is textural variation, both vertical and horizontal. The soils have been classified according to the texture of the subsoil to a depth of 1·83 m, and

1. A class supposed to pay gifts at ceremonial occasions.

2. Estimate based on Jensen-Haise equation for monsoon climate; $ETP = 0{\cdot}011\ (T - 19{\cdot}9)\ R_s$.

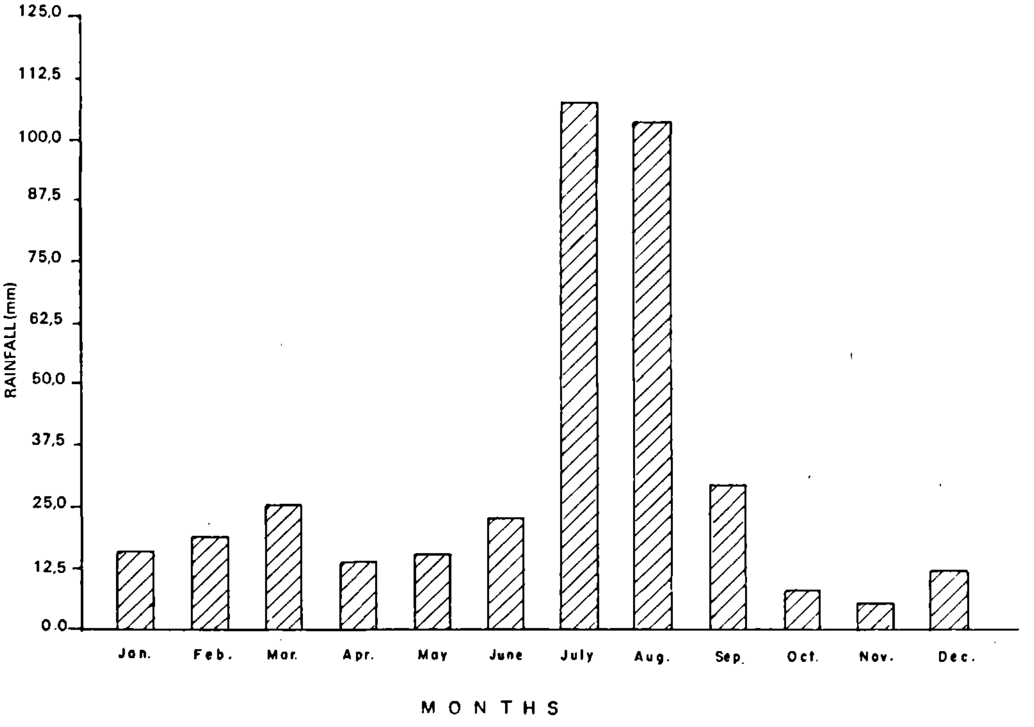


FIG. 4. Average monthly rainfall of Sargodha area

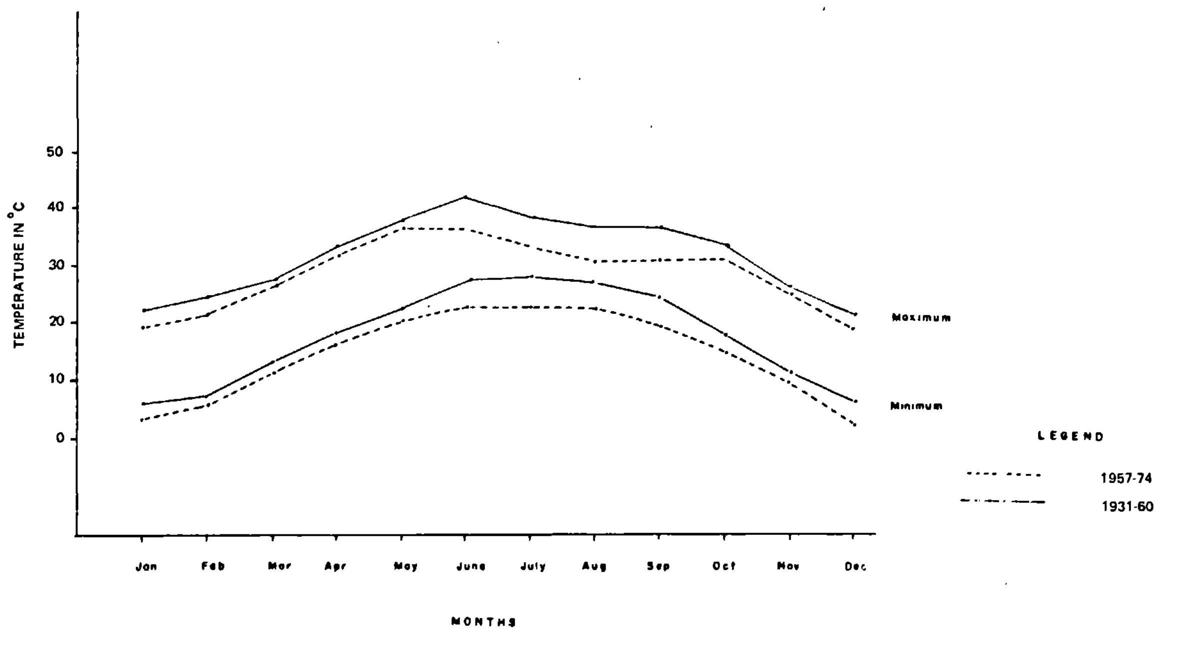


FIG. 5. Mean monthly temperatures at Sargodha

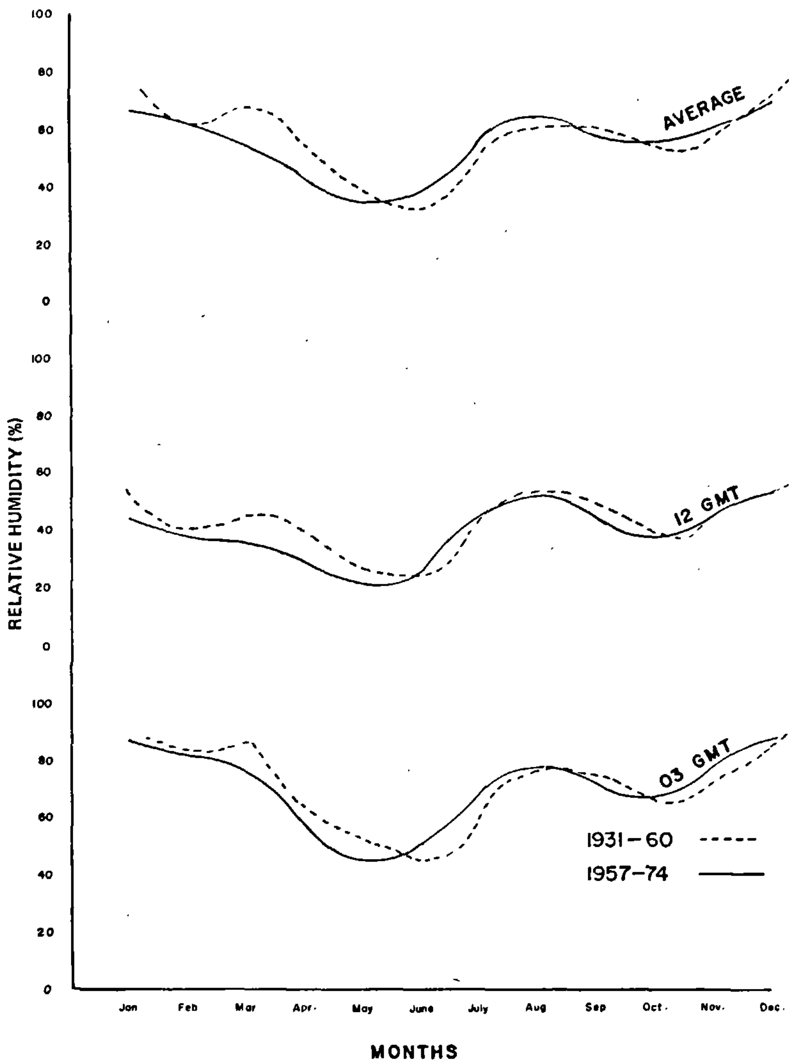


FIG. 6. Mean monthly relative humidity at Sargodha

five soil series are recognized: Jhuang (coarse), Farida (moderately coarse), Buchiana (medium), Chuharkana (moderately fine), and Nokhar (fine-textured). These are further divided into categories on the basis of surface soil and substrata textures. The surface-layer texture is important to crop production as this zone is the seed bed, the layer actually cultivated by the farmer. It contains most of the plant roots and controls the infiltration of water. The subsoil categories are helpful in assessing drainage problems. Greyish-brown and light-brown-coloured soils are most common, while rusty and reddish-brown mottlings have been observed in some profiles at variable depths. The soil material is usually calcareous except for coarse-textured soil material, which may be non-calcareous to slightly calcareous. Carbonate nodules occur in some profiles at variable depths.

The soil-series groups mapped in the area are shown on the accompanying soil map (Fig. 8) and the extent of their distribution in the two main physiographic settings is given in Table 7.

The distribution of major soil associations in the area, as mapped on the basis of a reconnaissance soil survey by the Soil Survey Project of Pakistan, is given in Table 8.

The Hafizabad association comprises non-saline, non-alkali, well-drained soils consisting of brown to dark brown, very friable, massive calcareous loam with weak subsoil structures and a distinct zone of carbonate accumulation containing common carbonate nodules (*kankar*) in the lower subsoil. Bhalwal association soils are deep non-saline, non-alkali, well-drained, calcareous and moderately fine-textured, with a distinct *kankar* zone in the lower subsoil. Shahpur association soils are deep, moderately well drained, calcareous and fine-textured, with weak subsoil structure and weak zone of carbonate accumulation in the lower subsoil.

Impact of irrigation on the environment

Ground-water regime

After the introduction of the canal system the dynamic equilibrium of the ground-water reservoir was disturbed, owing to the addition of new sources of recharge, i.e. seepage from the canal system, irrigation applications to crops and greater infiltration of the rain-water due to impeded run-off. Under

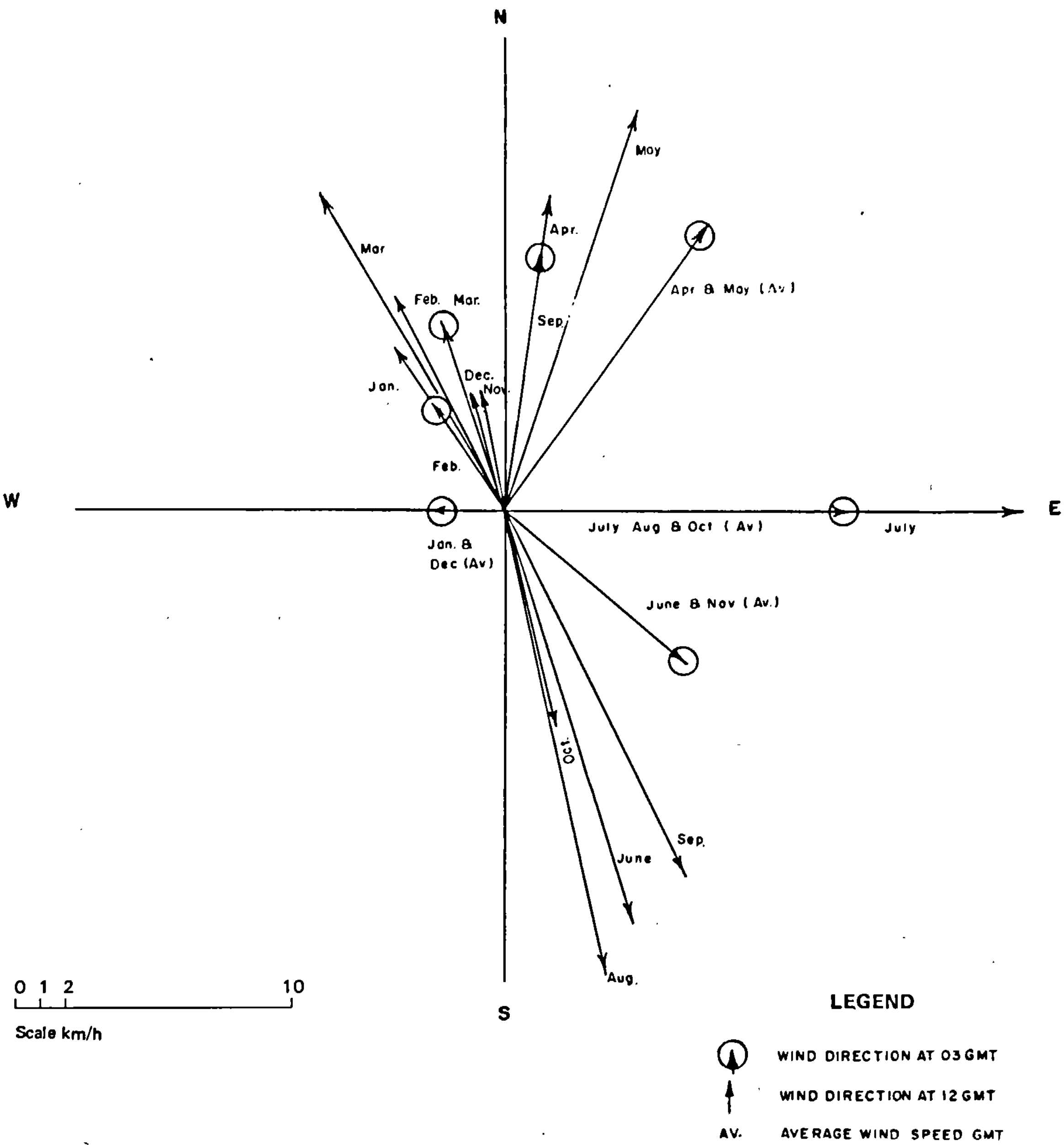


FIG. 7. Monthly average wind direction and speed at Sargodha (based on data from 1931–60)

the changed hydrologic environments the water-table started gradually rising, as indicated in the sample well hydrograph given in Figure 9. The hydrograph shows that the rate of rise was fast in the beginning for the areas where there was a deep water-table. As the water-table rose towards the land surface, the ground-water reservoir decreased through evaporation losses and a new equilibrium was attained which is indicated by the gradual levelling of the hydrographs. The change in the depth to water-table between the pre-irrigation period (1900) and 1965, is given in Figure 10 and the average hydrograph for the project area indicating the historic rise is given in Figure 11. The depth to water-table in July 1965 prior to the introduction of the tube-well project (Fig. 12) indicates that the water-table prior to the reclamation measures had come very close to the land surface, resulting in waterlogging.

Soils

With the introduction of canal irrigation and the consequent rise in the water-table, there has been continuous accumulation of salts in the soil profile, and much land was taken out of cultivation between the period of introduction of canal irrigation and the installation of tube-wells for salinity control and reclamation. The relative extent of different categories of surface salinity as well as profile salinity has been determined from surveys by the Water and Power Development Authority in the study area and is given in Table 9.

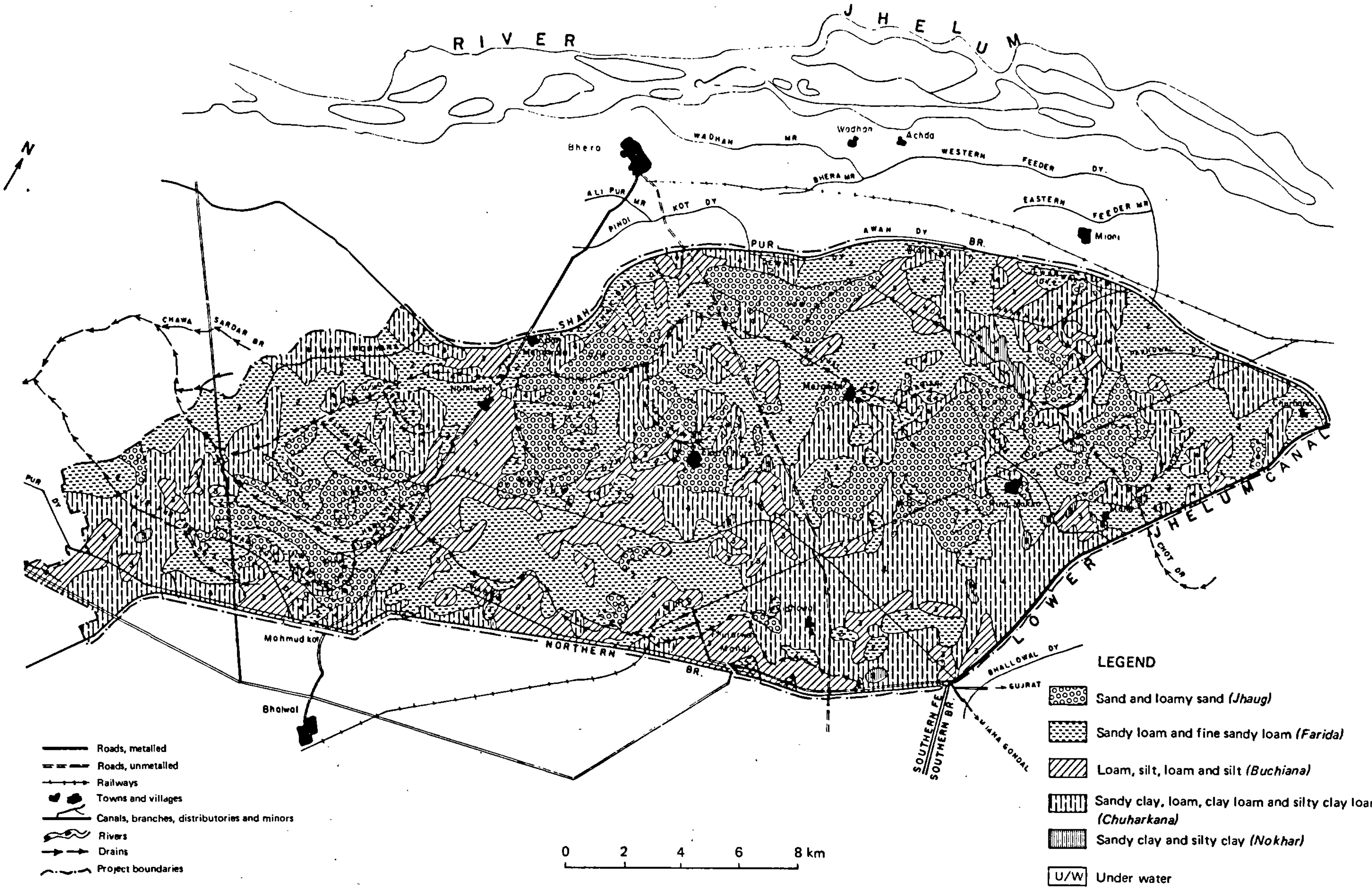


FIG. 8. Soil series

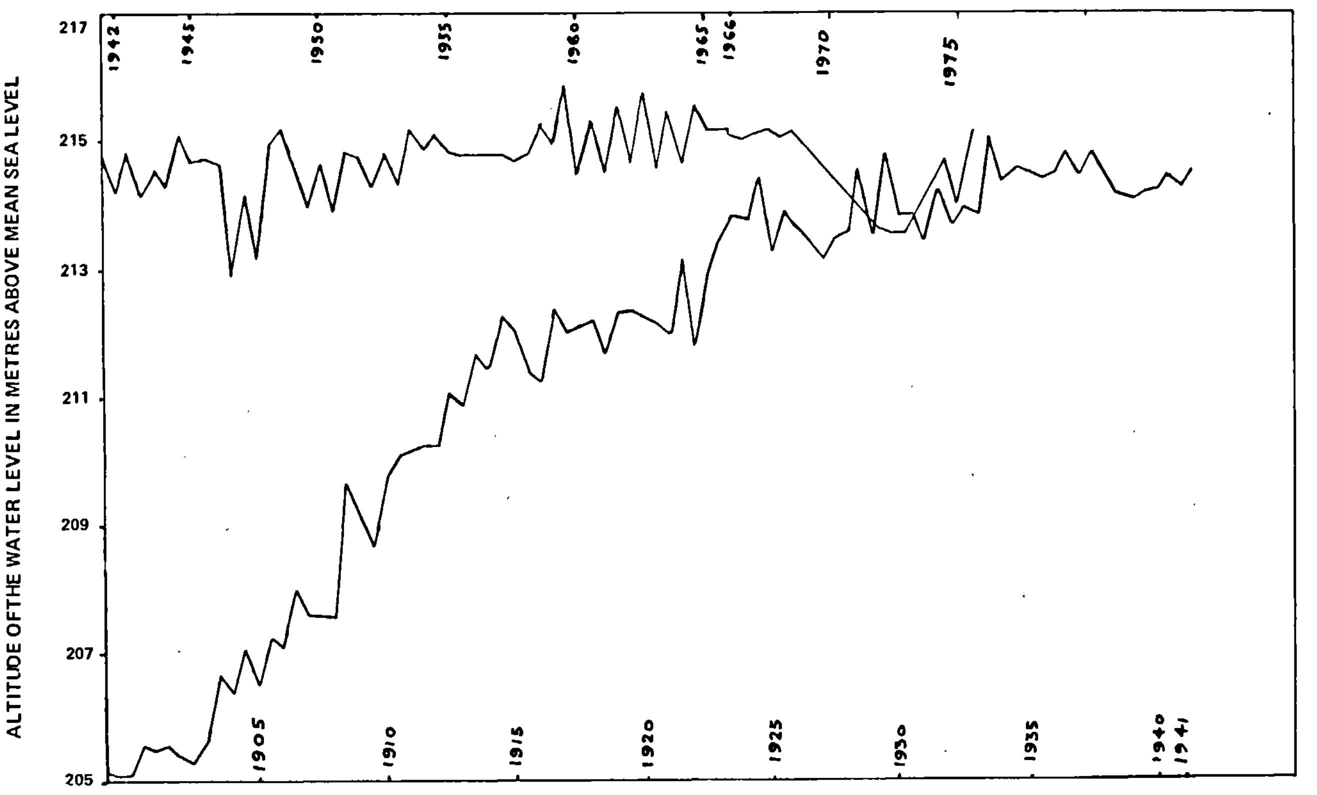


FIG. 9. Fluctuations of water level in well no. PL/CL/IX/10/6 in the Mona Reclamation Scheme, 1920–65

TABLE 7. The relative extent of various soil groups in different physiographic settings

Group number	Soil series	Area (%) Meander flood-plain	Area (%) Scalloped interfluve	Total (%) project area
1	Jhang soils (sand and loamy sand subsoil)	17·3	3·5	11·7
2	Farida soils (sandy loam and fine sandy loam subsoil)	42·7	30·6	37·7
3	Buchiana soils (loam, silty-loam and silt subsoil)	11·5	23·6	16·3
4	Chuharkana soils (sandy clay, loam, clay-loam-textured subsoil)	24·7	41·1	31·2
5	Nokhar soils (sandy clay and silty clay subsoil)	0·7	0·3	0·5
—	Miscellaneous land type (settlements, roads, streams and graveyards, etc.)	3·1	0·9	2·5
	TOTAL	100·0	100·0	100·0

TABLE 8. Proportionate extent of major soil associations in the Mona project area

Soil association	Percentage of the total area[1]	Soil association	Percentage of the total area[1]
Hafizabad	43·5	Rasulpur	8·8
Bhalwal	29·7	Shahpur	8·6

1. The remaining 9·4 per cent of the total area is occupied collectively by Gandhara, Miani, Missan, Gujranwala and Feroz associations. Their individual percentages are insignificant.

The different categories of surface salinity as shown in Table 9 comprise the following:

— None-saline area (no symbol): Neither soil nor crops are affected by salts. The soluble salt content is less than 0·2 per cent.

— Slightly saline area (S_2): The area mapped in this category includes one-fifth of the area or crop affected by salinity. Crop growth may be uneven or patchy.

— Moderate saline area (S_3): The area in this category is between one-fifth and four-fifths of the total area. The average salt content of the area mapped under this class varies from 0·50 to 1 per cent.

— Strongly saline area (S_4): More than four-fifths of the area mapped under this category have been affected by salts. Such areas are usually devoid of any vegetation other than salt-tolerant

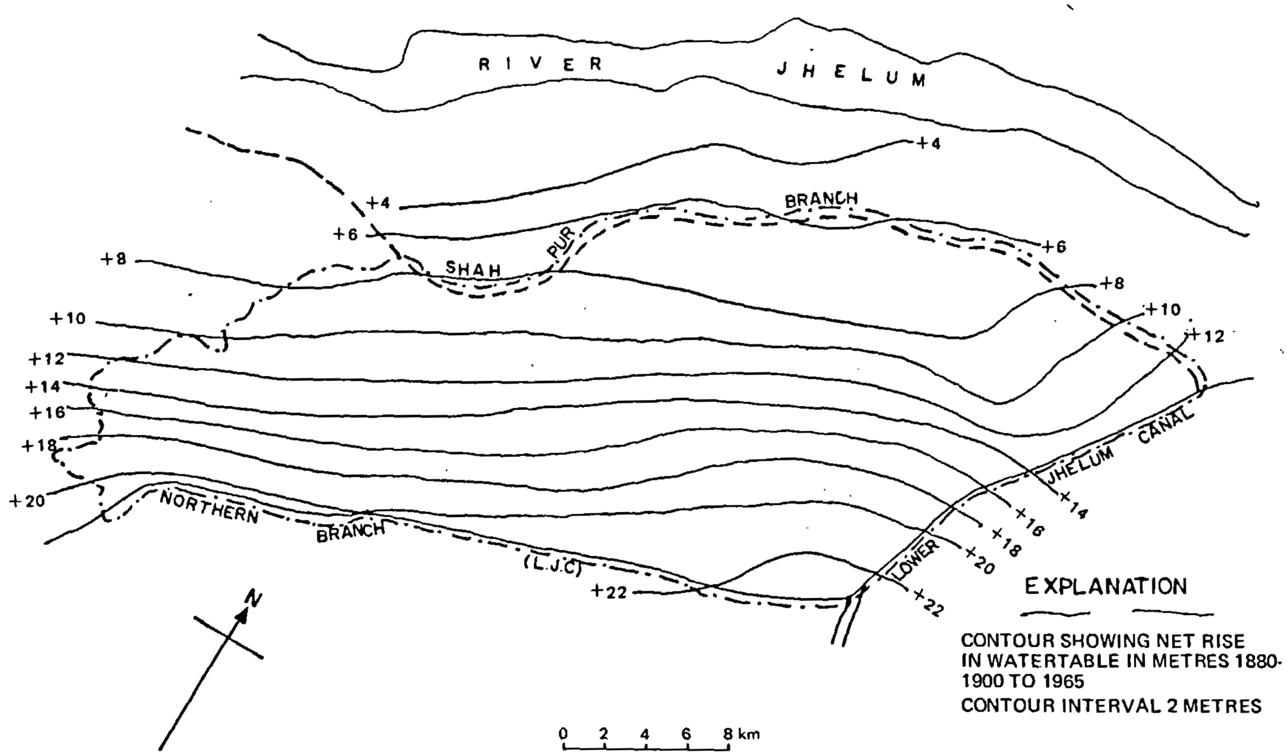


FIG. 10. Approximate change in altitude of the water-table in the Mona Reclamation Scheme during the period 1880–1900 to 1965

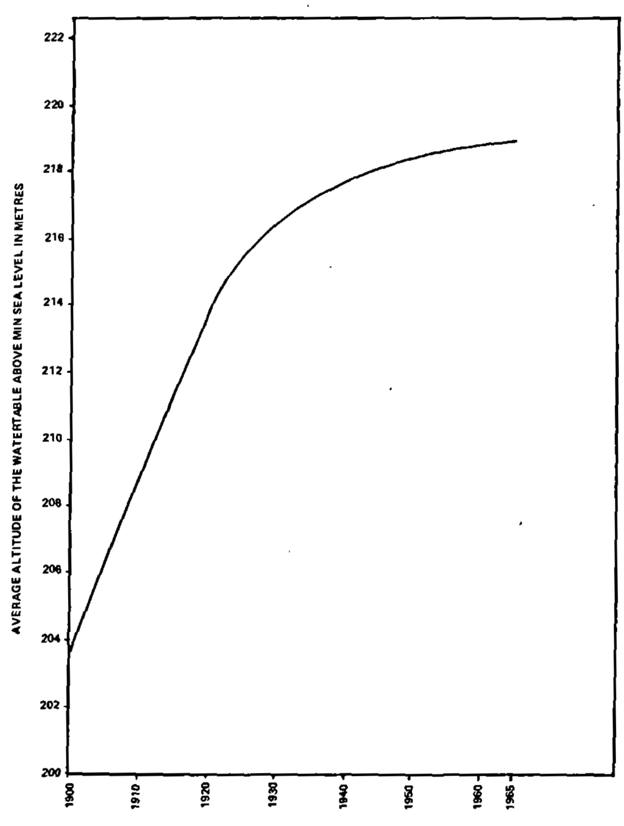


FIG. 11. Graph showing average rise in water-table since 1900

plants. The average salt content of the area is more than 1 per cent. Generally, a fluffy salt layer is evident on the soil surface.

In areas where salinity developed as a result of prolonged evaporation of irrigation water in the root zone the soils have not been affected physically, but where saline-alkali conditions existed owing to alternating salinization and exchange of calcium with sodium, the soil structure was destroyed wherever leaching occurred and the soils became impervious to air and water. These soils have been classified as non-saline alkali (about 17 per cent of the total area) and saline alkali (about 28 per cent of the area) respectively. The saline alkali soils in the Mona project almost invariably have gypsum in the profile and are therefore amenable to reclamation by simple leaching.

TABLE 9. Proportionate extent of different categories of surface salinity

Surface salinity class	Percentage
Salt-free area	78·6
Slightly saline area (S_2)	9·1
Moderately saline area (S_3)	6·7
Strongly saline area (S_4)	0·8
Miscellaneous land type	4·8
TOTAL	100·0

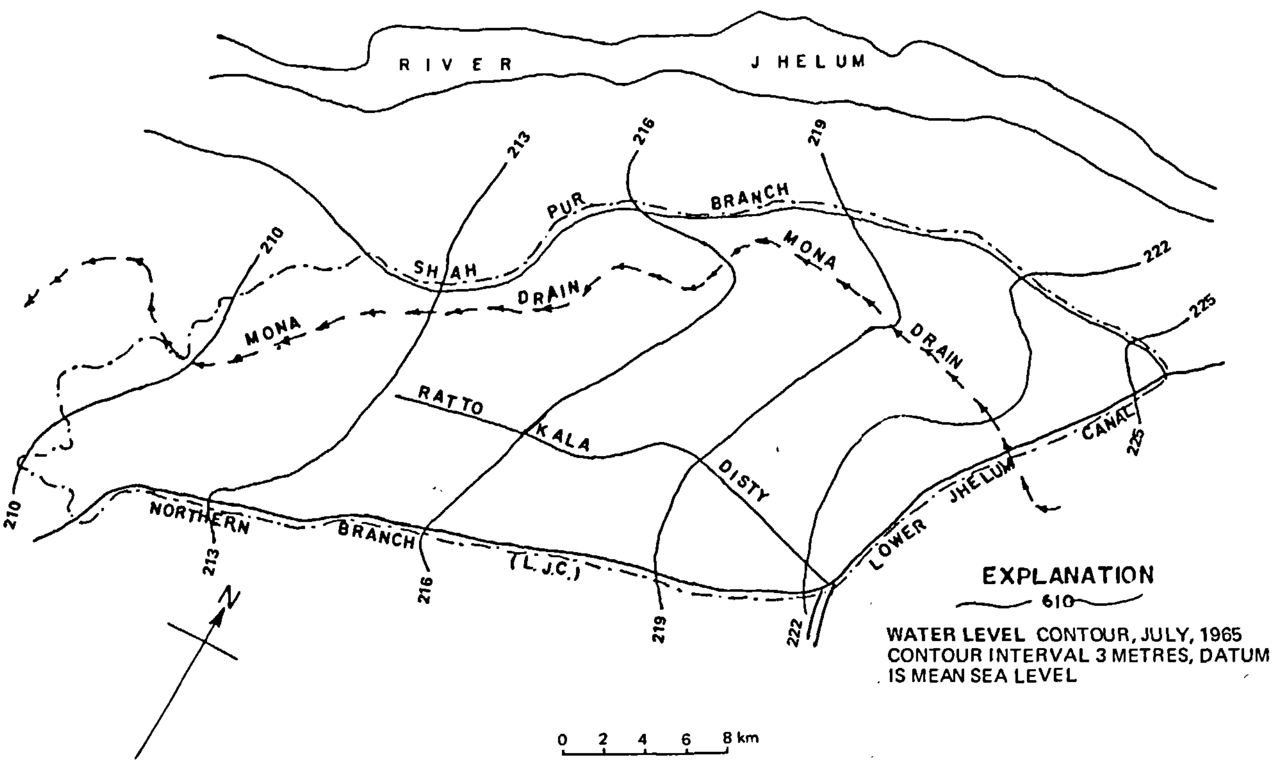


FIG. 12. Map showing the approximate altitude of the water-table in the Mona Reclamation Scheme in July 1965

The visual appraisal of surface salinity in the Mona project area was based on aerial photographs, the conditions of crops, the kind of natural vegetation, and the visible concentration of salts on the soil surface (Fig. 13).

Cropping pattern

As a result of irrigation in the study area, apart from a gradual increase in the cropped area, the cropping pattern shifted more towards cash crops and the local variety of cotton was replaced with improved strains (Table 10). Crop yields increased, but were still lower than those of many other countries.

Vegetation

In the irrigation period the existing flora prospered. As more land was brought under cultivation, the planting of *kikar* (*Acacia arabica*) and *tahli* or *shisham* (*Dalbergia sissoo*) was continued according to existing settlement rules. This resulted in a specialized arboriculture for the production of *kikar* and *tahli*. Under the canal colonization, lands were given to tree planters who were required to plant *kikar* or *tahli* and in this way these plants became extensive, particularly on cultivated land. Among the trees which had been introduced in the irrigation period with success were the *mulberry* (*Tutmorus alba*), the *dhrek*, *tand* or *bakain* (*Melia azedarach*), the poplar or *shuraida* (*Populus alba*), and willow or *haint* (*Salix*).

In depressions and in areas close to the canals, grasses such as *dab* (*Eragrostis cynosuroides*), *kana* (*Sachharum munja*), *kahi* (*S. spontaneum*), *Eleusine flagellifera*, *E. aegyptica*, *bui*, *Peristorum archnoides*, *Cynodon dactylon* became established. In the abandoned fields there were numerous weeds: *jhujan* (*Sesbenia aculiata*), *datura* (*Xanthium strumarium*), *bui* (*Maireana indica*), *Blumea* spp., *bathu* (*Chenopodium alba*), and *bhung* (*marijuana*) were plants seen growing in the area.

Fauna

With the development of a widespread system of irrigation canals, a number of habitat changes took place. Most of the tropical thorn-scrub plain was converted into irrigated agricultural land, linked to the riparian habitat by the canal system. Villages became more numerous and more complex, connected by a network of roads and railroads, and the sandy hummocky areas, although not physically modified, were more heavily grazed. Along with these changes, the spread of human settlement led naturally to a greater amount of contact between men and the larger mammals. This resulted in increased hunting pressure on certain species. Most of these developments had probably been taking place in a slow and irregular way in the study region for a long time but the irrigation period led to their acceleration.

Several large mammals, which were probably not very abundant to begin with, were apparently completely eliminated from the study area by hunting and trapping. These included the tiger, cheetah and

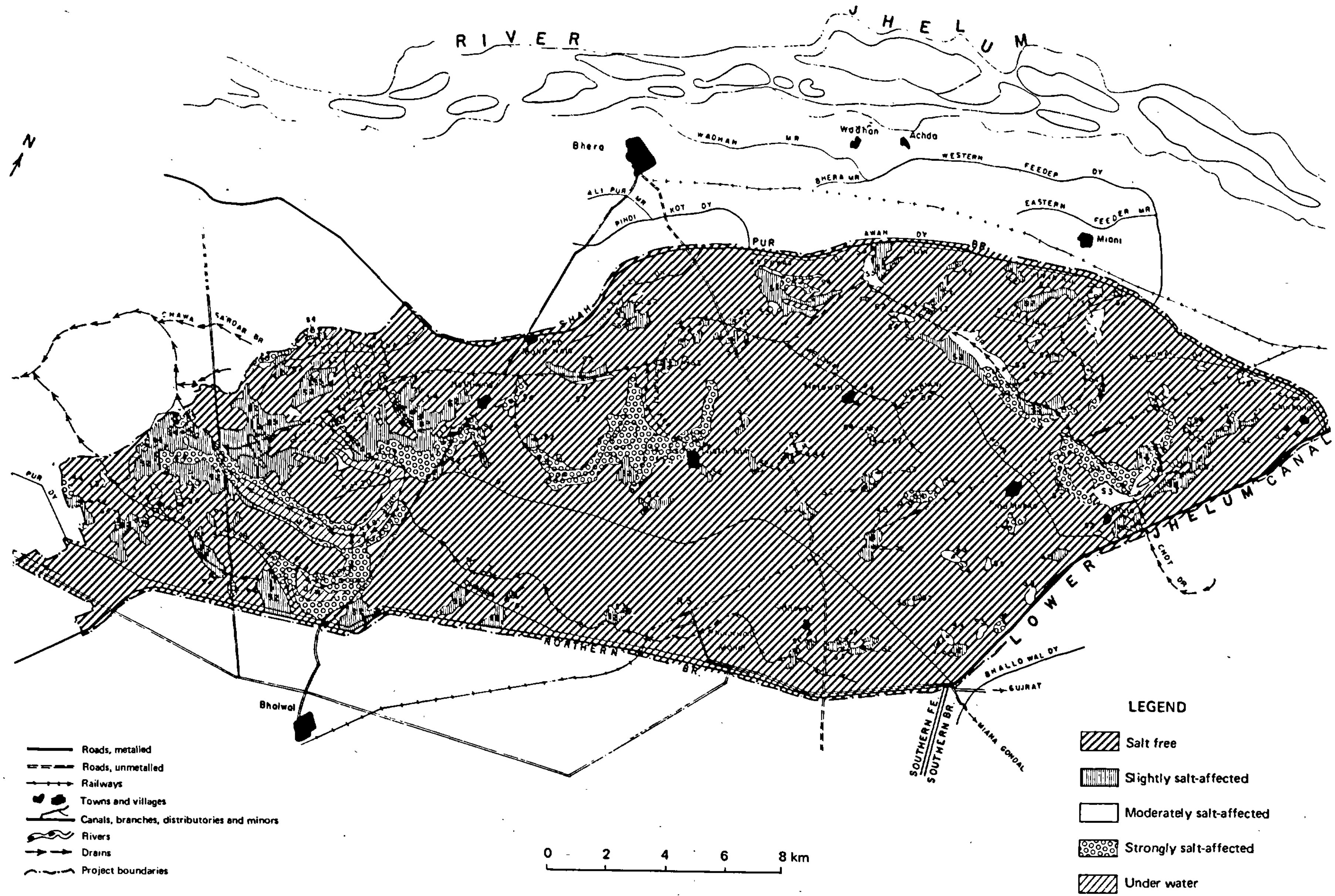


FIG. 13. Soil salinity before the rehabilitation programme

TABLE 10. Cropping pattern of Sargodha District (ha)

Year	Total cropped area	Crop											
		Rice		Wheat		Maize		Sugar-cane		Cotton		Oil-seed	
		Area	%	Area	%	Area	%	Area	%	Area	%	Area	%
1890–91	226443	888	0·4	101458	44·8	—	—	479	0·2	16295	7·2	13085	5·8
1903–04	313359	2160	0·7	154522	49·3	—	—	497	0·1	12327	3·9	6417	2·0
1910–11	476518	3074	0·6	208488	43·8	7901	1·6	3314	0·7	38369	8·9	—	—
1920–21	444991	1761	0·4	156990	35·3	6144	1·4	2927	0·7	49598	11·0	32133	7·2
1930–31	523755	1480	0·3	178057	34·0	8386	1·6	3585	0·7	56172	10·7	27934	6·1
1940–41	650670	2063	0·3	208975	32·1	9238	1·4	4887	0·7	89836	13·8	16985	2·6
1955–56	752187	7603	1·0	226869	30·2	17333	2·3	11125	1·5	86024	11·4	14791	2·0
1970–71	899615	22229	2·4	283814	30·2	25363	2·8	46231	5·1	100902	11·3	6357	0·7
1972–73	967489	25040	2·6	289119	29·9	25227	2·6	35000	3·6	89210	9·2	13403	1·4
1973–74	990890	24297	2·5	291551	29·4	23757	2·4	40384	4·4	92999	9·4	14271	1·4

Source: Directorate of Land Records, Punjab, Lahore.

hog deer. Other animals almost exterminated by hunting or trapping were the wolf and the *nilgai*. The remaining fauna of the tropical thorn plain suffered severe reduction due to habitat destruction. A few relict areas supported small populations of the little Indian field mouse, Wagner's gerbil, the desert gerbil, and the Bengal fox. The Indian crested porcupine, the Indian hare and possibly the long-eared hedgehog have managed to survive widely at the edges of the cultivated land.

In contrast, some surviving members of the river and flood-plain fauna have apparently benefited from a great increase in available habitats. This new habitat includes the well-watered canal-banks, cropland, and irrigated forests. The species which apparently increased or spread westwards include the Asiatic jackal, jungle cat, wild bear, short-tailed bandicoot rat, the Indian gerbil and the rabbit. The wild bears and jackals did much damage to the crops.

The fauna of the village and its environs increased tremendously owing to the suitable habitats. It is possible that some members of this fauna, such as the soft-furred field rat and the fawn-coloured mouse, were not present in the study area a century ago, but were introduced subsequently. Squirrels became common and damaged the flora at early stages of growth, and the rats and porcupines caused damage to the crops at the sapling stage. Dogs also became a problem in the villages.

During the irrigation period, indigenous birds of all types still existed, although their activity in the cultivated area became less pronounced. Grey partridges concentrated in Pakhowal Forest, but black ones were found only in the vicinity of the riverine area. A good number of migratory birds such as quails (*battair*), sandgrouse (*bhatitar*), demoiselle cranes (*kunj*), falcons and ducks flocked down in winter from the western hilly areas in the Nabi Shah Lake and other places and remained there during the winter season. The teal, shovellers and smaller kinds of pochards came early and stayed late. The mallard, like the geese, arrived with the colder weather, and some birds like the red-crested pochard were usually found at the end of the season only. Most species of ducks were exterminated by excessive shooting. Crows, parrots, woodcutters, woodcock and sparrows were ubiquitous, and considerable damage was done by sparrows. Red jungle fowl and *sissi* were not uncommon in the area.

Locust swarms visited the area up to the 1960s and caused a great deal of damage to standing crops.

Population

Density

According to the 1961 census the total population of the study area was 122000 (67000 males and 54500 females) which gave a man–land ratio of 0·36 ha/person. Compared with the 1951 census, this represents an increase of about 25 per cent in the population. In this area 11 per cent of the villages had less than 0·4 ha of land/person, 58 per cent of the villages had over 0·4 ha but less than 0·8 ha/person, in 26 per cent of the villages the land per capita was 0·8–2·0 ha and in the remaining 5 per cent the land per capita was 2 ha or more. In a few villages, the land per capita exceeded 8 ha, as shown in Figure 14; these were landlord-dominated villages.

According to the available information, the population density in the contiguous area, which is also true of the case-study area, was 21 inhabitants/km^2 in 1891 and 69 inhabitants/km^2 in 1911. After the introduction of the Lower Jhelum Canal, pressure on land increased in the area and the density of population also increased. With assured water supply from the canal and settlement rights on the land, the people gradually changed from a pastoral life to settled agriculture. In 1951 the population density in the case-study area was 147 inhabitants/km^2 rising to over 1544 inhabitants/km^2 in 1961. According to the census of 1961, children under 15 years of age constituted 44 per cent of the population, while people between 15 and 54 years of age and those 55 years or over made up about 46 and 10 per cent respectively. With effective control measures over epidemics, diseases and infant mortality, the proportion of younger people increased and life expectancy also increased.

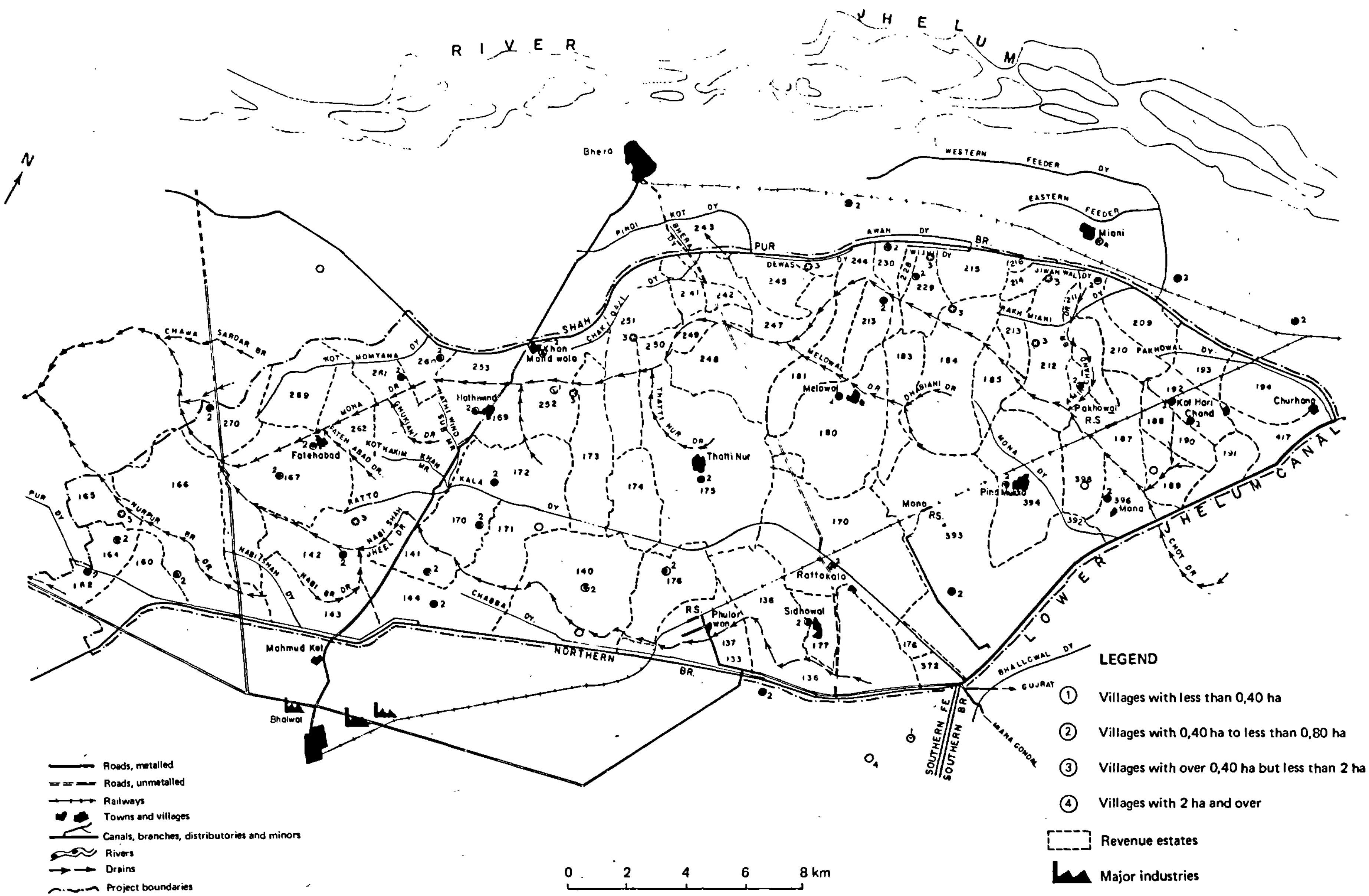


FIG. 14. Per capita man–land ratio, revenue estates and major industries

Migration

No data are avilable on the migration of the inhabitants of the case-study area to other parts of the country or abroad. However, it appears from the records of Shahpur district that inward migration increased after the opening of the canal system. Out of 687400 persons enumerated in the district in 1911, about 542000 belonged to the district by birth, whereas the rest came from other areas. On the other hand, about 35500 people of this district had moved to other parts of the country or possibly abroad.

Fertility and mortality patterns

Table 11 shows the fertility and mortality rates of Shahpur district before and after the introduction of canal irrigation.

Deaths during 1901–10 were above average because of epidemics of plague, cholera and smallpox. Fertility and mortality figures for 1965, based on a country-wide survey, show that the gross birth rate per year was 50 per thousand and the corresponding death rate about 20 per thousand. According to the 1965–66 survey in the study area, the population planning programme did not make any impact on the people; 98 per cent of the people did not use any birth-control measures.

Health

Prior to the rehabilitation period, most of the farm families were living under unhygienic conditions, with poor domestic water supplies and drainage and with cattle tethered in the courtyards of their houses. Improper operation and maintenance of canals, and an inadequate drainage system in the area, led to the creation of marshy lands which became breeding grounds for insects harmful to public health. Certain water-borne diseases and malaria had increased and wet ground in the villages resulted in increased fungus infection. Health services were quite inadequate and for quite some time the dispensary at Bhera remained the only place in the vicinity where the sick people in the study area could go. Even until 1965–66 there was only one small six-bed hospital in the entire case-study area, and people had to use the facilities of the hospitals and dispensaries near the project boundaries.

Education

In 1911 there were fifty-four literate males to every 1000 males in the Shahpur district. The literacy rate among women was very low; only eight literates to every 1000 females in the area. In 1917 in Bhera Tehsil, of which the study area is a part, there were two English-Pakistani-language secondary schools, one Pakistani-language secondary school, seven primary schools for boys, four schools for girls and two high schools in Bhera town.

Gradually the educational facilities in the area improved, but not at a rate sufficient to meet the requirements. In the eighty-three villages of the study area, in 1961 there was only one high school and three secondary schools. There were thirty-six primary schools in the area, which means one primary school for every 3391 persons. The total literacy in 1961 was about 9 per cent for the rural areas and, among the rural females, only 2 per cent were literate. With time the literacy figures in the area have improved. According to a Lyallpur Agricultural University survey of 1965–66, about 17 per cent were literate in the case-study area, out of whom about 92 per cent had received schooling up to the age of 12. Out of a sample of 394 respondents having male children of school age, 66 per cent were sending them to schools, whereas, out of 389 respondents who had school-age female children, only 7 per cent were sending them to school.

Family structure

According to the survey of 1965–66, the family structure in the case study area was patriarchal, patrilocal and patrilineal. In 86 per cent of the families, all decisions and plans affecting the family were taken by the oldest male member, who was the head, and all other members had to abide by those decisions. Even decisions which fundamentally affected the lives of young people lay in the hands of the elders, e.g. the young were not supposed to talk about or take part in the decisions regarding the selection of their future marriage partners. The size of the average family in the study area was 7·5 persons, compared to 4·6 persons per family in Bhalwal Tehsil in 1961. Nearly 84 per cent of the respondents had families of five or more persons, and 16 per cent had families with less than five persons, as is shown in Table 12.

Customs and traditions

As regular sociological surveys were not carried out, information on trends and modes of social change in the case-study area is not available. However, the way of life in general had changed in the course of

TABLE 11. Fertility and mortality rates in Shahpur district

Births and deaths	Years		
	1881–90	1891–1900	1901–10
Births (‰)	37	40	45
Deaths (‰)	26	32	37

TABLE 12. Size of families

Number of persons per family	Number of families	Percentage
Two	18	3·2
Three	35	6·5
Four	38	6·8
Five	66	11·9
Six	75	13·3
Seven	77	14·0
Eight	63	11·2
Nine or more	184	33·1
TOTAL	556	100·0

time with better communication systems and inter-village co-operation, because of dependence on a common irrigation system.

In the survey conducted in 1965–66, it was found that there was an emerging consciousness on the part of the rural people that productivity and prosperity go hand in hand, and that the traditional belief that all that happens in life is predetermined and that man has to accept it as a *fait accompli* had significantly weakened. Over two-thirds of the farmers were willing to abandon their traditional agricultural practices in favour of improved techniques, and to borrow money to invest in agricultural operations. Almost 75 per cent of the farmers thought that only hard work could change their fate. An element of rationality could be observed from the fact that 87 per cent of the respondents in the rural communities were of the opinion that it was better to send a sick person to a hospital, where better treatment was possible. In the survey it was, however, observed that the marriages of the children were predominantly arranged by the parents, and 87 per cent of the respondents supported this practice of arranged marriages. Over 75 per cent of the marriages were of endogamous type, and most were between the first or second cousins.

There had been no significant change in the food habits of the common people and their diet remained the same as during the pre-irrigation period. Their food continued to be simple and pure, which was the reason for their good physique and health.

Agriculture

Crops

The canal waters created an agricultural revolution in the area, and the results were manifested almost immediately with an increase in the cultivated area in general and in the area under cash crops in particular. Sugar-cane, cotton, orchards and fodder crops gained importance. Wheat, gram, bajra (millet), jowar (sorghum), etc. were the main food crops, while cotton, sugar-cane, oil-seeds and orchards were the cash crops. The most important crop in the area continued to be wheat, which was the staple food crop and could be grown on a variety of land types. After canals were introduced, the area under sugar-cane and orchards grew steadily, as did the area under fodder crops.

There was an immediate increase in the area under cultivation after the introduction of the canal system. According to the available statistics, the area under cultivation in Bhera, which was about 74 500 ha during 1890–94, increased to about 138 000 ha in 1909–14. The irrigation system also brought changes in cropping patterns developed during the pre-irrigation period. The cropping patterns in Bhera area before and after the introduction of canal irrigation are given in Table 13 and show that cotton, oil-seeds and grams gained acreage to the detriment of millet and sorghum. The data for Sargodha district also indicate that there was a gradual increase in the cropped area with time, and that there were changes in the cropping pattern. The areas under sugar-cane, orchards and fodder crops grew gradually. The area under oil-seeds also increased, and rose to over 6 per cent in 1930–31. However, there was a marked decline in the area under this crop thereafter, and it dropped to about 2 per cent in 1955–56. This decrease has been attributed to the sensitivity of the crop to salinity, which had developed during this period.

The cropped acreage in the district increased progressively with time. Table 14 gives the area under various crops in the case-study area in 1965–66.

According to the information from the early period of canal irrigation, there was practically no systematic crop rotation. In areas adjacent to Mona, only 15–20 per cent of the cultivated area was left fallow throughout the year, and about 60 per cent was put under *rabi* crops and 20–25 per cent under *kharif*. This meant that a large area was put under wheat year after year, with an occasional change to oil-seeds, followed by cotton or fodder, succeeded after a fallow by cotton. However, a common crop rotation was sorghum, or millet, fallow, wheat and so on. In 1965–66 the cropping intensity was about 100 per cent. The wheat yield per hectare in the irrigated areas was 1 100 kg, compared with 550 kg in the pre-irrigation period in areas of dry farming. No improvement was registered in the *barani* (rain-fed farming) areas. However the yield of cotton decreased, which may have been due to a lack of on-farm management and the appearance of waterlogging and salinity in the later period.

The adoption of agricultural innovations was slow in the case-study area during the post-irrigation period. Some improved inputs like chemical fertilizers and superior varieties of seeds were almost unknown, and synthetic fertilizers were introduced as late as the 1950s. Initially, fertilizers were distributed free of charge and farmers were induced to make use of this important input through demonstration plots. In the beginning, the farmers were reluctant to use chemical fertilizers and to change their centuries-old system, mainly because of illiteracy. Gradually, however, the farmers began to realize the benefits of the use of improved inputs, when through demonstration they themselves saw the advantages of the changes shown in increased yields and consequent higher incomes.

TABLE 13. Distribution of crops in Bhera before and after irrigation

Crop	Percentage of total cropped area 1890–94	1909–14
Wheat	43	43
Cotton	6	10
Oil-seeds	4	8
Grams	6	8
Millet	17	8
Sorghum	6	2
Pulses	3	2
Barley	2	1
Other cereals	10	18

TABLE 14. Area under various crops in the case-study area in 1965–66

Crop	Area (ha)		Relative area (%)
Kharif crops			
Sugar-cane	1510		
Cotton	6263		
Rice	1182		
Maize	1261		
Fodder	7150		
Orchards and vegetables	2064		
Miscellaneous	100		
Subtotal		19530	45·9
Rabi crops			
Wheat	9960		
Barley and oats	1470		
Pulses	494		
Oil-seeds	601		
Fodder	6213		
Sugar-cane	1510		
Gardens and vegetables	2290		
Miscellaneous	12		
Subtotal		22590	53·1
Total area under *kharif* and *rabi* crops		42120	99·0

Livestock

According to the 1965–66 survey, livestock constituted a sizeable segment of the farm industry in the study area. Over 40 per cent of the total farm expenditure was on capital, feed and shelter for animals. Livestock included both draught and milch animals and amounted to eight adult units per holding. A relatively large number of livestock was maintained in the non-perennial farming area. This was necessitated by factors such as larger farm size, greater fragmentation of holdings and the need to conserve moisture for the *rabi* crops. The number of draught animals was smaller on the owner-cum-tenant farms, primarily because of the small size of those holdings. On other irrigation and shared-tenancy farms, the strength of draught animals was almost the same. The cost of draught animals amounted to 15 per cent of the total farm costs. The figure was slightly higher in the non-perennial area on the owner-operated farms, owing to the large number of livestock units and the fact that animals on these farms were generally highly priced and well-fed.

The number of adult units of buffaloes and cows per holding amounted to 4 and 0·6 respectively; those in milk averaged 1·9 and 0·3 respectively. Relatively large numbers of buffaloes were maintained in the non-perennial farming area and by the owner-operators, while cows were popular in the perennial farming areas and with tenants. The units of donkeys and horses amounted to 0·2 and 0·4 per holding respectively. The number of these animals was relatively high on the holdings of owner-operators, while horses in particular were numerous in the uncommanded area. The number of sheep and goats was small, especially the latter; their total units came to 0·3 per holding. Sheep seemed to be more common in the perennial farming areas, and with owner-cum-tenants and tenants.

Per capita income

No systematic survey of per capita incomes was carried out before 1965. However, the general impression is that the most significant impact of the introduction of canal irrigation had been the increased prosperity of the people in the study area. With the passage of time, unfortunately, the ill-effects of irrigation decreased the productivity of the land, and consequently the income of the people declined. According to the 1965 survey, most of the people in the study area were earning less than 5000 Rs. per family per year, which barely provided a satisfactory livelihood.

Marketing of agricultural products

During the detailed survey of 1965 it was found that five *mandi* (market) towns were serving the area. The marketing of various agricultural products was as follows.

Nearly 80 per cent of wheat production was retained at the farm and only 20 per cent was sold in the market. The survey showed that the monthly average prices of wheat did not exhibit marked seasonal variations. The market price was the lowest in April and the highest in December. The largest variation between the highest and the lowest price was 25 per cent, with an average variation of about 7 per cent. Fresh harvest of gram became available a fortnight to a month earlier than wheat. Arrivals and price fluctuation of gram were similar to that of wheat.

Fresh crops of rice were available by the end of September. During the following three months (October–December) about 60 per cent of the marketable surplus arrived in the market. Of this, about 36 per cent occurred during November alone. The surplus then tapered off and was at its lowest level in June, the only exception being that 20 per cent of the surplus was observed during February. The average price varied by 5–57 per cent from the base price, the average variation being 31 per cent.

Maize was not an important crop in the area. The harvest became available by November and started moving into the market in the same period. Over 20 per cent of the marketable surplus was taken to market in December. In the following three months, the arrivals were almost the same, being 9–10 per cent each month with slight improvement in May and July. The rest of the period ranged between 2 and 5 per cent.

Gur (raw molasses) from the new harvest became available from October to December. The production of *gur* from regrowth of existing *ratoon*, which matures one to one and a half months earlier than the newly planted crop, starts arriving in the market in October, but the bulk (about 75 per cent) is received at the market from November to February. During these months, market surplus was of the same order of size, except in December when it was slightly lower. Thereafter, the surplus diminished drastically and revived only with the new crop.

New cotton was available by October, when it started coming into the market. The main rush however started from November and was over by January. During this span of three months, 90 per cent of the produce reached the market for sale. Though prices in the harvest period were generally higher than those in the post-harvest period, they were at their lowest level when the arrivals were at their highest. Lack of demand was the chief reason for lower prices after the harvest period.

Agriculture-based industries

Agriculture-based industries existed in the case-study area as early as 1917, and included flour-milling, cotton-ginning and pressing, rice-husking and oil-pressing facilities. Rice-husking and wheat-flour mills were not independent, and were attached to ginning factories. Of these industries, some were located within or at the periphery of the area. The number of agriculture-based industries increased with the advent of canal irrigation and more or less kept pace with agricultural development, and the needs to the farming community. According to the 1965 survey, there were about seventeen cotton-ginning factories, nine rice-husking/wheat-flour mills and seven oil presses, either within or at the periphery of the area.

Conditions after the rehabilitation project (1965–76)

Objectives and appraisal of the Mona Reclamation Experimental Project

The main objective of the Mona Reclamation Experimental Project (MREP), which comprises the case-study area, was to derive information from operational research adaptable to the areas being developed under Salinity Control and Reclamation Projects (SCARPs) in the irrigated areas of the Indus Plains. The following research and investigations were proposed at the time of planning:
- development of methods and procedures to achieve effective use of water and land, the reclamation of saline land and agricultural development;
- preparation of detailed ground-water hydrological studies;
- tube-well operation, maintenance, rehabilitation and replacement;
- management of water supplies;
- determination of optimum cropping input–output relationships;
- transfer of knowledge to farmers and encouragement of its adaptation.

Before initiating the programme of research, an intensive socio-economic survey of the area, in co-operation with the Department of Agricultural Economics and Rural Sociology of the University of Agriculture, Lyallpur, was carried out in 1965. An evaluation of the hydrological factors and of ground-water quality was also carried out and the installation of observation pipes, water-stage recorders and rain gauges was completed. Since 1973, research studies in the field of water management have been carried out in co-operation with advisers from Colorado State University, U.S.A.

The research work in the project started during 1966–67 with the development of laboratory facilities for soil, water and plant analyses. The principal areas of research and objectives are reported in the following paragraphs.

Hydrology and tube-wells

The principal objectives of research in these fields are to provide data and its interpretation necessary to ensure effective management and operation of the project by:
- sufficient lowering of the water-table, so as not to interfere with plant growth nor contribute harmful concentrations of salts to the root zone of the crops by evaporation;
- providing sufficient supplementary irrigation supplies to satisfy leaching and consumptive use requirements;
- achieving operation and maintenance of the tube-well system at minimum possible cost, and studying the factors involved in maintaining a favourable salt balance.

To achieve these objectives, hydrological changes in the project and the performance of tube-wells are being continually monitored. An electrical analogue model of the project has also been made to evaluate the hydrological system fully.

Water management

Efficient management of water of varied chemical composition is a vital factor in agriculture. The present water-management practices being inefficient, the main objectives of research are:
- development and testing of materials and methods for watercourse rehabilitation and the feasibility of their adoption in Pakistan;
- measurement and evaluation of the effects of improved water-management practices;
- evaluation of seepage and other losses from existing and improved watercourse systems;
- demonstration plots for improved water-management practices and watercourse system;
- development of a complete water-management technology which is acceptable from social and economic viewpoints;
- preparation of manuals, literature and extension aids for the management of soil, water and crops based on the findings.

Soil reclamation

The main objectives are:
- determination of the most effective methods for reclamation of saline-sodic soils;
- promotion of the application of proven methods of reclamation among the farmers.

Agronomy

The basic objective is to develop methods of effective land and water use for more efficient crop production. The studies include a number of experiments on some of the crops such as cotton, rice, wheat, maize, etc. in order to obtain information with regard to the best variety, the optimum time of sowing and possible increase in yields by various combinations of nitrogen, phosphorus and potassium (NPK) to the soil, different seed treatments, fertilizer applications and different spacings between rows and depths of sowing, with particular reference to the quality of irrigation waters and irrigation practices.

Agricultural economics

The various studies that have commenced and are proposed cover the areas of resource development, water-use efficiency, input–output relationship, enterprise-selection, capital formation and investment, labour utilization, agricultural development, agricultural marketing, and co-operation and credit.

Agricultural extension

Objectives in this area are:

- development of the most rapid and efficient means of transferring technical knowledge to the cultivators;
- design of workable mechanisms and organizational arrangement for providing cultivators with requisites of production and other supporting inducements for agricultural change.

Long-term objectives are gaining the farmers' confidence in market-oriented production as a means for increased satisfaction of needs and bringing farm leadership to bear on local problems and providing media for concerted action by villagers in the interest of agricultural reform and improved living conditions. Various extension approaches are being followed and will be evaluated, along with a study of personal and other factors impeding the adoption of improved agricultural practices.

Environmental conditions

Soil salinity

The salinity of soils in the case-study area before the rehabilitation programme is illustrated in Figure 13. The percentage of each surface salinity class as mapped at the start of the project operations and during the latest survey carried out by the Central Monitoring Organization of Water and Power Development Authority are given in Table 15, and the present extent of soil salinization is shown in Figure 15.

This shows that about 85 per cent of the area is free from harmful salt accumulation. The increase in this category over the base year has been the result of reclamation of salt-affected areas and in particular the decline in the strongly salt-affected area. The reclamation of salt-affected soils was achieved by the simple process of leaching and the growing of suitable crops. For improving the fertility of soils, farmyard manure and chemical fertilizers had been applied and gave favourable results.

Water regime

The project tube-wells started pumping in 1965 to control waterlogging and to supply additional irrigation water. This introduction of new discharge sources on the ground-water reservoir changed the existing hydrological balance and the water-table began declining gradually. As a result of continuous tube-well operation over the past years the water-table has gone down by 0·9 to 1·8 m and is now stabilized over most of the area. Monitoring of tube-well waters has shown a minor deterioration in water quality. Tube-well performance studies have shown that discharge and specific capacities of wells have decreased, indicating that the wells have started to deteriorate. Corrosion and encrustation are likely causes.

Climate

No significant change in the climate has been observed in the period since the rehabilitation project went into operation.

Social and demographic changes

Population

The population of the case-study area has continued to rise, with more people turning towards agriculture and the better control of epidemics and diseases. This has resulted in an increase in land pressure. By 1972 the population was already about 173000 and the man–land ratio about 0·26 ha/person, with a population density of about 174 persons/km^2.

No recent estimates of fertility and mortality rates are available for the case-study area. However, the country-wide estimates for 1976 are 44 births as against 15 deaths per thousand per year.

About 70 per cent of the people are still directly engaged in agriculture. Although there have been changes in the ways of life of the people in the study area following changes in their outlook and food habits and an increase in living standards, no assessment has been made to evaluate the extent of these changes over the last decade.

The family structure continues to be patriarchal, patrilocal and patrilineal, although more consideration is now being given to the views of youngsters.

TABLE 15. Relative extent of different categories of surface salinity in the Mona Project

Surface-salinity class	Percentage	
	1965–66	1975–76
Salt-free area	80·6	84·5
Slightly salt-affected area	8·1	7·7
Moderately salt-affected area	2·1	1·8
Strongly salt-affected area	6·6	3·4
Miscellaneous	2·6	2·6

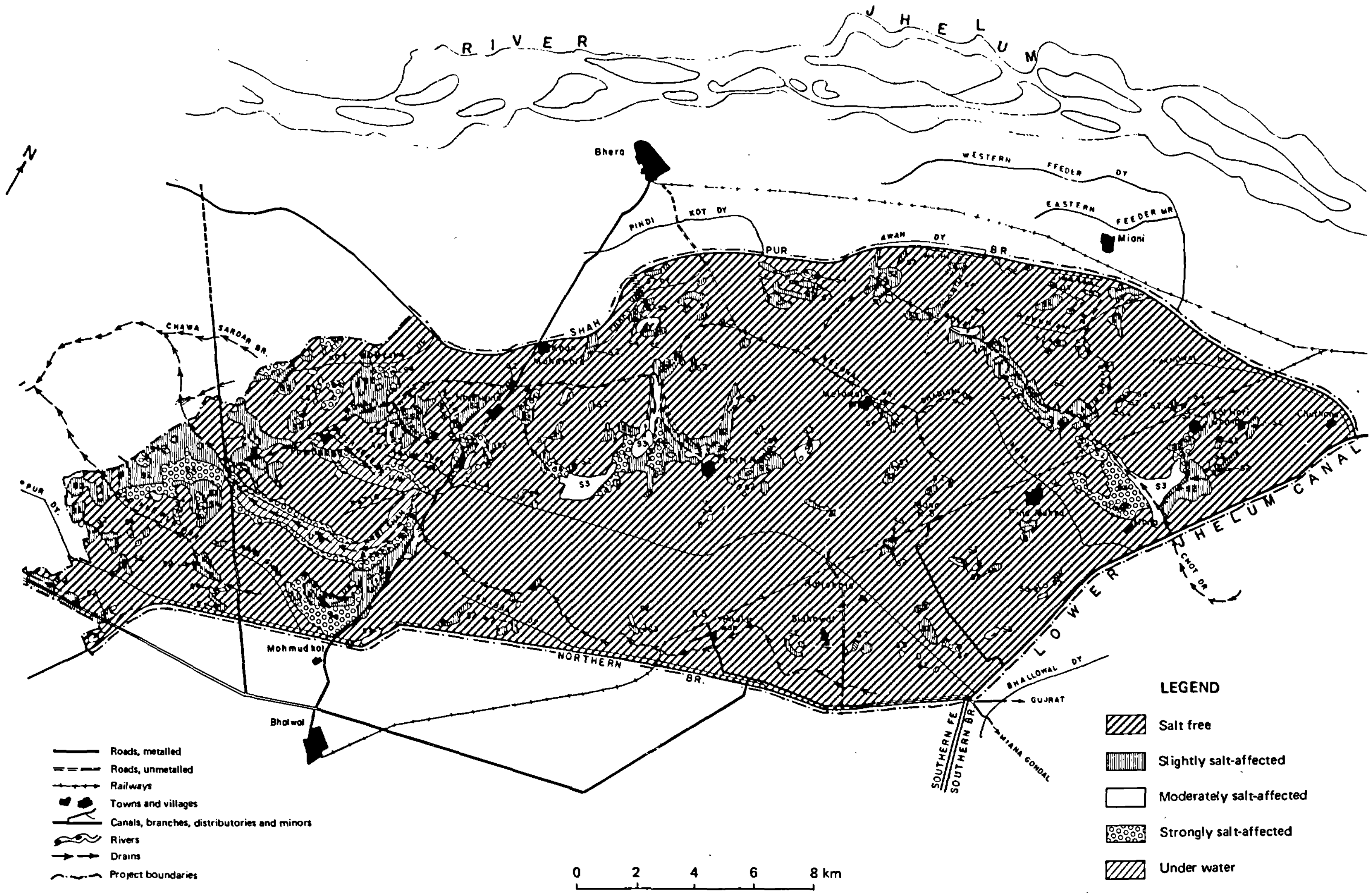


FIG. 15. Soil salinity: present status

No specific survey has, however, been carried out to evaluate the extent of these changes.

Migration

The increase in the village communication networks has resulted in greater mobility of the population. Urbanization and industrialization around the case-study area have intensified migration out of the villages. It was observed from a recent limited survey of a few selected villages that, during the period 1966–76, out-migration from the villages was nine times more than that inwards; a total of 229 people left the sampled villages during this period. The installation of heavy industries in the vicinity of the area has absorbed some of the surplus agricultural labour, while some people from the rural community have even gone abroad for employment. However, the outward migration to urban areas has been offset by the inflow of people from other areas. Those who have migrated from the rural communities were mostly the landless tenants and artisans.

It was noted that no large-scale migration due to desertification has taken place. The problem of salinization and waterlogging was arrested and before such a situation occurred brought under control by the implementation of the SCARP in the area.

Health

No cases of smallpox have been reported since October 1974. This is entirely due to intensified mass primary vaccination and the ultimate adoption of a high degree of preventive measures. The cultivation of rice has led to the breeding of mosquitoes in the area, which has increased the incidence of malaria. By and large, epidemics have been controlled and infant mortality has been reduced considerably. Sanitary conditions in the area have improved, although they are still far from satisfactory. No new hospitals have been built in the area, but facilities in the existing hospitals have been expanded. New rural-health schemes are expected to be implemented in the area in the context of overall rural-development programmes.

Education

The inhabitants of the study area have gradually realized that education is not a wasteful expenditure but rather an investment for the future. According to the 1976 survey there are two high schools for boys and one high school for girls, and eight intermediate schools for boys and one for girls. In addition, there are about sixty primary schools for boys and about twenty-two for girls. During the last few years considerable emphasis has been laid on universal education and the government is trying to provide at least one primary school each, for boys and girls separately, at every village level; primary education is free, as elsewhere in the country. In spite of the expansion in educational facilities and the awareness among people, the literacy figures are still low in the study area.

TABLE 16. Crop areas in the case-study area, 1975–76 (ha)

Crops	Overall project		Irrigation: Perennial		Irrigation: Non-perennial		Irrigation: Uncommanded	
	Area	Percentage	Area	Percentage	Area	Percentage	Area	Percentage
Kharif crops								
Sugar-cane	2786	6·75	1961	6·76	527	7·17	276	5·48
Rice	1618	3·92	1111	3·84	417	5·68	89	1·87
Cotton	5439	13·17	3974	13·75	815	11·09	650	12·91
Maize	1244	3·01	829	2·87	304	4·15	110	2·19
Fodder	7794	18·88	5484	18·97	1211	16·48	1099	21·81
Garden and vegetable crops	2777	6·73	2431	8·41	196	2·62	150	2·97
Miscellaneous	1406	3·41	644	0·24	199	2·71	563	11·17
Subtotal	23064	55·67	16435	54·84	3669	49·95	2937	58·40
Rabi crops								
Wheat	13254	32·10	9060	31·34	2384	32·46	1826	38·25
Barley	2004	4·85	1735	6·00	174	2·37	96	1·90
Pulses	191	0·46	106	0·37	62	0·84	23	0·46
Oil-seeds	598	1·45	310	1·07	136	1·85	152	3·02
Fodder	6907	16·73	4626	16·00	1304	17·76	977	19·39
Sugar-cane	3595	6·75	1961	6·76	527	7·17	276	5·48
Garden and vegetable crops	3105	7·52	2796	9·67	219	2·98	293	1·80
Miscellaneous	386	0·94	70	0·25	—	—	314	6·24
Subtotal	29233	70·80	20666	71·46	4806	65·43	3755	74·54
Total *kharif* and *rabi* area	52298	126·67	37102	126·30	8475	115·38	6692	132·94
				Perennial 28 907		Non-perennial 7345		Uncommanded 5038

Nutrition

A decade ago the people in the area were accustomed to using pure *ghee* (butter oil) as cooking medium, but owing to the rising cost a vast majority of the people have now turned to vegetable *ghee* (vegetable oil). However, with more income due to semi-commercialization of agriculture, the quality of their diet has improved, with more proteins and fruit. No specific survey has been carried out on this aspect, but the general trend is evident.

Economic conditions

The rehabilitation project had the desired impact on the economy of the case-study area. With the installation of tube-wells, the problems of waterlogging and soil salinization have been arrested. The additional water provided by the tube-wells encouraged crops which require more water. The area under wheat, rice, maize, sugar-cane and orchards has accordingly increased, while the area under cotton, bajra (millet), etc. decreased. The land-utilization pattern has improved. In 1965–66 the area sown more than once per year was 14 per cent of the total farm area, and this rose to about 30 per cent in 1970–71. The cropping intensities also increased from about 100 per cent to nearly 130 per cent. The rotation of crops has become more pragmatic. Wheat no longer follows year after year, but is rotated with crops such as sugar-cane, cotton, rice, etc. The value of livestock increased from 10 million Rs. in 1965–66 to about 17 million Rs. in 1975–76, and the values of crops have doubled in the same period. In addition, marketing facilities have improved.

TABLE 17. Cropping pattern in the case-study area (%)

Crops	Cropped area		
	1965–66	1970–71	
	Base year	Without project	With project
Food grains			
Wheat	35·86	40·79	42·54
Bajra	1·85	3·52	1·75
Rice	1·39	3·26	4·48
Maize	0·88	2·90	6·92
Subtotal	39·98	50·47	55·69
Cash crops			
American cotton	21·92	9·07	9·78
Desi cotton	1·00	0·21	0·20
Sugar-cane	4·24	8·07	8·70
Garden crops	4·20	6·83	8·67
Mehndi (*Lawsonia inermis*)	0·67	0·89	1·37
Vegetables	0·23	0·14	0·19
Tobacco	0·12	0·15	0·18
Oil-seeds	0·12	0·55	1·43
Subtotal	32·50	25·91	30·52
Pulses			
Grams	0·31	0·74	0·59
Other pulses	0·30	0·24	0·26
Subtotal	0·61	0·98	0·85
Fodder crops			
Kharif	21·21	18·99	24·62
Rabi	16·51	17·37	16·69
Subtotal	37·72	36·36	41·31
ANNUAL TOTAL	110·81	113·72	128·38

Crops

The main food and cash crops in the study area are wheat, fodder, cotton, orchard produce, sugar-cane, rice, vegetables, maize and barley. During the post-rehabilitation project period, crops like sugar-cane, fodder crops, orchard produce, rice and maize have gained prominence over others such as grams, bajra (millet) jowar (sorghum), poppy, etc.

The crop acreage in the area has progressively increased. The total cropped area during 1975–76 under perennial, non-perennial and uncommanded conditions, as given in Table 16, was 52298 ha. This shows an increase of 10215 cropped ha since the inception of the rehabilitation project in 1965–66.

The cropping pattern in 1965–66 and for 1970–71 is given in Table 17 for areas both with and without project conditions. A comparison of the corresponding figures reveals that the cropped area under wheat, rice, maize, sugar-cane and orchards has proportionately increased, while the area under cotton and other miscellaneous crops has decreased. Reclamation efforts in the case-study area have paid dividends.

Cropping intensities in the area have also progressively increased. When reclamation activities were started in 1965–66, the cropping intensity was about 100 per cent. This rose gradually to about 127 per cent in 1972–73, as illustrated in Figure 16. This trend was also observed in subsequent years.

The yields of crops such as wheat, sugar-cane, cotton, rice, etc. have increased but are still lower than in many irrigated areas of the world. One of the important causes of low yields is the imbalance in agricultural inputs, meaning that, if all the factors of crop production are optimized in balancing the interaction of inputs, crop yields will increase many times more than what could otherwise be obtained.

TABLE 18. Yields of selected crops at various time intervals (kg/ha)

Land type	Year	Wheat	Cotton	Maize
Irrigated (wells)	1897	922	553	1106
Barani (rain-fed)	1897	553	369	—
Irrigated (canal)	1917	1106	323	1106
Barani (rain-fed)	1917	553	230	—
Irrigated	1965–66	1272	424	949
Barani (rain-fed)	1965–66	1023	341	802
Irrigated	1974	1843	710	1355
Irrigated	1975–76	2645	737	no data

Source: District gazetteers, *Man. Water and Economy* and Mona Reclamation Experimental Project Reports.

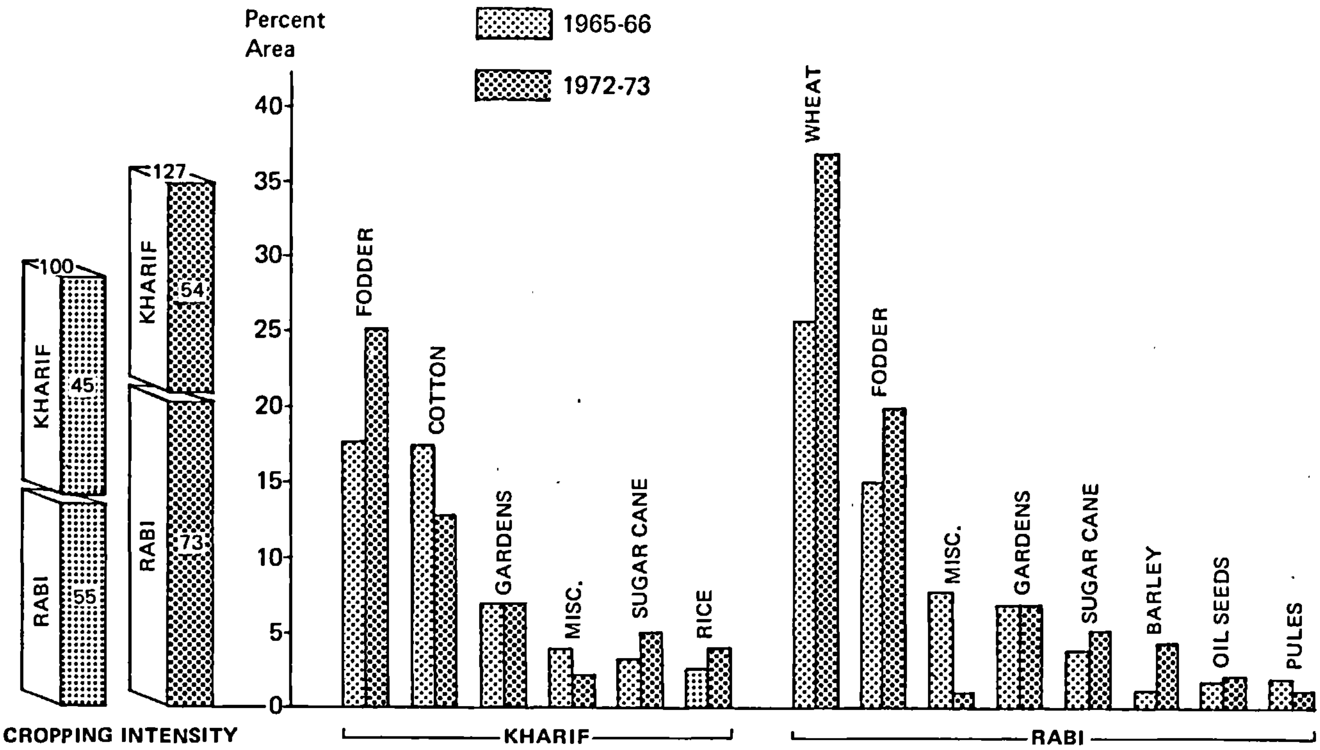


FIG. 16. Cropping intensity and cropping pattern in the case-study area

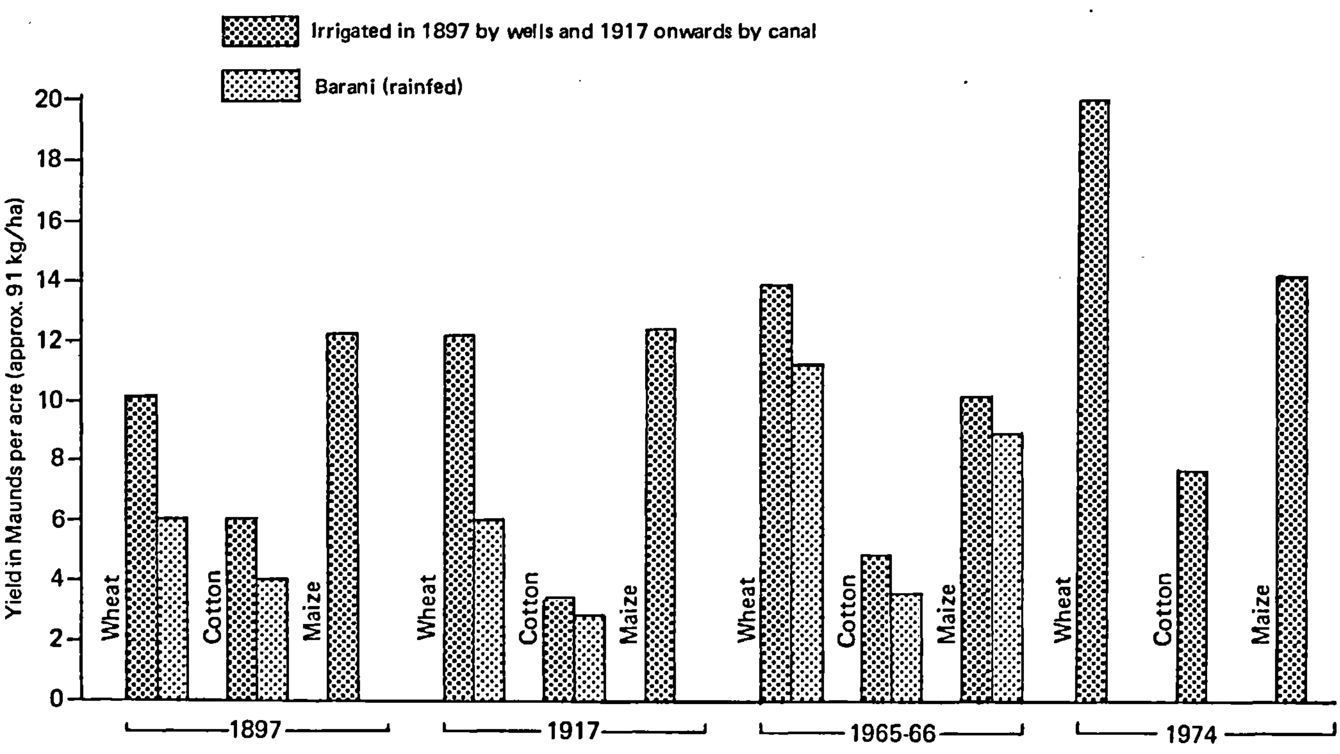


FIG. 17. Yield of selected crops at various time intervals in the case-study area

However, the value of crops has doubled since 1965–66. The yields of selected crops at various time intervals in the case-study area are shown in Table 18 and Figure 17 and the gross value of crops is given in Table 19.

Livestock

Cows, buffaloes and horses have continued to receive importance in the post-rehabilitation period. One of the best horse-breeding sites is located within the case-study area. Too-frequent outbreaks of contagious diseases in cattle have been checked to a great extent through government efforts. The gross value of livestock in 1975–76, according to an estimate, was about 17 million Rs., compared to 10 million Rs. in 1965–66.

Attitude regarding agricultural inputs

In traditional rural communities, where, instead of scientific rationality, folklore and superstitions dominate, the introduction and adoption of agricultural innovations is an intricate problem. The rural people are reluctant to adopt farm innovations unless they see clear, substantial and unequivocal returns. The installation of public tube-wells had clearly demonstrated that, with land and drainage and additional supply of water, the net farm income was almost doubled. The transistor radio has also played an important role in creating awareness about new innovations in agriculture. A decade ago less than one-third (31 per cent) of the farmers were using chemical fertilizers and more than two-thirds of them did not know about the availability of improved seeds. In 1976, about 95 per cent of farmers were using chemical fertilizers and over 90 per cent used improved seeds of wheat. A critical difference has been made by irrigation water and proper drainage conditions, as all dwarf and early maturing varieties need more water, besides other inputs. The adoption of the new innovations on the whole was higher on the perennial irrigated farms than on non-perennial farms. The adoption of improved varieties of crops in the area has been steadily rising and was higher than in adjacent areas. This is reflected in Table 20.

TABLE 19. Gross value (in Rs.) of crops/livestock in 1965–66 and 1975–76 in the case-study area

Year	Irrigation: Perennial	Irrigation: Non-perennial	Irrigation: Uncommanded	Total
1965–66				
Crops	18332201	3498225	1521151	23351577
Livestock	7785870	1070850	1170300	10027020
TOTAL	26118071	4569075	2691451	33378597
1975–76				
Crops	33158366	7572368	5512333	46243067
Livestock	11785950	2994750	2054250	16834950
TOTAL	44944316	10567118	7566583	51078017

Marketing of agricultural products

Marketing facilities for selling surplus produce have been greatly improved and the area is now well linked with important markets by rail and road.

Agro-based industries

Since the inception of the drainage and reclamation scheme, some major industries have been established in the vicinity of the area and have absorbed a considerable part of the surplus agricultural labour (Fig. 14). The notable ones are sugar-mills, dairy plants and textile mills. More rice husking/wheat-flour mills, etc. have also been set up, either within or at the periphery of the study area.

Income analysis

In the case-study area it was observed that net farm income per year for a 5-ha owner-operated farm was 1974 Rs. without tube-wells and 3654 Rs. with tube-wells, whereas for a 10-ha owner-operated farm, it was 3792 Rs. without tube-wells and 7741 Rs. with tube-wells. The gross annual income per cultivated hectare in the area in 1973–74 was 652 Rs., compared with 369 Rs. in 1965–66. The net income and the per capita income have also gone up. The net income

TABLE 20. Adoption of improved varieties of crops in the case-study area (%)

Types of farms	Year	Cotton: Improved	Cotton: Unimproved	Sugar-cane: Improved	Sugar-cane: Unimproved	Rice: Improved	Rice: Unimproved	Wheat: Improved	Wheat: Unimproved
Perennial	Base year (1965–66)	—	100	40	60	75	25	5	95
	Adjacent areas	16	84	83	17	84	16	82	18
	Case-study area (1975–76)	33	67	74	26	93	7	90	10
Non-perennial	Base year (1965–66)	—	100	37	63	28	72	5	95
	Adjacent areas	17	83	91	9	87	13	76	24
	Case-study area (1975–76)	21	79	76	24	87	13	86	14
Uncommanded	Base year (1965–66)	1	99	17	73	46	54	10	90
	Adjacent areas	9	91	81	19	85	15	76	24
	Case-study area (1975–76)	19	81	75	25	81	19	88	12

per cultivated hectare was 949 Rs. and 502 Rs. on tractor-operated and non-tractor farms respectively. The annual benefits from the rehabilitation project in the area came to 6·30 million Rs. when discounted at 6 per cent interest against the annual costs of 2·59 million Rs., showing a benefit–cost ratio of 2·43:1, and at 8 per cent discount rate benefits and costs came to 5·78 million Rs. and 2·57 million Rs. respectively, giving a ratio of 2·25:1.

Conclusion

It is evident from the above discussion that drainage and water-development technology has made a critical difference to the economy of the case-study area. Land utilization has improved, cropping intensity has gone up, the adoption of improved innovations has been hastened and net returns to the farmers have increased, thus making a substantial contribution to the welfare of the area and making it a demonstration model for other developing rural areas of the country.

Conclusions

The following conclusions have been derived as a result of this study.

Lessons learned

Soils and agronomy

— Soil salinization in the irrigated areas is caused by the upward movement of salts present in the soil, owing to capillary action and greater evaporation from the high water-table, import of salts present in the irrigation water, and scanty applications of irrigation water which are inadequate to leach down salts accumulated in the root zone.
— The reclamation of salt-affected soils can be carried out by the simple process of leaching, growing suitable crops, and addition of fertilizers.
— One of the important causes of low yields in the study area is the imbalance in the agricultural inputs. Optimization of the factors of crop production to balance the inputs and their interaction will result in manifold increases in yields.
— Marginal-quality irrigation water can be used for successful crop production, with applications of suitable additives.
— The fertility of the soils in the area can be improved and maintained by farmyard manure and fertilizers.
— Advisory services on the choice of crops for particular soils should be established.

Hydrology and drainage

— The level of the water-table can be controlled through vertical drainage by tube-wells, to create favourable conditions for plant growth. Observations of ground-water levels in the Mona Project area show that there has been a general fall of about 1–2 m in the water-table since the implementation of the project. However, changes may occur in the ground-water quality pattern owing to pumping, and should be carefully watched.
— Tube-well performance in the study area has not been as anticipated during planning; the discharge and specific capacity of wells have significantly decreased after ten years of operation.
— For the proper planning of future vertical drainage projects and their effective operation and maintenance, studies on the design of tube-wells and the development of suitable methods and procedures for their servicing, maintenance and rehabilitation are necessary.

Water management

— Applied research on a continuous basis is necessary to determine the appropriate irrigation schedules and the control of water applications for irrigating both traditional and new crops.
— It is necessary to set up pilot projects before embarking on large-scale project developments, to pave the way for a detailed analysis of future project operations. Apart from water requirements and applications, problems concerning the distribution and use of waters, the water and salt balance, and water losses may be considered.
— Research on water management has been started only recently, and limited observations have been made. Research on water management should be meaningfully interpreted only after a reasonable period and for a wide range of observations. Before using the research results in the field, they should be retested to prove their long-term validity and their application to different areas, with modifications as may be needed.

Climate

— The observational network within the project area is inadequate, but the available data indicate no significant changes in climatic factors.
— Extensive meteorological observations are required for agricultural planning.

Population, land tenure and health

— As the population is constantly on the increase there is a dire need for population planning in the area.
— Hospital facilities are inadequate in the area, and the rural health programme needs expansion and reorientation. Sanitary conditions also need improvement.
— The case-study area, as in other parts of Pakistan, has an over-population in the agricultural sector, meaning that it would be possible to reduce the number of workers in agriculture and still obtain the same output. Therefore, efforts should be made to plan a programme under which the surplus labour force can be utilized in economic agriculture-based industries. The

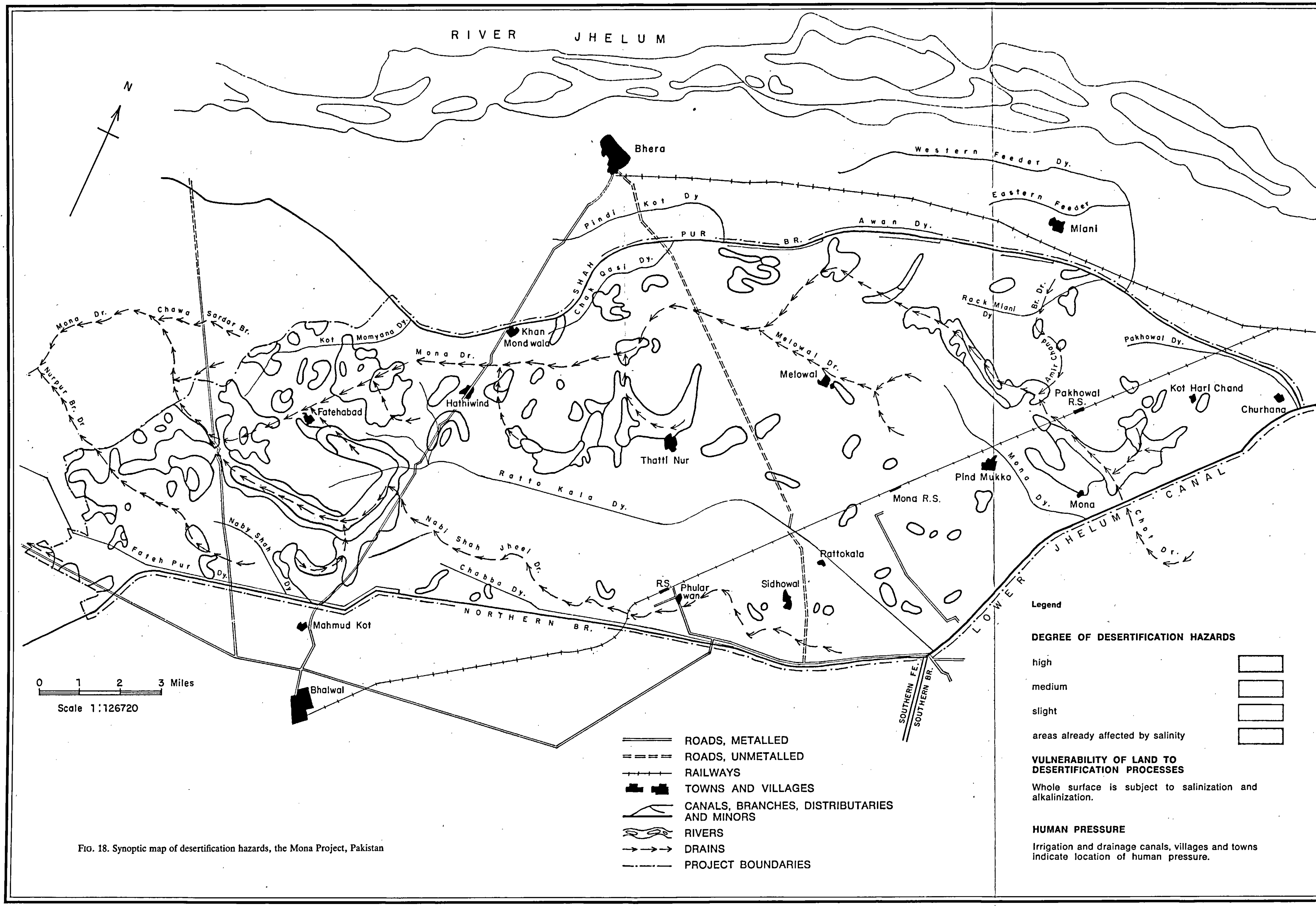


FIG. 18. Synoptic map of desertification hazards, the Mona Project, Pakistan

Integrated Rural Development Programme has been launched to achieve this objective, but there is still room for streamlining and improvement.

— There has been no change in land-tenure pattern due to the project; however changes have taken place as a result of legislation on a national basis. For the protection of the rights of the tenants, several laws have been enacted on a national basis from time to time since the introduction of canal irrigation; the latest ones were promulgated in 1972 and 1977.

Agricultural extension

— Experience gained in the Mona Project indicates the need for a qualitative and quantitative improvement in the extension service, as this is a critical link in the success of the programme for obtaining increased agricultural production.
— Extension facilities have been weak on the motivation approach; these have been person-oriented rather than programme-oriented.

Flora and fauna

— Efforts should be made to preserve and propagate beneficial flora and fauna in the area of irrigated agriculture.
— In executing schemes for draining wetlands, due care should be given to the preservation of waterfowl habitats.
— In land-use policy, due attention needs to be given to wildlife conservation.

Livestock, poultry, sericulture, etc.

— There is need to develop ancillary agricultural activities in the area, and in particular attention should be given to livestock, poultry, sericulture, etc. in this context.

Fields which need research

The accomplishments in the Mona Project notwithstanding, there is still room for intensive and extensive investigations and research in many fields. Some of the fields hitherto unexplored or which require further investigations, are given below.

Soils and agronomy

— Mineral uptake by plants under differing conditions, and the depletion of macro- and micro-nutrients.
— Types of drains, their performance and maintenance, and the water balance of drainage areas, keeping in view the technical and economic feasibility of systems under local conditions; saline effluent disposal.
— Salt-tolerance of plants, and salinity/fertility interactions.
— Use of marginal-quality irrigation waters for irrigation leaching requirements; use of manures and fertilizers.
— Optimization of balanced agricultural inputs for increasing crop yields.

Hydrology and drainage

— Water-budgeting and study of the future response of ground-water systems to development activities.
— Long-term effects of subsurface drainage and tube-well waters on agricultural production.
— Long-term changes in water quality owing to ground-water pumping and its effects on the leaching/salt balance.

Water management

— Water losses in the main conveyance channels and watercourses, their extent, and methods of effective control.
— Water-distribution and the scheduling of irrigation.
— Combined use of surface and ground water for successful crop production.

Population and health

— Effective measures of controlling the population increase.
— Statistical health surveys, especially for intestinal worm diseases and anaemia due to malnutrition, and the effective control of these diseases.

Climate

— Micro-climatic investigations to study the effect of individual as well as of co-ordinated factors on the desertification process, at both transnational and international levels.
— Agro-meteorological investigations for agricultural planning.

Flora and fauna

— Methods of propagation and preservation of beneficial flora and fauna.
— Study of the life cycles of flora and fauna.

Appendixes

Appendix I

Land tenure in the study area

Tenure system, number and size of holdings

In the pre-irrigation period various types of holding, i.e. areas for which a separate record of rights had been made, were held under joint *zemindari, pattidari* and *bhaiyachara* tenures. The prevalent tenure was the *bhaiyachara*, where the extent of possession was the measure of each man's rights. After the introduction of irrigation, the joint rights of ownership in land were separated. The restoration of individual ownership rights in land encouraged farmers to develop their land faster, and the standard of cultivation went up to a certain extent. For the district of Sargodha as a whole, it appears that 39 per cent of the cultivation was done by the owners or grantees themselves, 2·3 per cent by occupancy tenants and 58 per cent by the tenants-at-will, while the remainder (less than 1 per cent) were the squatters.

The defective land-tenure system, highly biased in favour of the landlords, persisted for many generations and created an overworked, underpaid and oppressed peasantry, along with an opulent, lazy and parasitic class of landlords.

In 1965–66, in the case-study area, three tenurial classes existed, i.e. owner-operators, owner-cum-tenants and tenants. Under owner-operators or peasant-proprietors, the farm land is cultivated by the owner himself with help from family members or hired labour. The owner-operators include natives and settlers, as well as refugees. The natives are the original inhabitants of the area, and hold right of ownership to the land since times immemorial. Their forefathers held large pieces of land, which had been subdivided continuously among the heirs, generation after generation. The settlers were given title to the land at the advent of canal irrigation in the area, and a two-square holding was granted to each of them, with the condition that a mare would be maintained on it for the supply of horses to the cavalry. The settler holdings were also reduced in size owing to subdivision through sale or purchase of land. The holdings of the settlers were thus no longer uniform in size. The refugees were allotted the evacuee land on the basis of their landed property in India on the eve of independence in 1947. The size of these holdings also varies considerably.

The owner-operators were an important class of cultivators of the area, as they constituted 42 per cent of the total cultivators and operated 43 per cent of the farm area. Nearly 56 per cent of them were concentrated in the perennial, and 12 per cent in the non-perennial, areas. The remainder were in the uncommanded areas. On the whole, more than half of these cultivators had landholdings below the subsistence level.

The survey in 1965–66 revealed that very few cultivators liked to be tenants when they had land of their own. Though as many as 50 per cent of the owner-operators held operational units below the subsistence level, they did not like to have additional land on rent. Again, only about 20 per cent of the cultivators were owner-cum-tenants, operating about 17 per cent of the total farm area. As many as 37 per cent of the cultivators in the case-study area were tenants, a landless class depending directly on cultivators of land for their livelihood. They operated 40 per cent of the total farm area.

In all, 1211 cultivation units, ranging from less than 0·4 ha to about 35 ha, were recorded, and 229 different sizes of holding were observed during the survey. The average size of holding by tenure and irrigation is given in Table 21. As may be seen from this table, the average size of holding was about 5·7 ha, which compares well with the average size of holding in Sargodha district, which was 5·4 ha. The distribution of landholding by size, type of irrigation, and land tenure is given in Table 22, which indicates that the number of smallholdings was disconcertingly large in proportion to their share in the cultivated area. This distribution of holdings was analogous to that of the Sargodha district. At the district level, 36 per cent of the holdings were under 2 ha, 65 per cent under 5 ha, and 87 per cent under 10 ha. Of the 12 per cent of the holdings of 10 ha or more, only 2 per cent were of economic size.

There was no direct impact on land tenure by the introduction of the project, as changes are subject to legislation for larger areas than those involved in the project. However, substantial changes have taken place in the land tenurial and inheritance patterns in the area since the introduction of canal irrigation. The most spectacular change has been that joint estates which were held with communal rights, or on the *pattidari* or *bhaiyachara* tenure, were now given to individual owners. The whole system of land revenue was re-examined and was made realistic, keeping in view the the capacity of the farmers to pay. Individual ownership of land encouraged owner-operators to make independent decisions, and

TABLE 21. Average size of holdings by tenure and irrigation

Irrigation type	Owner-operators			Owner-cum-tenants			Tenants			Total		
	Number of holdings	Area (ha)	Average size of holdings (ha)	Number of holdings	Area (ha)	Average size of holdings (ha)	Number of holdings	Area (ha)	Average size of holdings (ha)	Number of holdings	Area (ha)	Average size of holdings (ha)
Perennial	279	1708	6·1	93	411	4·4	257	1348	5·3	629	3467	5·5
Non-perennial	61	355	5·9	22	132	6·0	62	481	7·8	145	968	6·7
Uncommanded	162	895	5·5	141	598	4·2	134	919	6·9	437	2413	5·5
All farms	502	2958	5·9	256	1141	4·5	453	2748	6·1	1211	6847	5·7

TABLE 22. Distribution of landholdings by size, type of irrigation, and tenure

Type of farm	Total holdings	Farm size (ha)				
		Up to 2·53	2·53–5·06	5·06–7·59	7·59–10·13	Over 10·13
		Percentage of total holdings				
All farms	1211	17·8	39·5	21·5	8·9	12·3
Irrigation type						
Perennial	629	20·0	37·0	23·4	7·5	12·1
Non-perennial	145	6·2	48·3	16·6	8·3	20·3
Uncommanded	437	18·5	40·0	20·4	11·2	9·9
Tenure type						
Owner-operators	502	22·7	31·9	21·2	9·8	14·5
Owner-cum-tenants	256	19·5	53·5	17·2	6·3	3·5
Tenants	453	11·5	40·0	24·3	9·5	14·8

sequently the gradual process of development of agriculture had started. This in a way had increased the risk-taking potential of the farmers. After the start of canal irrigation, the tenants with occupancy rights on land were given titles to such lands. Moreover, the rights of tenants-at-will were given due protection and several laws were enacted. The last ones were introduced in 1972 and 1977, which fully protected the rights of tenants. The arbitrary ejection of tenants by land-owners is no longer possible.

Fragmentation

In the case-study area, over 57 per cent of holdings, constituting about an equal proportion of the farm area, were found to be fragmented in 1965–66. The problem of fragmentation was most serious with owner-cum-tenants, with 92 per cent of the holdings, and 90 per cent of the area fragmented. The size of individual fragments ranged from less than 0·4 ha to over 10 ha, and the average size in the case-study area was 1·5 ha. About 65 per cent of the fragmented pieces of land were situated within a radius of 0·8 km from the main operational fragment. In the case-study area, 47 per cent of the fragmentation was due to inheritance. As time passes, there is going to be further subdivision of land, and hence more fragmentation. To minimize this, several years ago the government launched a massive scheme for the consolidation of holdings in each village. The subsistence holdings of 5 ha given to the tenants after the land reforms may not be subdivided any further.

Inheritance

During the pre-irrigation period and after, inheritance customs remained the same. Ordinarily the whole family remained together until the father's death, with the property under his control. After his death the whole of the father's estate devolved to the sons, who sometimes continued to live as a joint family but more often made a division among themselves of the movable property and dwelling-houses, and either then or afterwards divided the land also. All the sons took equal shares. If one of the sons had died before his father, his sons or widow took his share of the estate by representation. The daughters generally got no share of the property but were maintained by the family until marriage. The widowed mother did not get a share of the estate, and was looked after by her sons. Where the estate was divided, a portion was usually set apart for their mother's maintenace during her lifetime. Where there were no sons or grandsons, the whole of the estate devolved on the widow, two or more sonless widows taking equal share. The widow held the whole estate until her death or remarriage, and had power to make all ordinary arrangements for its management and to enjoy the whole of its produce. Generally, she could do as she pleased with the movable property, but could not alienate the immovable property without the consent of the husband's agnates.

After the creation of Pakistan in 1947, the Islamic Law of Inheritance was introduced. According to this Law, after the death of a person his property is divided among his sons, daughters and widow. The property is divided among all the heirs in such a way that every son gets double the share of a daughter or of the widow.

Renting practices

The most popular renting practice according to the 1965–66 survey was that of *batai* (share-cropping). If the owner-cum-tenants and tenants are classified according to the renting system in vogue, the following categories would emerge:

— *Batai* tenants or share-croppers under the *batai* system paid in almost all cases 50 per cent of the produce to the landlords, the majority of whom shared the costs of land revenue, water rates, and seeds. Some landlords paid the entire bill of land revenue and taxes, while the tenants bore the remaining costs. The share-croppers were by far the most important class, forming 89 per cent of cultivators taking land on rent. About 95 per cent of the tenants had taken land on *batai*, compared with 79 per cent of owner-cum-tenants holding lands on a share-cropping basis.

— About 4 per cent of cultivators consisted of cash and *batai* tenants with more than one landlord, and were paying crop-share to some and cash to others. Only 4 per cent of the tenants, as compared to 8 per cent of the owner-cum-tenants, had more than one landlord, having *batai* terms with some and cash terms with others.

— The cash-tenants, who formed only 7 per cent of the cultivators, tilled rented land on fixed-cash terms. Relatively speaking, a large number of owner-cum-tenants (13 per cent) had taken land on a fixed cash-rent basis, compared with only 3 per cent of cash-rent tenants, mainly because the former were in a better position to assume risks than the latter.

Realizing the oppressed conditions of the tenants and the need for social justice in the agricultural economy of Pakistan, the government introduced land reforms in the country in 1972. According to these reforms, the rights of tenants are protected by the following provisions:

— A tenant shall not be ejected from his tenancy unless it is established in a Revenue Court that he has: (a) failed to pay the rent in accordance with the terms of his tenancy; or (b) used the land comprised in the tenancy in a manner which renders it unfit for the purposes for which he held it; or (c) failed to cultivate the land comprised in the tenancy in accordance with the terms thereof, or if there are no express terms in this behalf, in accordance with the customary manner of cultivation in the locality; or (d) sublet his tenancy.
— The crop grown at any time during *rabi* 1971–72 on any land comprised in a tenancy shall, on its maturing, be apportioned between the tenant and the landlord in accordance with the law for the time being in force.
— As from *kharif* 1972: (a) land revenue and other taxes, cesses, surcharges and levies on land shall be payable by the owner; (b) the liability for payment of water-rate, and providing seed for any land, shall be that of the owner or other person in possession thereof, other than the tenant; (c) the cost of fertilizers and pesticides required for the land comprised in a tenancy shall be shared equally between the owner and the tenant; (d) subject to the other provisions of this regulation, a tenant shall have the first right of pre-emption in respect of the land comprised in his tenancy.
— No owner or person in possession of any land shall levy any cess on, or take any free labour from, any of his tenants.

These reforms were further augmented in January 1977.

Appendix II
Evolution of administrative structure, research and agricultural extension

Administrative structure

Pakistan has a long and rich experience in public administration. The present administrative structure dates back to the days of Akbar, the great Mogul Emperor, who had introduced sweeping reforms in the country and evolved a methodology for the assessment and collection of land revenue. The concept of career service and a system of personnel classification existed at that time. The empire was divided into provinces, divisions and districts and there was emphasis on village administration which centred around headman, accountant and watchman. This pattern continues to persist even today, with modifications made by the British colonists to suit their needs. The present structure of government, which reaches down to the villages and the tillers, is an adaptation of the structure in the British regime. Of course, there have been substantial changes since independence, as the result of many revolutionary reforms introduced in the country to meet the needs of the changing times.

In the present pattern of government, the central government is assigned special responsibilities in policy-making, and in planning and financing of major development projects, while the provincial governments are associated with the execution of the programmes. The Planning Commission and the National Economic Council have the responsibilities of preparing and reviewing the Five-Year Plans and the Annual Development Programmes, which include drainage and reclamation works. In the water sector, in which drainage and reclamation works have been included, the Water and Power Development Authority, under the Federal Ministry of Fuel, Power and Natural Resources, has direct responsibilities for the planning and construction of development projects on a unified and multi-purpose basis, and the provincial departments of Irrigation and Power are responsible for the operation and maintenance of the projects. The responsibilities of the Water and Power Development Authority in drainage and reclamation include ground-water and soil investigations, planning of land-drainage projects, and reclamation. After the construction of the projects, the execution, operation and maintenance responsibilities are transferred to the provincial Irrigation Departments, which are headed by a Secretary of the Department assisted by regional chief engineers, superintending engineers, executive engineers, subdivisional officers, sub-engineers, *zilladars* and *patwaris*. These departments have a Reclamation Directorate under them.

Activities in the case-study area come under two main heads: operation and management of tube-wells and research and investigation. Ordinarily, the operation and management of tube-wells in a Salinity Control and Reclamation Project area is the responsibility of provincial departments, but because of research activities in the case-study area the operation and management, along with necessary funds, rest with the project. In the project, water distribution, reclamation, extension research and experimentation have been centralized to achieve the results of co-ordinated research. Apart from project-staffing services, specialists in various disciplines, especially the socio-economic disciplines, are hired from the Agricultural University of Lyallpur (Pakistan). Under another agreement, a team of scientists from Colorado State University (U.S.A.) is collaborating in a research programme of farm-water management studies.

Research

In order to achieve an ever-increasing agricultural productivity to keep pace with population growth, agriculture in Pakistan needed to be set on a road of continuous growth. This was possible through research and the field application of its results. In Pakistan, the Department of Agriculture was carrying out conventional research, but no attention was paid to the much-needed applied research into rehabilitation measures to combat the problems of waterlogging and salinization in irrigated areas.

The research programme of the Mona Reclamation Experimental Project was conceived to satisfy this need for applied research and investigations. To start with, the scope of the work proposed in the project included monitoring of tube-well performance and ground-water quality and water-table behaviour, and research studies in the fields of hydrology, soils and reclamation, agronomy and agricultural economics. Although the overall research proposed was to be initiated in 1965, the gateway for intensified work opened in 1967 when approval from the National Economic Council was granted. Before initiating the actual programme of research and investigation a bench-mark assessment of pre-project conditions, such as a socio-economic survey, and surveys of hydrology and ground-water-quality status, were carried out to serve the assessment of future results. As the programme of research investigations progressed, long-range studies in all the related disciplines of agriculture were incorporated. In the early 1970s the entire programme of research was brought on a highly specialized footing. Keeping in view the observations made, the results achieved and the inferences drawn, a soil and water management programme was introduced for increasing crop production through the introduction of better techniques and the optimization of agricultural inputs. Great emphasis has recently been placed on the improvement of water-management practices. At present research in the project is very active and the results are being made available for practical utilization in the field.

Agricultural extension

Agricultural extension is the bridge, and the direct point of contact, between provincial departments of agriculture, research organizations and the farmers. The available evidence, however, indicates that with some exceptions this contact generally has been of limited effectiveness. This was in part due to general recruitment problems and administrative arrangements. Added to these was the problem of transport, which prevented extension workers from carrying their responsibilities in the whole of the areas assigned to them. Many farmers who were keen to accept new ideas and advice could seldom get an opportunity of meeting extension workers.

Realizing the need for reorientation in the approach by extension services, and considering that the output of research was of no practical benefit unless it could be transmitted to the farmers, special attention was given to the constitution of an effective extension service in the Mona Project. It was considered vitally necessary that the activities and approach should be such that the transmission of the results of research could be made with the least delay.

For the purpose of disseminating the results to the authorities, different techniques and approaches are being tried in the project. Some of the most effective techniques adopted are seventh-day schools, periodic farmers' gatherings, model farms and field demonstrations, libraries, agricultural competition, farm-guide clubs and seed-bank schemes. A special study has also been initiated to evaluate the effectiveness of extension activities and the impediments to the adoption of improved agricultural practices.

Appendix III. Extent of waterlogging and salinity in Pakistan

A. Waterlogging[1]

Province	Gross commanded area (million ha)	Area affected (million ha): Severely (0–1·5 m)	(%)	Moderately (1·5–3·0 m)	(%)	Total	(%)	Source
Punjab	9·63	0·58	6·05	2·43	25·18	3·01	31·23	Central Monitoring Organization, Water and Power Development Authority, 1975
Sind	6·04	0·71	11·73	2·27	37·67	2·98	49·40	Lower Indus Project Report, 1960
North-Western Frontier Province	0·40	0·04	10·00	0·004	1·00	0·04	11·00	Director, Land Reclamation
Baluchistan	—	—	—	—	—	—	—	
TOTAL	16·07	1·33	27·78	4·74	63·85	6·03	91·63	

B. Soil salinity

Province	Area surveyed (million ha)	Normal soils (less than 0·2%)[2] Area (million ha)	(%)	Slightly saline (about 0·2%)[2] Area (million ha)	(%)	Moderately saline (0·2–2·5%)[2] Area (million ha)	(%)	Highly saline (more than 2·5%)[2] Area (million ha)	(%)	Total Area (million ha)	(%)	Source
Punjab	9·51	7·87	72·64	1·41	14·80	0·40	4·30	0·62	6·50	2·44	25·63	Central Monitoring Organization, Water and Power Development Authority, 1975
Sind	5·34	0·10	1·73	1·10	20·64	1·45	27·12	2·69	50·49	5·24	98·26	IBRD (1974), Lower Indus Project Report, 1966
North-Western Frontier Province	0·40	—	—	—	—	—	—	—	—	0·04	9·00	Director, Land Reclamation
Baluchistan	0·65	—	—	—	—	—	—	—	—	0·04	6·88	Director, Land Reclamation
TOTAL	15·90	7·97	74·37	2·51	15·81	1·85	11·66	3·31	20·85	7·76	48·83	

1. Waterlogging figures pertain to the months of April–June when the water-table is at its lowest. It is highest in September–October, when the waterlogging area increases up to 1·5–2·0 times the waterlogged area in April–June.
2. Soluble salts.

Appendix IV. Distributaries in the Mona Project and their authorized full supply[1]

Serial number	Canal	Perennial/ non-perennial	Distributary	Authorized full supply (m^3/s)	Area (ha): Gross area (GA)	Culturable area (CA)	Culturable commanded area (CCA)
1.	Lower Jhelum, Main Line	Perennial	Pakhowal	0·65	3511	3313	3313
2.	Lower Jhelum, Main Line	Perennial	Mona	0·88	4846	4580	3856
3.	Lower Jhelum, Main Line	Perennial	Rattokala	2·77	14340	13758	12737
4.	Lower Jhelum, Northern Branch	Perennial	Fatehpur	1·53	5515	5405	4311
5.	Lower Jhelum, Northern Branch	Perennial	Chabba	0·48	2174	2155	2151
6.	Shahpur Branch	Non-perennial	Wijhi	0·25	866	860	714
7.	Shahpur Branch	Non-perennial	Rakh Miani	0·54	1841	1769	1582
8.	Shahpur Branch	Non-perennial	Kot Mamyana[2]	0·23	1734	1491	1044
9.	Shahpur Branch	Non-perennial	Dewas	0·25	821	798	798
10.	Shahpur Branch	Non-perennial	Chak Qazi	0·54	1709	1614	1589
11.	Shahpur Branch	Non-perennial	Jiwanwala	0·11	378	362	362

1. Information in this table is based on hydrologic and tube-well performance appraisal in the Mona Reclamation Experimental Project 1965–70 by Ch. Ata-ur-Rehman, Central Monitoring Organization, Water and Power Development Authority, Publication No. 96, 1971.
2. Data from the Irrigation Department, Lahore.

7 Associated case studies in Australia, China, Iran, Israel, the Union of Soviet Socialist Republics and the United States of America

Introduction

A number of associated case studies were presented to the United Nations Conference on Desertification by governments with experience of combating desertification. These usefully extend the geographical and environmental range of the six commissioned case studies and contain valuable additional information on biophysical and human aspects of desertification and its controls.

Full versions of the associated case studies are to be published elsewhere, but it is considered that their close complementarity with the commissioned case studies warrants the inclusion of shortened versions in this volume. The summaries presented below are largely based on *Synthesis of Case Studies of Desertification*,[1] which formed Item 4 of the Agenda of the Desertification Conference on Processes and Causes of Desertification.

The editors gratefully acknowledge the active support of Dr Mostafa K. Tolba, Executive Director of the United Nations Environment Programme and Secretary-General of the United Nations Conference on Desertification, and the co-operation of the responsible governments and authors of the associated case studies, in the preparation of this chapter.

1. United Nations Document A/CONF./74/4.

Desertification in the Gascoyne Basin, Western Australia

Case study presented by the Government of Australia

Case history

This river basin occupies an area of 64 000 km^2 in the north-west of Western Australia. It is arid, with a variable annual rainfall averaging 200 mm. Rain comes with summer cyclones or thunderstorms, often in heavy falls, or with frontal disturbances in winter. The basin forms part of the western slopes of the interior plateau and comprises extensive plains with lesser areas of upland on the north-eastern and south-eastern margins. The vegetation is tall *Acacia* shrubland with an important perennial lower shrub layer, including chenopods, and perennial and annual grasses and forbs.

The basin was settled by European pastoralists about one hundred years ago and is now divided into thirty-one large long-term pastoral leases carrying about 290 000 sheep and 17 000 cattle based on the natural pastures. The area is fenced into large paddocks by wire fences, and 1 800 bores and wells, drawing on shallow ground water, have brought most of the area into pastoral use. The products are wool and meat for export, valued in excess of U.S.$2 million annually. The European population is 320, and the unit of settlement is the pastoral station homestead.

Part of the evidence for desertification in the basin can be found in the trends of stocking rates over time, which rose rapidly in the first decades of settlement, peaked in the mid-1930s with about 650 000 sheep equivalents, and have subsequently fluctuated according to rainfall and economic conditions, but have not regained earlier levels. The increasingly marked fluctuations of stocking rates with rainfall are attributed to the diminution of the desirable perennial elements in the pastures and to an increasing dependence on annuals. Comparison of early reports by pastoral inspectors with those of later surveys confirms that valuable perennial pastures such as chenopod shrublands have been eliminated in many areas, and that there has been an increase in undesirable and unpalatable shrubs. This is substantiated by comparison of deteriorated areas with relict areas in less accessible but comparable landscapes, where vegetation remains close to the climax form. Furthermore, floods which threatened irrigation farms near the outlet of the Gascoyne River at Carnarvon in 1961 were attributed to desertification in the upper catchment.

In this evidence of long-term deterioration, the Gascoyne Basin is representative of much of arid pastoral Australia. It was chosen for the case study because it was the only part of that area in which:

- a survey of the composition and condition of the vegetation and of the erosional status of associated soils had been carried out;
- agreements had been reached with pastoralists on a reduction of livestock numbers over the next ten years and on the exclusion of stock from parts of properties;
- monitoring sites had been set up to determine range trend in de-stocked areas;
- a series of long-established exclosures had been monitored for vegetation changes;
- extension workers had conducted field days at which pastoralists had participated in rangeland assessment.

The rangelands were surveyed in 1969–70. The area was mapped into rangeland types on the basis of pastures and land-forms using aerial photographs, and these types were established as reliable and repeatable mapping units by ground observations at evaluation sites. At these sites, assessments of pasture condition and potential and the vulnerability of the rangeland to erosion were made, for each of fifty-one rangeland types.

The survey indicated that 15 per cent of the basin was so badly degraded and eroded that continued grazing would result in irreversible deterioration, that 52 per cent was degraded with some erosion and was in need of range management, and that 33 per cent was in acceptable condition. Most of the rangeland taken up between 1920 and 1939 was found to be moderately to severely degraded. Valuable perennial chenopod shrublands had been transformed into unproductive short-lived annual pastures, there was an increase in undesirable spiny shrubs, and many perennial communities showed signs of senescence, with little evidence of regeneration under grazing despite periodic heavy rainfalls.

Present deterioration is a reflection of inherent vulnerability to degradation following sixty years of heavy grazing. In the earliest years, with scarce surface water, semi-nomadic shepherding of large flocks led to severe overgrazing of the more productive and accessible lands. Past and present systems of use have demanded utilization of all available vegetation to the exclusion of the needs of the pastures for maintenance, or of the landscape for stability. Despite the establishment of a supervisory Pastoral Appraisement Board in 1917, the lack of pastoral inspectors hampered the introduction of controls on stocking, while there was little research into the management of rangelands before 1950.

Severe degradation of pastures is most common in the more productive lands on soft shale in the lower catchment area, and on alluvial plains, both areas of erodible soils, whereas the lands in acceptable condition are mostly hilly and stony short-grass pastures of low natural productivity in the upper catchment area.

Severe water erosion existed on 21 per cent of the locations surveyed, in the form of sheet erosion on alluvial flats and gully erosion on gentle slopes, and is fostered by heavy cyclonic summer rains. Shallow and stripped soils and heavy run-off from degraded surfaces have reduced the store of moisture available for plant growth. Serious wind erosion was noted at 8 per cent of locations, in the form of surface deflation, abrasion of soil surfaces, destruction of vegetation by sand-blasting, sand-drifting, and sand accumulation in hummocks. Comparison of photography from 1958 and 1964 shows that all forms of erosion continue to be active.

The most severely degraded rangelands were judged to require remedial treatment, including de-stocking, to allow regeneration of vegetation and the healing of eroded surfaces. On some pastoral stations this might be offset by heavier stocking of outlying paddocks. Moderately desertified rangelands were classed as needing supervised management, with stocking rates reduced to levels where not more than 50 per cent of dry-matter production was grazed, and with deferred grazing to allow the regeneration of perennials after heavy summer rains. Acceptable condition refers to areas with little erosion, but with vegetation reduced to unpalatable or ephemeral status. The 1969–70 survey suggested a reduction in livestock numbers from 417000 to 237000 sheep equivalent units in order to prevent further erosion and to assist in rangeland rehabilitation.

In general, costs will not allow mechanical controls of erosion such as contour-furrowing or reseeding of degraded rangelands, except perhaps in valuable chenopod shrublands to improve livestock breeding prospects or in measures to protect strategically important areas, nor is it financially possible to fence off small areas of more productive range within larger areas of unproductive types. One brighter outlook is the current eastward invasion by the valuable perennial buffel grass (*Cenchrus ciliaris*) on newly deposited sands in river frontages, and this may be assisted by seeding and the use of a light harrow. Elsewhere, recovery will have to be achieved through an ecological approach, with natural regeneration of the pastures under protection and management, and the process will be slow.

The future of the pastoral industry in the area will be determined by the ratio of costs to prices received. Costs have increased since 1950, while the index of prices received to prices paid shows a steady decline over that period. Labour inputs at 4000 sheep per labour unit appear to represent maximum achievable efficiency under the existing system. The level of indebtedness of lessees is appreciable, and much capital equipment, particularly fences, cannot be replaced at present costs. The industry is no longer attractive as an investment for outside capital.

It is estimated that the minimum station flock for profitable operation in the lower part of the Gascoyne Basin is 5000 sheep, but on several more remote (eastern) stations or on those with difficult terrain and higher costs the threshold figure could be 10000 sheep, and it would be reasonable to accept 10000 as a general level for viability by 1984. Some of the less-productive stations in the upper basin cannot foreseeably achieve this stocking level, and many of these properties are likely to be abandoned during the next decade, despite the fact that this is the less degraded rangeland. The more productive country, although more degraded, will remain in use, but unless remedial action is taken this could in turn become unprofitable.

It is not likely that any major change of land use will occur in the basin. There has been some introduction of cattle in the upper part of the basin, where numbers peaked in 1971. This has not been accompanied by modifications to fencing, yards, etc., and control of cattle grazing is generally ineffective.

Following the assessment of range condition in 1972, joint inspection and discussions with pastoralists in the field by officers of the Western Australian Department of Agriculture in 1974 have reached agreement as to the level of stocking and the deployment of livestock to be achieved over the next decade on each station.

Lessons learned

Agreements reached by discussion in the field with pastoral lessees have confirmed findings of an earlier survey concerning the degree of desertification and the need for combative action in the Gascoyne Basin, and have vindicated the use of aerial-photograph interpretation supported by field traverses as a means of assessing range condition, where this assessment is carried out by experienced officers familiar with the region. Subsequent use of LANDSAT imagery may lower initial costs of photography in such surveys, will reduce the need for field confirmation, and will provide a basis for monitoring subsequent changes in range condition. On the other hand, it was not possible to discern the extent of the more subtle forms of erosion on aerial photographs at a scale of 1:40000, notably sheet erosion of alluvial flats. Such changes are, however, revealed in successive ground photography of sample areas, and these are recommended as a source of evidence.

Remnants of climax vegetation in the basin show that desertification, in the form of rangeland deterioration, is a phenomenon of European pastoral settlement, with its introduction of large numbers of hooved herbivores in place of soft-footed native herbivores at low and flexible levels of grazing.

There is limited scope for improvements in animal husbandry, including selection of ewes and rams for improved wool production and reproduction, local breeding of rams suited to the harsh conditions, and joining in early summer in small grazing paddocks used in yearly rotation.

However, the key to progress in the control of desertification does not lie primarily with improved animal husbandry, nor in more capital development, but in the perennial rangeland vegetation. The importance of the perennial species resides in providing protection to the ground surface, assisting the germination of annuals, providing a high-protein forage component in dry season, and in the ability to respond more effectively than the annual pastures to the more frequent smaller falls of rain.

In ecological grazing strategies, short-term deferments need to be related to the possibility of effective rainfall. Calculations with a water-balance model suggest that frequent opportunities for plant growth do occur, and field observation confirms that the vegetation response by perennial species is superior to that of annual species.

Emphasis must be on important species in this perennial component, and on the rare occasions when regeneration takes place. Too much attention tends to be given to drought periods, and not enough to runs of good seasons when regeneration of pastures can be attained, and when alleviation of grazing pressure is critical. Control of livestock is imperative on the occasions when regeneration occurs. Because the optimum temperature of 16°C for the germination of the desirable chenopod shrubs occurs in the March–May period when rain can be anticipated with some confidence, management schemes which will promote the germination and establishment and therefore regeneration of these important browse plants will necessitate the removal of livestock during this period and the following winter. If winter rains fail, grazing must not recommence until a further season of effective rain occurs.

An ecological approach should aim at achieving 'proper use', defined as the degree of grazing which will allow the more desirable forage plants to maintain their stand and vigour and thereby prevent undue run-off and erosion. The four factors entailed in the correct manipulation of rangelands for grazing are proper numbers of livestock, proper class and kind of livestock, proper season and sequence of use, and proper distribution of livestock. In the study area it is possible only to adjust livestock numbers as the major method of maintaining the resource base. A programme of reduced numbers and exclusion of stock from specified areas should halt the erosion processes and stabilize the pastures, and should reduce the violent fluctuations in livestock numbers between rainfall years.

In programmes of ecological improvement, work on the least-eroded and better-quality rangelands should receive priority, rather than on grossly eroded sites, as is the common practice.

Some important perennials may take a whole generation to recover. To the extent that owner-occupation of individual leases is seldom this long, the advantages of improved management may not be obvious to the individual pastoralist, and the importance of government policy for fostering responsible land use is increased.

The longevity of certain desirable perennial shrub species was an important factor in the maintenance of rangelands, subject to grazing by native herbivores under conditions of highly variable rainfall. Failure of these perennial plants to regenerate under existing practices is reflected in a marked senescence among individuals of these long-lived species. This evidence of exploitation of rangelands without regeneration is general in arid Australia, and in southern arid Australia could result in the massive death of important forage species; unfortunately it is generally taking the form of an insidious patchy mortality which is unlikely to arouse public awareness of the need for action until irreversible damage has occurred. The case study on the Gascoyne Basin will have been worth while if it heightens awareness of the need for research, extension and administrative action before it is too late.

It will be important to maintain a monitoring programme using large-scale aerial photographs and ground measurements, to determine if and when rehabilitation occurs on the areas from which livestock have been removed.

The study indicates the importance of economic factors in the use of rangelands for the production of livestock products for export. At the international level, lack of control over fluctuations in world commodity prices introduces an element of uncertainty which adds to and may compound the risks of land use in an uncertain arid environment. At the level of the financial institution, there is a need for long-term credit at low interest to overcome the season-to-season fluctuations due to climatic and market factors and to assist in forward planning with an appropriate management perspective.

In the past, financial institutions appear to have been slow to learn that past and contemporary production records for pastoral properties do not indicate future levels; no amount of skill, technological application and financial assistance can redress the situation in the Gascoyne Basin or elsewhere in arid Australia on grossly deteriorated and poor rangeland.

The case study has demonstrated the importance of discussion and co-operation between pastoralists, research scientists engaged in range assessment, and those responsible for recommendations on rangeland policy. Following the 1974 inspections there have been requests from pastoralists for field-days with participatory sessions, and attendance has notably improved. A side-effect of the initial survey and its aftermath has been a more active local branch of the Pastoralists' and Graziers' Association. The combination of local research and practice augurs well for an agreed implementation of the various measures available to combat desertification, and for fruitful rangeland-management programmes on stations with a reasonable resource base.

In considering the relevance of the findings of the Gascoyne Basin case study to other parts of arid Australia, two factors should be considered, namely the absence from this area of the European rabbit, which elsewhere may hamper the regeneration of desirable pasture plants, even where domestic livestock are removed, and the occurrence within the native pastures of the study area of perennial shrubs capable of enhancing and stabilizing the population and productivity of sheep and cattle.

Tame the wind, harness the sand and transform the *gobi*

Case study of the experiences of the Sinkiang Turfan People in combating desertification, presented by the Government of China

Case history

This case-study area is situated in the central part of the intermont Turfan Depression in the Sinkiang Uighur Autonomous Region, western China. The Turfan is a basin within the Tienshan Ranges, its lowest point being 154 m below sea-level in Lake Aidin. The area consists almost entirely of wind-eroded alluvial plains (*gobi*), sand dunes and closely dissected hills. The present oasis lies between the tributary piedmont fans and the lacustrine plain north of Lake Aidin.

The basin is protected to the north by the Tienshan Range, and the climate is hyper-arid with a mean annual rainfall of only 16·6 mm. It is a continental climate with large seasonal temperature ranges; summers are very hot, while there is a frost period averaging more than 100 days. Pan evaporation is 3000 mm. It is very windy, with frequent sandstorms and resulting sand drift and dune formation. Permanent snow cover on the Tienshan Range provides an important perennial supply of surface water (300 million m^3/yr). The basin also has important artesian ground-water resources with an annual discharge of 200 million m^3.

Turfan has been an agricultural area since ancient times, and before 1950 the land had suffered greatly from overgrazing and undue extension of cultivation. As a result of uncontrolled land use and over-exploitation of natural resources, the area became desertified. The vegetation cover was largely destroyed and wind action had caused accelerated sand drifting and dune mobilization, particularly threatening the oasis perimeter. The sandy sediments of the flood-plain and lacustrine plains were severely eroded, resulting in uneven wind-scoured *gobi* surfaces.

During the last twenty-five years the following measures have been taken to reduce sand drifting and dust storms in and around the oasis:

— In the sandy areas surrounding the oasis, grazing and the cutting of pastures was initially severely restricted, and grasses and shrubs were established using ground water and the tail-water from irrigation during the winter months. A good cover of herbs and shrubs has now been established, wind velocities have been significantly reduced, and rotational grazing is now possible.

— On the margins of the oasis, mixed tree belts have been established along irrigation ditches. They include both quick-growing and longer-lived, tall and low tree species. Wind velocity has been reduced to a quarter in zones extending from one to three times the height of the shelter belts downwind.

— Within the oasis, small grids of tree belts have been planted, 5–15 m wide with a spacing of 150–200 m. These have reduced wind velocity significantly.

In addition, lined canals have been built to bring the snow-melt water from the mountains, reservoirs constructed to conserve flood-water, and mechanical pumps installed on wells to make better use of ground water. The irrigation flow in the area is now 30 m^3/s, whereas before these measures were introduced irrigation water supplies, restricted to pit-wells, amounted to only 13 m^3/s.

The *gobi* plains forming the lower parts of the piedmont fan have been reclaimed by contour terracing, planting of tree shelter belts, digging trenches in the lee of the belts, filling them with prepared soil and planting vines, and by carefully timed irrigation from pit-wells to suit the requirements of the vines.

The area has now become an important centre of viticulture.

These measures to combat desertifiation have been employed in the area since about 1950, when the communal system of land-ownership and cultivation was introduced. At present, 70 per cent of the cropland is under the protection of shelter belts, cultivated areas formerly ruined by wind erosion and sand drift have been restored, and sandy tracts that could not be cultivated formerly have been levelled and brought under cultivation. The area of the oasis has been doubled and the production of food crops, cotton and hides has tripled. The effectiveness of the protective measures was demonstrated during strong wind-storms in April–May 1975, when damage was restricted to 4 per cent of the cultivated area and farm production was barely affected.

Lessons learned

This case study demonstrates the potential of measures to counter desertification in and around oases in hyper-arid areas where supplementary irrigation water is available. It confirms that measures to stabilize dunes and drifting sand, including mechanical reshaping of dunes, are justified where they threaten valuable irrigated land and settlements, and are best assured of success where irrigation water is available to assist revegetation.

It provides a good example of successful measures to reduce wind velocity and control sand drifting and wind erosion through the restoration of vegetation cover in sand-source areas and the establishment of shelter belts to protect agricultural lands:

— In areas of grassland and low shrubs surrounding the oasis a ground cover of 80 per cent, which may take three years to achieve, will reduce wind velocities by up to 50 per cent and effectively trap drifting sand. As the vegetation is very low, it is essential that the belts of grassland cultivation be sufficiently wide, in this case 300–500 m across. Once a grass cover of 60 per cent has been established, the introduction of rotational grazing is possible.

— On the oasis perimeter, shelter belts of planted trees can reduce wind velocities by 70 per cent in a sheltered zone extending downwind as much as seven times the tree height. Where drifting sand is abundant, multiple tree belts may need to be planted 50–100 m apart. Tree species should be chosen for quick growth and long life, and taller varieties interplanted with shorter to give a serrate upper surface of greater roughness to be more effective in lowering wind velocity. An outer belt of particularly wind-resistant varieties is useful, in this case the sand date (*Elaeagnus angustifolia*). From the outset ditches must be dug along the tree belts to control irrigation, prevent salinization and alkalization, and to wash away accumulated sand.

— Within the oasis, farmland plots can be further protected from wind by a network of tree belts. The greatest reduction of wind velocity can be achieved where the plots are small and where the network of tree belts has a spacing as low as 70 m.

The case study exemplifies the point that measures to combat desertification need to be integrated within programmes of land protection and controlled management. For example, sand-control measures were here linked with the introduction of cultivated pastures and the establishment of systems of rotational grazing, and the programmes of *gobi* reclamation and planting of shelter belts formed part of the further development of irrigation. This integrated programme was facilitated by the organization and management of land on a communal basis; however, the effectiveness of the measures is a recommendation for their adoption in integrated schemes for the protection and development of other oasis settlements with access to water for supplementary irrigation.

Control the deserts and create pastures

Case study of the experiences of the Wushenchao commune, Wushen Banner, Inner Mongolia, in combating desertification, presented by the Government of China

Case history

The Wushenchao Commune is situated in the centre of the Ordos Plateau in the northern part of the Maowusu sand desert, in the Inner Mongolia Autonomous Region. The commune covers an area of 1600 km^2, and over half of this area consists of shifting sand, mainly with crescentic dunes. About one-third of the area, consisting of fairly stable low dunes and interdune areas, is usuable pasture land, and the remainder consists of salt lakes and alkaline flats. Ground water is abundant, often within a few metres of the surface, with further resources at depths of over 300 m.

The climate is continental and semi-arid with monsoon characteristics. Average annual rainfall is 377 mm, mainly in summer, and potential evapotranspiration is 2253 mm. Strong north-westerly winds, which are prevalent during winter and spring, are responsible for severe sandstorms.

Before 1958, when the current programme of pasture reclamation and sand-drift control was begun, the pastures had become severely depleted through overgrazing, causing extensive mobilization of sand. The main desertification hazard is dune-building and dune encroachment to the south-east.

Sand fixation and pasture reclamation are achieved by the use of grass *kulun*. These are areas enclosed by wire or wooden fences or walls, within which grass is grown, often together with trees, fodder crops and vegetables. The two main topo-edaphic environments of the sand country are treated appropriately:

— On the dunes, protective native shrubs (*Artemesia ordosica*) are planted in rows transverse to the main winds on windward dune slopes, beginning at the foot and extending upslope over a period of years. As plant cover increases, sand drift is checked, the surface is stabilized and there is an appreciable increase in the organic content of topsoils. Sand-tolerant sand willows

(*Salix microstachya*) are planted on lee dune faces and in interdune depressions in front of advancing lee faces to prevent dune advance. Plant cover is maintained on the dunes by cultivation, interplanting smaller shrubs between established rows of shrubs and trees, replacing plants in wind-eroded areas, and by protecting the pastures from cutting and grazing. Trees (*Salix* spp.) and taller shrubs are planted as forest belts in interdune depressions with better moisture conditions. Willows planted in rows up to 5 m apart produce a dense cover in three years. The protective forests effectively stabilize the sand and provide shelter within which pasture grasses can be planted. Eventually a three-element tree–shrub–grass complex is established. The trees can also be used as a source of timber.

— On grassland plains between dune areas, with better soil conditions and available water, four-element water–grass–forest–fodder combinations have been established. Where necessary, dunes are first levelled and marshy depressions filled in. Pit wells are used to draw on shallow ground water, and deeper wells for artesian ground water below 100 m. Water distribution is by lined canals, and recently spray irrigation has been introduced. Protective forest belts of willows are planted 50 m apart as wind-breaks. Leguminous fodder grasses (*Melilotus alba*), alfalfa and millet are also planted. Other developments include plant nurseries, fish ponds, vegetable and fruit growing and bee-keeping. Production from these areas is now three times that of unimproved native pastures.

Two other types of *kulun* have been established for the protection and cultivation of natural pastures in other sandy areas. This is done by prohibiting cutting and grazing during the growing season. Under such protection pastures show marked improvement in density, height and cover, and especially in the component of palatable *lai* grass (*Aneurolepidium dasystachys*), and improvement in soil structure and nutrient content. The increased vegetation cover leads to greater resistance to wind erosion, even in the higher exposed parts.

So far, 15000 ha of sand country have been stabilized under the programme, of which 6000 ha have been transformed into productive pasture lands. In addition, a somewhat smaller area of natural pastures has been rendered productive. The function of these pastures is now undergoing a change from that of providing winter and spring fodder to that of seasonal, rotational grazing. The *kulun* have also been growing in size and the larger ones have occasionally been subdivided into smaller ones to attain maximum economy of operation. The number of cattle supported in the area has increased fivefold.

Lessons learned

The study shows the importance of recognizing the various topo-edaphic settings that make up a particular desert landscape, and of treating each appropriately in a co-ordinated programme of reclamation and improvement. Dunes, interdune depressions and sandy plains have been reclaimed in different ways, but each contributes in complementary fashion to the present managed land-use complex.

The study demonstrates the possibility, under the prevailing semi-arid climate and with the predominantly sandy soils, of developing vegetation and land-use complexes within controlled fenced areas known as *kulun*. Depending on the availability of water and on soil conditions these may be four-element *kulun*, including crops based on irrigation, or three-element *kulun*, comprising tree–shrub–grass components, as in areas of dune stabilization. The *kulun* also demonstrate the development from purely protective anti-desertification measures to the establishment of productive managed pastures supporting year-round rotational grazing.

The study demonstrates that dune fixation and rangeland reclamation must be accompanied by controlled pasture management, by fencing, and by the prohibition of grazing and cutting during the growing season. Maintenance of planted areas by cultivation, protection and plant replacement is also important.

The study provides important evidence of the improvement in soil structure, organic content, and nutrient status solely through sand stabilization and the establishment of a layered vegetation cover in which trees, shrubs and grasses play important complementary protective roles.

The effectiveness of seasonal protection and locally of cultivation in increasing the productivity of natural pastures in grazing *kulun* has also been demonstrated. It should be noted that protection does not mean the removal of pastures from use for many years, but their use in seasonal grazing systems suited to the composition of the pastures, i.e. tall-grass pastures are used for hay-making in autumn as well as grazing during winter and spring.

The study shows the importance of the development of irrigation from ground water in increasing and stabilizing production in the *kulun*, first in establishing pastures of high and stable yield, and second in the growing of alfalfa and grain crops as a guarantee against lack of grass in the winter and spring months.

The *kulun* system exemplifies the value of diversification within an integrated land-use scheme, comprising hay production, the growing of high-quality grass and grain fodder, and winter pasturage for sheep, in addition to irrigated food crops, fish ponds, etc.

Combating desertification in China

Case study of the experiences in combating the extension of desert conditions, presented by the Government of China

Case history

This case study reviews the experience of the Chinese people in combating desertification in a variety of dryland environments, and in transforming areas which were previously desertified into productive agricultural lands. It draws on the two case studies described above, as well as evidence from other settings.

The hyper-arid and semi-arid lands of China are important by virtue of their extent. They exceed 1 million km^2 or 11·4 per cent of the total land area. The main arid regions lie west of 160°E. longitude, mainly in intermont basins, and consist of almost equal areas of largely mobile sand dunes and stony desert. Rainfall is generally below 200 mm and locally below 50 mm, and temperature regimes are extremely continental, with a pan evaporation of 2500–3000 mm reflecting high summer temperatures. In these areas agricultural settlements are confined to irrigated oases and to riverine tracts on the lowest parts of piedmont alluvial plains. The semi-arid drylands east of 160°E. consist of open steppes and grassland with minor areas of vegetated sand dunes. They have a rainfall of mainly between 200 and 450 mm, coming with the south-east monsoon.

Before the 1950s, much of China's drylands had suffered greatly through uncontrolled land use and over-exploitation of the natural resources, particularly over-grazing and the undue extension of cultivation. In many parts this abuse of the land had been taking place for over 250 years. The vegetation cover had been largely destroyed in many areas, causing extensive mobilization of sand and the encroachment of dunes on agricultural land.

Since 1950, with the reorganization of land management into systems of communes, the local inhabitants of the various desert areas have developed, through trial and error, a number of effective methods of bringing their deserts under control. Because of their widespread distribution and their differing climatic and geological conditions, the various dryland regions require different methods of treatment, and this case study describes several locally oriented, integrated measures all involving mass community participation:

- In arid areas where oases are subject to sand encroachment, a combination of measures has been used. On the oasis perimeter, tree belts are planted as wind-breaks to combat the encroachment of sand; inside the oasis, networks of tree belts are established to reduce wind velocity further and to protect the fields; in adjacent desert tracts an increased coverage of vegetation is fostered to control local sand movement. Wherever surface water is available, expansion of the cultivated area has been possible.
- In semi-arid areas of stabilized and semi-stabilized sand dunes, *kulun* enclosures have been constructed to control grazing and develop pastures for animal husbandry. In addition, a combination of tree belts, shrub wind-breaks, and networks of grass herbage, developed over a period of three to five years, is used to stabilize the shifting sands which occur scattered through this type of desert.
- Over vast areas, efforts have first been concentrated on the marginal lands along the desert edge, in river plains and in lake basins. Reservoirs have been constructed to store water from intermittent floods, and irrigation channels constructed for small flows. In addition, wind-breaks have been planted to protect the newly reclaimed fields.
- Along communication lines such as railroads and highways passing through the desert, sand-stabilizing works have been vigorously promoted, aided by measures to improve the vegetation cover. Where sand stabilization could not be achieved through the planting of vegetation alone, various engineering methods have been applied, including works to stabilize, check, or remove adjacent mobile sand dunes.

Great changes have been achieved through the methods outlined above, and by developing water and soil resources. Local communities in many areas have successfully stopped the spread of desert conditions and have turned former barren land into productive pastures and cropland. The most important protective measure has been the planting of forest belts, which have proved to be extremely useful in reducing wind velocities, thereby controlling sand drifting and checking the encroachment of sand. One integrated system of protective forests in northern China alone is over 800 km long, 500 km wide and provides protection for about 3 million ha of farmland. The area of productive agricultural land in many areas has been greatly increased by cultivating shrubs, grasses and crops under the protection of forest belts and using the system of *kulun* enclosures. This has been aided by controlling grazing and utilizing water resources in irrigation.

Lessons learned

The report exemplifies the range of measures to combat desertification required in many different dryland environments in China.

Measures to combat sand drifting and to protect threatened farmlands have been established from experience around many oasis settlements in the arid lands of north-western China. These require the construction of perimeter forest belts, combined with networks of shelter belts within the oasis. Where low dunes threaten the oasis, plots of quick-growing and sand-resistant tree species such as poplars and sand dates should be planted, extending into the dune belt which then becomes partly levelled by the wind. Loose sand surfaces can be stabilized by mulches, clay cappings and sand-stabilizing plants such as *Haloxylon ammodendron*. In flatter sand country, trees and shrubs should be planted to check sand drift, the proportion of shrubs being highest towards the sand source and the tree belts predominating on the inner perimeter. Tree belts 300–500 m wide have been found to reduce wind velocity by up to 60 per cent within a range of thirty times tree height, and sand drift by 70 per cent at the outer edge. Where the oasis is bordered by gravel *gobi* or wind-eroded *gobi* and the principal menace is high winds or sand corrosion, multiple tree belts should be combined with irrigation ditches built beforehand. These facilitate watering and washing away of the sand. Rows of trees of differing height increase the roughness of the upper canopy and the sheltering effect. The choice of tree varieties will depend on local soil conditions.

Within the desert oases, networks of tree wind-breaks will reduce wind velocities and further protect farmlands against invasion by aeolian sand. The network progressively reduces wind velocity towards the centre of the oasis. Depending on conditions, each shelter belt should consist of three to eight rows of trees of different heights, with spacings of 200–500 m. The outer belts in the network should be supplemented by shrub layers. Tree species should be selected for fast growth and long life. On the windward margin, hardy, low, spreading varieties such as sand date should be added, while low, spreading trees of economic value such as mulberries and apricots should be planted on the sheltered side. Shelter belts are normally planted on either side of ditches and roads. Local stabilization methods should be applied to areas of mobile sand within the oasis.

In the semi-arid areas the higher rainfall allows the stabilization of sand surfaces through revegetation with a combination of trees, shrubs and grasses. As exemplified from the Maowusu Desert, a combination of planting of willows or poplars in low-lying areas in front of advancing dunes, and at the same time planting the lower parts of windward slopes with sand willows or shrubs (*Artemesia ordosica*) will be effective. The higher dune tracts are then levelled off by wind and the levelled dunes can then be planted with trees. Over a period of five years plant cover can be increased from an original 5 per cent to 50 or 60 per cent and locally to 80 per cent. There are many variations on this method. One consists of planting a shrub belt of sand dates on the lower windward slope, to be followed by the planting of additional belts as the dune area in the lee is reduced to an undulating surface by the wind. In another, a tree belt is first planted on the leeward side to block the dune advance, following by planting on the wind-levelled windward slope. In other cases trees and shrubs are planted simultaneously on low dunes and undulating sandy land, and subsequently the shrubs are removed to facilitate forest growth. Again, grasses may be planted on lower-lying inter-dune areas, reinforcing the tree and shrub belts as described. Experience has shown that sand surfaces can be stabilized in three to four years and that a considerable increase in soil organic matter and soil-moisture retention follows. However, since the shrubs will compete with the trees for available moisture, it is important to follow shrub-planting, usually in the autumn, with tree planting in the spring. Eventually the shrubs may be removed. In some cases leguminous trees are planted.

In semi-arid areas of higher rainfall (300–600 mm), where the moisture content of the sands attains 3–6 per cent, measures to establish extensive pine forests on the dunes can be taken after establishing sand-stabilizing vegetation, particularly shrubs. A number of pine varieties can be used according to the moisture regime. These are generally planted two to three years after the initial establishment of vegetation, when sand surfaces are quite stable but before the root systems of the stabilizing shrubs are so extensive as to compete effectively for moisture with the young trees. Camphor pine (*Pinus sylvestris* var. *mongolica*) is particularly effective in these measures because of its extensive root system. The pines are generally interplanted within established rows of shrubs.

In the arid areas, measures to stabilize sands with tree shelter belts should be supplemented by the planting of perennial grasses and low shrubs in adjoining undulating sandy areas. These measures may be locally supported by irrigation and by the manual cultivation of grasses. The principal species include *Alhagi pseudalhagi* and *Karelinia caspica*, with *Phragmites communis* and tamarisk where higher water-tables bring a risk of salinization, and with *Capparis spinosa* on wind-eroded land. After two to three years, with a vegetation cover of 60 per cent, the sand-carrying capacity of the surface wind is severely reduced, and moving sand is trapped.

In the semi-arid areas the corresponding supplementary measures consist of the creation of fenced grass *kulun* with the objective of developing livestock farming. The Wushenchao case study outlines various types of *kulun* depending on natural conditions. Tree–grass–shrub systems are designed to surround shifting and semi-stabilized dunes and eventually provide pasture lands; grass *kulun* in lower-lying areas between sand dunes and near salt lakes provide hay and grazing, while more favourable level low-lying land around sand dunes with better soil and moisture regimes will support four-element *kulun* allowing the establishment of forest and the growing of fodder crops supported by irrigation from ground water. Experience has shown the efficacy of such measures in reducing wind velocity and sand drifting, in stabilizing and improving the soil, in improving the composition and productivity of pastures and affording the development of a large livestock industry.

Valuable experience has been gained in protecting railroads and highways against sand drift. Where these lines of communication cross shifting sands and stabilized and semi-stabilized dunes in semi-arid areas, cladding of sand surfaces may be carried out in the sections of mobile sands. Elsewhere the side slopes of the road-bed are protected by the establishment of vegetation on either side, including sand-stabilizing shrubs and trees. Where available water allows, pine shelter belts may be established locally. In arid areas, gravel platforms may be constructed on either side of the road-bed to facilitate the removal of sand by wind and hence prevent the advance of sand dunes. Also, sand surfaces are stabilized with mulches and by planting vegetation in belts up to 500 m wide on the windward side. In *gobi* areas, where roads and railroads are endangered by sand drift, canals may be built to allow the planting of tree shelter belts under irrigation. Dunes may be cladded with clay or covered with vegetation mulches where sand drifting is excessive.

In many parts of the drylands it has been possible to develop water and soil resources to create new oases in integrated schemes of planned land development. In riverine tracts in the semi-arid drylands, where large amounts of water are available, it can be used by means of artesian channelling or pumping to flatten dunes and create level sandy fields. In some areas flood-waters have been used similarly. By this means soil structure is improved by the addition of clay particles to the sands, and there is also a significant increase in the organic and nutrient contents of the soil during subsequent improved land use.

These methods have been used in association with the development of rice cultivation.

In the intermont basins of the arid parts of western China, use can be made of snow-melt waters from surrounding mountains. Canals can be constructed in the piedmonts to lead water to the desert basins. In addition, reservoirs collect and conserve flood-waters in interdune plains, near lakes and in river flood-plains. At the same time the soil is improved by the input of nitrogen from flood-waters, by the addition of sand to fine-textured or crusting soils, by the cultivation of green manure crops such as alfalfa, and by drainage measures to counter salinization and alkalization.

As evidenced by the Turfan case study, *gobi* surfaces on the lower parts of alluvial plains can be transformed into vineyards or forest land by the construction of lined canals and irrigation ditches, the planting of wind-breaks, the terracing of fields protected by the tree belts, and the establishment of vines in soil-filled trenches dug sufficiently deep to remove accumulated salts.

The study points out that these accomplishments in combating desertification and transforming the deserts must be credited to the mobilization and participation of local populations.

The integrated systems used to protect and reclaim the land have been developed from single-purpose measures through practice and improvement by experience. It is important to recognize that in different areas technical knowledge is applied by testing to find a set of effective measures suited to the local environmental conditions.

The Turan Programme

Case study presented by the Government of Iran

Case history

Almost all Iran except for the Caspian coast is semi-arid, arid or hyper-arid, and most of this area, apart from the small prportion that is cultivated, is considered desert by Iranians. The area has experienced several millennia of land use, and cultural and natural factors are inseparable in the problems of desertification. All sources of information indicate that desertification has accelerated over recent decades in Iran, and increased pressure of grazing and the spread of dry farming are obvious factors. On the other hand, population growth and economic expansion call for maximum sustainable activity throughout the Iranian territory, and the large areas of desert hold considerable potential for production and settlement, despite low productivity per hectare.

Accordingly, the Department of the Environment has formulated a comprehensive programme of ecological research, experimentation and management aimed at improved land use in and around the central deserts, with the immediate objectives of protecting and conserving the natural resources and combating processes leading to desertification.

The Turan Programme consists of intensive study and experimental management of 1·8 million ha on the north-east margin of the central desert. This region, which was already a Protected Area and which became a Biosphere Reserve in 1977, was selected for its diversity, representativeness, economic importance and accessibility. It contains a variety of habitats including mountains, upland plains, a saline river system, large areas of broken country and 200000 ha of sand cover, including mobile dunes. Rainfall probably ranges from 200 mm on the uplands to 100 mm on the plains, with a snow cover of up to four months in the mountains and for shorter periods on the higher plains. The perennial vegetation consists mainly of woody shrubs with annual and ephemeral grasses and forbs, and may be regarded as degraded steppe rather than subdesertic. By 1971 the pastures were assessed as severely degraded, partly caused by overgrazing of domestic livestock under poor conditions.

The case study presents preliminary results based on a representative area of 50000 ha which demonstrates in historical perspective several of the cultural, biological and physical processes involving both increase and decrease in productivity and living standards. It is an island of agricultural and pastoral production amid barren sand desert and saline flats (*kavir*), in which land-forms and vegetation have been significantly modified by land use.

The main part of the study is devoted to the description of the natural resources of the area and their exploitation by man, together with a reconstruction of the ecological history from the beginning of human activity, including the various agricultural and pastoral technologies and their productivity and ecological efficiency. Fluctuations in demographic, social and economic conditions are related where possible to climatic and other natural fluctuations, using maps where appropriate. A sample community is depicted, with emphasis on its spatial organization in relation to resources. The Turan Programme aims at integrating social, human biological and natural scientific approaches to establish an ecologically more efficient land use as a means of combating desertification.

The detailed study area has a resident population of 2000, but the life systems of up to 20000 people in adjacent areas overlap and affect the region. The dominant land use is pastoralism, both transhumant and sedentary, and up to 150000 sheep and goats are shepherded in the area in winter. Of these, 80 per cent belong to pastoralists resident outside the area, with emphasis on sheep for meat production. Livestock owned by local residents include a larger number of goats, with greater emphasis on the production of wool and milk. These flocks may be pastured around the villages or moved within the area according to seasonal conditions.

Agriculture is carried on around the villages, mainly on the piedmont fans. A constant acreage of cereals is grown each year by irrigation and a fluctuating area by dry farming. The main irrigated crops are wheat, barley, cotton, tobacco, vegetables and fruit, cotton and tobacco being important cash crops.

The main processes of desertification are the deterioration of pastures and deforestation, and the consequent drifting and accumulation of sand. These are interrelated with others, less evident but equally adverse, including changes in the numbers of the population and in its socio-economic and legal status.

Preliminary surveys suggest that the vegetation is already degraded and is deteriorating further in quantity and quality through excessive grazing. Unpalatable plant species typical of overgrazing and disturbance are found in the pasture lands, in former dry-farming areas, on mobilized sands, and in the heavily grazed zones around villages and sheep pens. Shrubs and small trees decreased in number in the past as a result of cutting for fuel, charcoal burning, construction of sheep pens, and camel browsing. Several small settlements and *qanat* systems were abandoned through sand drifting in the 1940s and 1950s. This problem has, however, diminished in the last two decades.

The human population appears to be declining, labour problems have arisen from excessive out-migration of the young, and medical and other social services are non-existent.

Lessons learned

The case study shows that agricultural activity over at least 1000 years has generally improved the resources of part of the area, but that associated activities have at times led to degradation in other parts. Desertification is an old problem, and indigenous experience in adaptation to desert stress is most valuable. It tends to be overlooked through cultural prejudices, arising from differences in rates of change between city and desert, and which tend to reinforce neglect and abuse of the deserts. Consequently, desert areas often receive less investment of expertise and capital than areas closer to the cities; correspondingly, those desert dwellers who migrate to the city have difficulty in obtaining services equivalent to those enjoyed by city dwellers.

The case study shows that, in the processes of desertification of the Turan area, cultural, socio-economic and natural factors are inseparable and must be considered together. For example, technological changes have profoundly affected the course of desertification. A partial recovery of vegetation in recent decades has been assisted by the prohibition of charcoal manufacture, the decline in camel herding through the introduction of motorized transport, and through the use of insecticides which makes it unnecessary to burn down and replace sheep pens at frequent intervals.

The study also demonstrates the importance of exogenous factors in desertification, especially those which affect the relationships between the region and neighbouring, more fertile areas. Among these, the nationalization of rangelands and forests in 1963 has tended to disadvantage local residents in relation to transhumant graziers through the subsequent granting of grazing licences. It has also tended to reduce the flexibility of pastoralists, has removed an element of personal investment, and may have contributed to a lessened sense of ecological responsibility. The development of urban meat markets has favoured the transhumant pastoralists who, as meat producers with larger flock units, have more successfully adapted to market needs. In general, an increase in the authority of the central government has diminished the control by local villagers over their regional resources. The change from camel transport to motorized transport has left the region more isolated, and has led to a reduction in local opportunities to provide services to through traffic.

Competition from urban industries is affecting pastoralism through high labour costs, particularly for shepherding, which is an arduous occupation with low cultural appeal. This may eventually favour the self-employed resident mixed farmer relative to the transhumant pastoralist.

The case study, through its use of archaeological and historical evidence, shows that desertification in Iran may have been more serious in the past than at present. But from a national point of view it is more critical now because of the increasing differentiation between rates of socio-economic change in the city and the desert, which tends to reinforce neglect and abuse of the desert and to disregard indigenous experience in adaptation to environmental constraints. Lack of interest in marginal areas encourages their further deterioration and eventual abandonment, with loss of production. There must be conscious effort to reduce the basis of cultural discrimination between urban and rural living in arid zones, through provision of amenities, public education and communications in desert communities, and by improving and developing medical facilities and health-care services.

The case study also shows that, while certain socio-economic and cultural conditions are more likely to be associated with degradation of resources than others, generalizations about pastoralism or agriculture in relation to desertification are likely to be misleading. Vulnerability to desertification varies, among other things, according to the wealth of individual land-owners, their connections outside the area, and their ability to switch resources.

The case study suggests that careful attention should be given to building on existing technology and working within existing traditions. Emphasis should also be placed on maintaining the interdependence and range of interlocking life systems and on livelihood diversification and flexibility, although it is recognized that this may be in conflict with need for the development of central settlements as a basis for the provision of services, and with the tendency towards increasing specialization of production in response to market opportunities.

Migration should not be seen as flight from desertification, but as the calculated use of other resources among the range of options that the desert dweller must maintain if he is to retain the flexibility and interdependence essential to successful adaptation to the arid environment. Conversely, human settlement and exploitation offer a means of combating desertification, and care should therefore be taken not to displace existing populations by undermining their technological basis. High priority should be given to building on existing technologies, supporting innovation within existing traditions, and introducing new technologies only where profitability and risks are well-defined. Alternative sources of energy should be developed to relieve pressure on the vegetation, which constitutes the major natural resource of the area.

Desertification processes in vulnerable arid and semi-arid areas are inseparable from social and economic processes in neighbouring more fertile areas. Accordingly, it is necessary to introduce large-scale planning and long-range management procedures that include desert and related non-desert areas and apply the same ecological and economic standards to both.

The case study indicates that the struggle against desertification should be conducted through management programmes based on the reconstruction and evaluation of the ecological history of vulnerable areas. Such programmes should be fully comprehensive and should integrate:

- theoretical and field applications of the physical, biological and social sciences;
- functions of research, experimentation and management;
- participation of the research team, the local population and relevant decision-makers.

The most important theme that issues from the study is the importance of investment in the maintenance of productivity and settlement in desert lands. In Turan, social decline, decrease in investment and desertification are seen to be intimately related. In order to provide an element of personal investment in the human-use systems of arid rangelands in Iran, and induce the population generally to recognize the value of these renewable natural resources, the government has recently decided to embark on a programme of long-term leasing of rangelands to individual pastoralists.

The Negev—a desert reclaimed

Case study presented by the Environmental Protection Service, Government of Israel

Case history

The Negev covers some 12000 km^2. Rainfall decreases from about 300 mm in the semi-arid north, along the boundary of settled agriculture in the Judean Hills, to less than 28 mm in the south. Rain falls in winter from depressions in the Mediterranean, in variable and localized amounts. Dewfall is also significant (*c.* 25 mm annually). Summers are hot and dry and the area is subject to scorching *hamsin* winds. Evaporation is between 1700 and 2700 mm.

Over most of the area arid and somewhat saline rocky hills and stony slopes support a degraded shrubland, with perennial *Zygophyllum* and *Artemisia* spp., and *Haloxylon* shrubland occurs on loess plains. Denser and larger vegetation, including *Atriplex* and *Retama* and trees such as *Acacia* and the Atlantic pistachio occur along the *wadi* flats, local dunefields carry closer shrub cover with *Calligonum,* and there are groves of woodland, notably of tamarisk, in areas of shallow ground water.

This vegetation is in a degraded state owing to pressure of land use over several millennia, with the earliest settlements dating back 8000 years. Settlement in the area has undoubtedly been affected by rainfall fluctuations, particularly in the northern areas of critical rainfall gradient. For example, settlement south of the Dead Sea appears to have been abandoned in a dry period between about 6000 and 7000 years before the present. Nevertheless, archaeological evidence suggests that there has been no major change in ecological conditions during the period of man's occupation.

On the other hand, many native plant communities have been eradicated through their use for fodder, fuel and building materials. For instance *Populus euphratica,* used in buildings around the Dead Sea in the fourth century A.D., has disappeared from the area. The last wave of deforestation occurred during the First World War, when wood was used for railroad construction and transportation, as well as for fuel. Despite favourable climatic conditions, regeneration of these communities has been prevented through grazing of emergent plants by goats.

The native vegetation has been subjected to grazing for several millennia, and overgrazing has caused the disappearance of many palatable and nutritious plant species. Most rangeland communities are now in an impoverished state. Pressure on the ecosystems has been influenced by the history of the region, which has occupied a strategic position between the civilizations of Egypt and Mesopotamia.

The last major period of agricultural settlement in the Negev was that of the Nabatean-Roman-Byzantine period from the third century onwards, when several towns were founded and extensive flood-farming systems were developed. After the seventh century there was a decline in agriculture and fixed settlement, and the area was largely given over to nomadic pastoralism, linked with dry farming in the north. This reached its maximum development in the mid nineteenth century, but subsequently declined. By the 1920s the nomadic pastoral systems were in a state of imbalance due to restriction on grazing movements by State frontiers combined with growing population pressure, and some sedentarization of nomads was already taking place.

The present population of 230000 consists of 190000 Jews and 40000 Bedouins. The Jewish population has grown markedly since the early 1950s with the settlement of large numbers of immigrants. Much of this Jewish population is urban (85 per cent) and is employed in industry; the remainder is settled in communal agricultural settlements, particularly in the north of the area. The main Bedouin settlements or seasonal encampments are in the Beer Sheva region.

Several towns have been established, including the new quarters of Beer Sheva, the administrative centre of the region, and new settlements such as Dimona and Arad. The construction industry and the production of building materials are also important in this area of urban colonization.

Sedentarization of the Bedouins has continued. Initially it took the form of spontaneous settlement with clusters of temporary structures lacking services, but since the middle 1960s the Israeli authorities have begun to establish planned villages for the Bedouins. The numbers of Bedouins have fallen from 70000–90000 in 1946 to 30000 in 1973. The tribal structure of the Bedouins provides an administrative framework. The old rhythm of autumn and winter pasturing on rangelands and return of the flocks to graze the stubble on croplands near the permanent villages and main watering points has increasingly broken down, owing to the attraction of wage labour in the towns and the greater dependability of agriculture supplemented by irrigation.

Before 1948 land was owned individually by Bedouins and the landless were share-croppers. Now the land is increasingly leased from the State by individuals on a regulated basis. The settled Bedouins increasingly live from wage labour, with crops providing a subsistence and cash element, and livestock a capital reserve and an additional cash increment. The transition from a mixed nomadic economy to wage labour takes at least a generation, and final sedentarization is often linked with the selling off of stock.

Lessons learned

Water policy in combating desertification

Reclamation of the Negev is linked with the water-development policy of Israel, based on the National Water Carrier from Lake Tiberias, which reached the Negev in the 1950s. Water is a scarce resource in Israel, and water use must be supported by the most advanced technology and every effort made to supplement existing supplies, for example:

Improved irrigation methods, including:
- sprinkler irrigation using closed pipes;
- drip or trickle irrigation to give more effective wetting and leaching of the root zone and to reduce evaporation;
- use of fertilizers and pesticides;
- research into crop varieties, techniques of water use and cultivation;
- assistance with marketing and finance;
- extension services;
- economies of scale, as on the *kibbutzim* and, by co-operative arrangements, in *moshavim.*

Water harvesting. Construction of dams across shallow watercourses can provide water for the supplemental irrigation of rain-fed winter grain crops, or the water can be led into infiltration basins for recharge of suitable aquifers which can then be pumped for summer irrigation. Nabataean flood-farming systems have been demonstrated to work at Avdat, together with the use of micro-catchments for tree crops, but costs are too high for commercial farming.

Use of brackish water. There are large reserves of brackish or saline ground water in the central Negev. This can be used for irrigation, particularly trickle irrigation, often in conjunction with fresh water applied during the period of crop emergence. Deep drainage will be required to maintain the level of salt accumulation below the root zone, but fortunately there are no shallow freshwater aquifers to come under threat in this area. The method is suited to salt-resistant crops and to forage crops.

Brackish water can also be used in industrial processes and in municipal sewerage, and then recycled or purified by spreading on shallow aquifers and recovered by pumping. These waters are not suitable for drinking, but costs of desalination are justifiable for domestic water supplies, although not for irrigation.

Desalination of sea water. This provides town water for Eilat, but its wider use will be dependent on costs, particuarly fuel costs, and there are problems arising from the high organic content of sea water.

Rainfall enhancement. Increases in rainfall of up to 17 per cent have been claimed for seeded catchment areas further north in Israel, and this could indirectly benefit the Negev.

The case study is instructive in exemplifying possible improvements in water use induced by scarcity of water, as in irrigation techniques and the use of saline water. However, it indicates that drought compensation and subsidized water supplies must be controlled, so that incentives for increased production and the necessity to adjust land use to the local environment are not removed.

Improvements in dry farming

Increased use of nitrogenous fertilizer in the wetter north has been associated with the introduction of semi-dwarf high-yielding wheat cultivars which do not lodge. In the semi-arid northernmost zone, with above 320 mm rainfall, wheat–sorghum–vetch (hay) rotations have been developed and there is a possibility of continuous or more intensive cropping with wheat. However, this leads to weed infestation, which requires the costly use of herbicides. With less than 320 mm rainfall, wheat–fallow systems are likely to continue, and tests show that the fallow effectively stores soil moisture as well as providing an increment of nitrogen from weeds. There is no response to nitrogen where rainfall is below 200 mm.

Land preparation accounts for 25 per cent of production costs in dry farming and the effectiveness of different forms of tillage, such as deep and shallow ploughing and subsoiling, has been compared. None showed any particular advantages, although in all cases yields were higher than when land was sown without ploughing.

Improvements in livestock farming and rangelands. These include:
- Use of dairy cattle (Israel-Frisians) on feed lots using hay and concentrates.
- Beef cattle on rangelands in the extreme north of the area, grazed in fenced paddocks of 100–300 ha at stocking rates of 5–8 ha per beast. Breeding herds also graze wheat stubble with supplementary feed in summer and autumn in drought years, and calves are fattened in feed lots.
- Sheep are raised mainly for meat (*merino*) but also for milk for cheese. The milch sheep use local winter pastures and stubble, but both systems depend heavily on imported concentrate-feeding.
- Semi-nomadic sheep and goat-herding by Bedouin tribesmen, with winter grazing of

rangelands and fallow, and summer grazing of stubble. Stocking densities are low, of the order of one sheep per hectare.

In the better-watered north there is potential for development of annual sown pastures or fertilized native pastures, which are equally productive, but planting of forage species such as *Atriplex* does not justify the cost. This could support an intensified livestock production of 5–10 sheep per hectare in conjunction with arable farming. In the drier south there is unlikely to be any important change in livestock management, since with less than 200 mm rainfall the pastures show no worthwhile response to nitrogenous fertilizer. The exceptions are areas naturally receiving run-on, where the application of fertilizer is justified. These areas could supply supplementary feed for productive animals. In these areas generally, the traditional pastoralism and dry farming represent the most efficient forms of land use, although there are possibilities for technological improvements as in methods of tillage, selection of cultivars, and water harvesting. It is on the semi-arid margins that the maximum impact of technological improvements will be felt.

Development of the Negev has been part of the settlement policy of Israel. In the initial phase emphasis was on pioneer agricultural communities, and there are now 29000 Jews living on *moshavim* and 20000 on *kibbutzim* in the Negev. In the northwest, with better rainfall on deep loess soils, grain farming is linked with irrigated agriculture and livestock rearing. In the central highlands rainfall is too low for winter crops and less water is available from the Carrier. Deciduous tree crops are at present important, but this area will depend on the utilization of brackish underground water. In the Arava Valley there is only brackish water, but advantage is taken of the warm climate to produce early vegetables and flowers for local overseas markets.

Agricultural pioneering has been supported by modern technology, including surveys of underground water resources, the establishment of research institutions, road-building, and the provision of power and water supplies, housing, health and educational services. Later development has concentrated more on urban and industrial growth. A thorough investigation revealed limited mineral resources, and industry must therefore concentrate on finished products of high labour input, rather than the export of primary materials. Urban industries include textiles, the manufacture of fertilizers, pesticides and other chemical products linked with the Dead Sea deposits, metal goods, glassware, etc.

Some early attempts to construct Bedouin villages were unsuccessful because they failed to take account of social differences among the Bedouins. It was mainly the younger wage earners who occupied the houses provided. Recent policy has been to provide lots on which the Bedouins can build, allowing for those extended families still engaged in the traditional economy, giving a better accommodation of tribal and social groupings, and leading to greater involvement of the Bedouins themselves in the development of the settlement. It is also recognized that the establishment of settlements must be linked with the provision of local employment. Experience indicates that adjustment from nomadic to settled life must be gradual, that the design of settlements must take account of social structures, that the local population must be involved in planning, and that the establishment of settlements must be linked with the provision of employment.

It is recognized that excessive centralization of governmental control over development in the Negev has tended to deter investment from overseas governments. On the other hand, too much confidence was placed on foreign technology and inadequate effort given to local research and development.

The programme for the development of secondary products based on the limited raw materials of the region was insufficiently bold and imaginative and resulted in the export of raw materials rather than of finished products. For this reason, industry has not played the role in the development of the Negev that it must do in future.

The Negev is becoming an increasingly important recreation area, and there is a need for parks and reserves and recreation areas. Provision of these has been hampered by lack of water, but the need is recognized and planning is in progress. Tourism has great economic potential, particularly near Eilat and along the Dead Sea, with a warm winter climate and mineral springs. Much development has already occurred.

Town planning was not good in the early stages. There was a tendency for open layouts, owing to the availability of cheap land, resulting in exposure to excessive solar radiation and to desiccating winds and dust storms, apart from expensive services. The newest towns have higher density housing, and in the older towns the empty spaces are being filled in and large tenement blocks provide shelter for intervening areas. Improvements in housing design are needed; at present the middle range of housing is less successful than the traditional Bedouin tent in coping with climatic constraints. It will not be possible to provide mechanical air conditioning for the average house, and low winter temperatures make a tropical design unsuitable. Experiments are being made with patio-style housing, which offers shade and privacy.

Development to combat desertification of the Golodnaya Steppe

Case study presented by the Government of the Union of Soviet Socialist Republics

Case history

The case study is typical of the central Asian deserts, where irrigation is used to intensify land use and combat desertification. In the Aral Sea Basin 6·2 million ha of irrigated lands produce 92 per cent of the agricultural output and provide employment for 95 per cent of the agricultural population. The 1976–80 five-year plan aims to add 180000–200000 ha annually to the irrigated area, and by 1990, when local rivers are fully utilized, the irrigated area will have reached 9 million ha.

The area of the case study is a piedmont plain of loess and alluvial soils extending between the Turkestan Range and the Syr Darya River, and contains about 600000 ha of arable land. It has a continental semi-arid climate with 250–350 mm annual rainfall in the winter half of the year. Summers are warm and winters very cold, and the growing season is 210–220 days. The climate is sunny but notably windy, with strong north-east winds in winter and drying westerly winds in summer.

Throughout the nineteenth century the area remained dry steppe, sparsely used by nomadic cattle-raisers based mainly on upland valleys where there was restricted agriculture. Unlike adjoining regions, there was no development of irrigation in piedmont oases. The population was probably less than 2000. The region shares the disadvantages of large parts of the central Asian territories, namely inadequate rainfall, soils subject to salinity, insufficient population and lack of bases for development. Its subsequent development has been based on the use of the waters of the Syr Darya River for irrigation.

Irrigation began about one hundred years ago in the north-east of the area, as part of the settlement of Turkestan. Only the distributary canals were provided, and field ditches remained the responsibility of the tenants. The pattern of land-ownership, with large estates and individual small farmers, hampered progress, as did lack of irrigation skills among the local population and 'resettled' Russian nationals alike. Only 23000 ha had been brought under irrigation by 1920.

The area forms a hydrogeological basin with intake in the piedmont margin and increasingly shallow water-tables in the north, posing problems of soil drainage under irrigation. No artificial drainage was provided under the early irrigation schemes and eventually more than 60 per cent of the soils became saline owing to waterlogging and the rise in the water-table.

Modern irrigation schemes were introduced in 1921, and subsequent development of the Golodnaya Steppe has been in three phases:

— From 1922 to 1930 development was carried out by co-operatives and collective farms in 'reclamation associations', responsible for agricultural and water developments under government subsidy. Irrigation was extended over 50000 ha, mainly in the north-west of the region.

— From 1930 to 1956 there was an important additional development of State farms of up to 10000 ha. It was an important constructional phase during which main drains were provided in the north, and eventually the whole of the north-west of the Golodnaya Steppe was brought under irrigation, at the rate of 8000 ha/yr giving an irrigated area of 250000 ha. It was a period of mechanization of agriculture, with the large-scale introduction of cotton cultivation. Development suffered from two handicaps, namely, the exclusively agricultural objectives of the scheme and the separation of responsibility for land and water development, the latter being under governmental water authorities.

— After 1956 the development of irrigation, particularly in the central and south-central parts, was under an integrated scheme in which land and water development, provision of construction industries, supporting services, communications and settlements, management, social services, training schemes, etc. were linked. This integration is achieved through a single government planning authority. Objectives are optimal use of scarce water, a balanced economy, economic development, and increased income for the population; at the same time deterioration of the natural resources is to be avoided.

The preparatory stage of the integrated development of the new lands of the Steppe lasted from 1955 to 1961. Distributary canals and drainage systems were completed, construction industries established, roads, railways and power grids built, and five main settlements founded.

The second stage, that of large-scale land development, began in 1961 after completion of the main canals and drainage systems. Development of new irrigated lands was at the rate of 17000–20000 ha annually, involving the establishment of 3–5 State farms. Each State farm community, over a period of four years, carried out its own land preparation and constructed its own agricultural settlement. This growth rate involved an annual migration of between 6000 and 10000 people into the area, particularly from densely settled areas such as the Ferghana Basin. Development included the necessary training of agricultural and support workers. This period lasted until 1969, when the area under irrigation exceeded 250000 ha. This period also saw a significant reduction in the extent of heavily salinized soils in the older lands and an improvement of crop yields in consequence.

Since 1969 the scheme has been in the stage of establishment of integrated projects, such as cotton ginneries and food canneries. The area under irrigation has continued to increase and, more important, the intensity of cultivation. This stage has been marked by a high level of mechanization of agriculture and by technical innovations such as wide-row sowing and tillage of cotton and the application of herbicides at the time of sowing. Cotton output per worker has continued to rise, to the present annual level of 19 tonnes.

Environmentally, the scheme is seen as a dynamic complex with inputs of water and modifications to land and drainage, and subsequent responses in water-table and salinity conditions and in many other sectors. This dynamic aspect is shown in assessments of water and salinity budgets under the present scheme. For instance, inputs of 12270 million m^3 of water from rainfall, irrigation and ground water in 1973 were balanced by losses from evapotranspiration and drainage outflow. At the same time there was a net loss of almost 1 million tonnes of salt through removal in leaching and drainage, in excess of an input of almost 2 million tonnes of salt in irrigation water. Changes in soils include compaction through irrigation and silt input, and an increase in porosity through the removal of interstitial materials such as gypsum in solution. At the same time there is an important addition of mineral nutrients with the irrigation waters, assessed as 20 kg nitrogen, 100 kg potassium and 4500 kg calcium per hectare annually.

Among other environmental changes brought by irrigation are a reduction in maximum temperatures, a raising of relative humidity, and a local decrease in wind velocities through the planting of wind-breaks, all constituting an amelioration of the harsh desert climatic conditions.

Lessons learned

Irrigation is a most efficient means of increasing the productivity of desert lands and bringing into play the natural advantages of high sunshine hours, heat energy and soil fertility. At the same time it improves the economic basis and employment opportunities and provides an insurance against regional famine through drought.

An integrated approach to irrigation development is desirable, linking it with agricultural and socio-economic development in successive stages from design to completion under a single planning authority. The establishment of dynamic environment-production-irrigation complexes using systems analysis and comprehensive planning in stage-by-stage programmes leads to economically sound development and deals effectively with related socio-economic problems. Intensive land development is assisted where technological measures are reinforced by an organization which makes possible the collective use of land and water, eliminates small-scale farming, and establishes a high level of mechanization.

The transformation of natural environmental conditions under irrigation must be a controlled process, and this should be reflected in the planning of structures and in field management. Drainage, land levelling, soil leaching and land amelioration in combination are essential for the successful development of desert lands through irrigation.

Measures to control desertification in the Turkmenian Soviet Socialist Republic

Case study presented by the Government of the Union of Soviet Socialist Republics

Case history

The Turkmenian S.S.R. comprises an area of 48800 km^2 in the south-west of central Asia, in the zone of temperate deserts. More than 90 per cent consists of the sandy plains of the Karakum and other desert territories, and about 4 per cent of irrigated oases. It is typical of the arid zone of the Soviet Union, where vast territories of desert are used in conjunction with comparatively small oases.

The climate is arid and continental, with a variable spring and winter rainfall which increases from 80 mm in the northern plains to more than 250 mm in the southern uplands. The summers are practically rainless. This seasonal rainfall favours the development of a soil-moisture reserve which benefits pasture growth. The frost-free period is 200–300 days.

As part of the former Transcaspian region, the area remained backward and undeveloped, with much of the cultivated land and livestock in the hands of large land-owners. Cultivation was devoted mainly to cereal crops, although there was a minor and inefficient production of cotton. The Karakum Desert was primarily used for raising fat-tailed sheep and camels, with karakul sheep locally in the east. The nomadic herders had developed traditional skills in their seasonal use of the desert pastures, controlled through the ownership of watering points, and in their selection of livestock. Two-thirds of the territory remained unused.

In the oases, irrigation practices were primitive, involving flood irrigation with the use of lifting devices (*chigir*); distribution systems were inefficient and there was no artifical drainage, with the result that waterlogging and salinization of soils were widespread.

In the desert pasture lands, drought and inadequate water supplies led to excessive grazing pressure on the more accessible and better-watered pastures. This, together with the cutting of shrubs and trees for fuel, had caused impoverishment of the plant cover, sand drifting and dune development. Degradation was pronounced along the southern margin of the desert, and sand movement was most marked in the west, where winds are strongest and where sand mobilization also resulted from the local development of oilfields.

Since the establishment of the Turkmenian Republic in 1924, measures to combat desertification have formed part of general agricultural and economic development, linked particularly with the use of the waters of the Amyr Darya through the construction of the Karakum Canal.

Development of irrigated agriculture

The construction of the Karakum Canal, the world's largest desert hydrotechnical project, took place in three stages after 1954, and further westward extensions are planned. It is now 900 km long, with a discharge capacity exceeding 400 m^3/s in its upper part and with twelve storage reservoirs with a combined capacity exceeding 1·6 km^3. Supplemented by 2000 km of main distributary canals and a storage and drainage network of 12500 km, it has brought more than 750000 ha under irrigation, apart from watering a vast territory of desert pastures. It also constitutes an important waterway, in part through roadless desert.

The irrigated area has been developed through the establishement of fifty-five State farms. Prime emphasis is on cotton (455000 tonnes annually), but vegetables (130000 tonnes) and fruit, including grapes (120000 tonnes) are also important. In addition, the oases support 490000 head of cattle, with high milk yields, and many poultry farms.

Some problems persist and require continual attention. Areas of salinization and waterlogging in seepage zones and of ground-water exhaustion call for the reclamation of irrigation and drainage networks or the provision of storage reservoirs for further application of water. Construction of canals through desert areas had resulted in local sand drifting, and the discharge of tail-water had resulted in the salinization of desert depressions. One example of such an environmental side-effect was the growth of weeds in the Karakum Canal, which was solved through deepening and the introduction of plant-eating fish.

Among the beneficial environmental consequences of irrigation is the amelioration of local climate in the irrigated areas. Relative humidity has been increased by a factor of 1·5–2 and dust nuisance has been reduced, aided by decreased wind velocities. It has also been possible to extend recreational facilities, such as parks and aquatic sports areas.

Development of the livestock industry

The desert pastures include tall shrublands of the sandy desert, well suited for perennial grazing by sheep, camels and goats, semi-shrub pastures of desert flats with heavier-textured soils, suited to winter and spring grazing, and grassland pastures of the foothills, suited to grazing by small stock in spring and summer. Shrubs and trees are important in winter, when there is snow cover and when the productivity and nutrient value of the grasses is lowest.

Major improvements in stock-water supplies have been made in an attempt to bring all pastures into effective use and to spread the grazing load more evenly. Ground water is the main source, from 5200 wells, 54 bores, 600 surface storages and 330 springs. These tap shallow, somewhat saline, ground water in the north and deeper and better-quality aquifers in the south-east. The deep wells are equipped with motor pumps and the shallower wells use camel-power. Some run-off into desert flats is also collected into surface storages. The situation is still not satisfactory and up to a third of the pasture remains unwatered. Supplementary supplies are being brought in by trunk mains to remedy this.

The management of pastures has also been radically changed. The small nomadic farms have been amalgamated in collective and State farms to which between 27000 and 670000 ha of pastures have been allocated following a geobotanical survey. Studies have shown that six to ten years of continuous grazing, withdrawing more than 70 per cent of the harvest, leads to deterioration requiring five to fifteen years for recovery, particularly in sandy areas. The present system is based on moderate grazing pressure of 3·5–6 ha per sheep, consuming not more than 25 per cent of production from shrubs, associated with rotational grazing in alternate years. This is achieved by alternate use of watering points. On a smaller scale, grazing is practised on alternate strips out from watering points at intervals of one to three days between waterings, in accordance with traditional practice. Concentrated feedstuffs are provided for sheep during winter, to supplement the pastures, and this now accounts for 20 per cent of intake. As a safeguard against dry years, fodder reserves are maintained for bulk feeding.

The nomadic system has been changed, and use is now made of vacant grazing lands within the territory attached to the farm, rather than remote pastures. Only those directly concerned with herding move with the flocks, and the others, including older people and school-age children, stay at the base farm. This facilitates the provision of social services. At the same time, nomadic practices have been modernized by the use of vehicles, spotter aircraft, etc.

Pasture improvement is still in progress, and 20 per cent of the pastures remain substandard, particularly in areas of loose sandy soils (1·5 million ha), where the tree and shrub cover has been depleted or eliminated by cutting, and on the foothills (3 million ha), where grassland pastures have been reduced to degraded annual communities. Improvement takes the form of cultivation and planting of native grasses and shrubs. These are planted in ploughed contour strips on the foothills and in contour furrows, especially around wells, in the sandy country.

There has been an important concentration on the rearing of karakul sheep, which now account for 70 per cent of the 4·25 million sheep population, with an annual production of 1 million pelts. Livestock industries account for 27 per cent of gross input.

Mining developments

Oil deposits in western Turkmenistan have been developed in conjunction with the Krasnovodsk refinery, while another refinery is being completed in the eastern Karakum. In addition there are important natural gas fields, with production more than sufficient to meet local needs. Other minerals produced include sulphur, iodine, bromine, bentonite and mineral salts. Some devegetation and sand mobilization have resulted in western Turkmenistan, together with areas of waterlogging and salinization, as by-products of mining activity. All this development has been accompanied by an appropriate growth of industry, energy supplies, and the construction of pipelines and communications. The construction of roads and railways has opened up the desert area and assisted its rational development.

Control of moving sands

This has the threefold aim of: restoration of *Haloxylon* desert woodlands in river flood-outs and areas of shallow ground water, where production can attain 40 t/ha; protection of oasis perimeters; and protection of communications, settlements and other installations. The sand-fixation programme covered 140000 ha in 1951–68, 300000 ha in 1971–75 and aims to treat 330000 ha in 1976–80.

Lessons learned

Despite the effectiveness of measures taken to combat desertification, there is still need for improvement of technology, particularly in view of the continuing development of agriculture and industry in the region.

Irrigated farming should continue to receive attention. New methods should be developed in water application, such as underground, trickle or sprinkler irrigation. Possibilities of extending sprinkler irrigation in sandy soils should be investigated and new forms of drainage should be investigated to counter salinization, such as closed or vertical systems.

There should be further development of livestock farming in oases, based on alfalfa grown in cotton rotations, and on irrigated pastures.

There should be a development of small farming oases in the desert. The remainder will be used for livestock raising, and it is necessary to continue study of the ecosystems as a basis for the rational use of pastures. Pasture studies should include:

— nature of the grazing impact on plant communities, to discover optimal stocking loads;
— selection of improved native forage plants;
— study of productivity and nutrient levels of pastures in order to assess the necessary animal ration.

Pasture management should be extended to all karakul farms. The pastures presently unwatered should be provided with supplies through the extension of piped water systems. There should be an expansion of work on pasture improvement. Means of mechanization should be sought in the production of hay from coarse grasses and in the harvesting of seeds from pasture plants.

To maintain a high and economic level of stocking in the karakul industry, emergency fodder stocks should be established, native hay pastures in foothills and valleys should be brought into use, and there should be an increase in the area of fodder crops, including the use of sprinkler irrigation and of brackish irrigation tail-water on sands. Further improvement of livestock strains is called for, both in karakul sheep and camels.

It is necessary to further developments in oil and gas mining, industries based on mineral deposits and electricity power stations using solar energy and hydro-electric installations in Soviet central Asia. Further developments are also needed in the design of urban communities in relation to their economic function. All these developments should be carried out with due regard to conservation through rational use of natural resources and the regeneration of degraded ecosystems as required, including sand-drift control through afforestation and planting of sand surfaces with native and introduced plants using underground water, including mineralized water.

Attention should be given to development of the recreational and health-regenerative role of the desert, and to the provision of health-cure centres.

There is a need for ecosystem monitoring to maintain the balance between exploitation, conservation and restoration of natural resources, and in the longer term there is a need for 'ecological forecasting', to predict changes over specified time periods through quantitative physico-geographical studies aided by mathematical modelling.

Increasing pressure on desert lands calls for regular education of the public in environmental protection. There is a need for large-scale propaganda of nature conservation among all groups of the population to ensure awareness of the tasks and to involve the population in measures to combat and prevent desertification.

Vale Rangeland Rehabilitation Programme, Oregon

Case study presented by the Government of the United States of America

Case history

The Vale district of the Bureau of Land Management occupies 2·6 million ha in the south-east corner of Oregon. It is mainly a rolling lava plateau deeply dissected by rivers draining to the Snake River along the north-eastern edge of the district. Elevations range between 600 and 2400 m. It has a cold arid to semi-arid climate with precipitation mainly between 180 and 300 mm, most of which, including the amount significant for plant growth, comes in winter as snow. The growing season is limited by winter cold and summer aridity to a short period in spring and early summer. Apart from the main river flats at low elevations, where a variety of crops are grown under irrigation, agriculture is limited to the harvesting of hay. Little perennial water exists over much of the area.

The population of the district (23380 in 1970) is concentrated in the irrigated areas, and only 850 live in the rangelands, making it one of the most sparsely inhabited parts of the United States. Livestock ranching, almost entirely of cattle, contributes about U.S.$15 million annually or 22 per cent of the total income. The public rangelands contribute about 25 per cent of the forage, and two-thirds of the ranchers have held grazing permits here since 1934. The area is dependent on agriculture and crop-based industries, unemployment is high and incomes are below average.

Prior to 1934 the history of the district was one of extensive uncontrolled grazing of free range, particularly following the Californian Gold Rush of the mid nineteenth century. It was a period of conflict between influential cattle barons, migrant sheep graziers, and homesteaders who sought to control and fence off the main water supplies. It was also a period of heavy stock losses from severe winters and from poisonous plants. For instance, cattle were virtually eliminated and sheep wiped out in the winter of 1889–90. Later, sheep owned by Basque shepherds dominated the use of the rangelands for some decades.

In the absence of winter feed and hay, use of the range was year-long, with dependence on chinook winds to melt the winter snows. Free right of transit and grazing favoured nomadic grazing, particularly of sheep. The exploitive impact of uncontrolled grazing was checked temporarily after the stock losses of 1889–90, but had become severe by the end of the century. The main vegetation is sagebrush (*Artemisia* spp.) with perennial bunch grasses such as bluebunch wheat-grass (*Agropyron spicatum*). Range deterioration led to a decline in the palatable bunch grasses and to an increase in brush density. Spaces between the brush were occupied by unpalatable species such as sagebrush and rabbit brush and by invaders such as Russian thistle and poisonous mustards which caused stock losses. From 1915 annual cheatgrass (*Bromus tectorum*) invaded the area, resulting in an increased number of wildfires. Range deterioration was most marked near waters and settlements, and in the more accessible and longer-used north of the area. Deterioration in range condition was accompanied by increased sheet and gully erosion leading to high sediment loads in local rivers.

In 1934 the Taylor Grazing Act was passed 'to provide for the orderly use, improvements, and development of the range'. It regulated the use of the range, the issuance of permits, set allotment boundaries, specified improvements and set grazing fees. Allocation of grazing privileges was on the basis of commensurate property and prior use. Advisory boards which consisted largely of ranchers acted to preserve the *status quo*. Migrant sheep herders were eliminated and sheep numbers fell drastically.

Very little was done in range improvement between 1934 and 1962. Brush control was carried out on 12000 ha (0·1 per cent of the range). There was considerable attention to watering points, and some drift fences were constructed. A survey was carried out over 30 per cent of the area to determine carrying capacity, but adjudication to determine commensurate property qualifications had been completed for less than half the permit-holders.

In 1962 the Vale Rehabilitation Programme was proposed. The aims were:

- to check soil erosion and downstream deposition;
- to increase production of forage for livestock and wildlife;
- to stabilize the livestock industry at present or higher production;
- to control fire, by replacing cheatgrass and sagebrush by perennial grasses, and by improved supervision;
- to check the spread of noxious and poisonous weeds;
- to accomplish adjustments in land tenure;
- to safeguard the public lands against improper recreational use;
- to provide roads, especially in areas of untapped recreational potential.

The programme has a novel emphasis on wildlife, recreational facilities, and on catchment values. There was an immediate emphasis on land treatment, rather than exclusively on regional survey, and priority of choice of land for treatment was based on potential for improvement rather than on degree of deterioration.

The programme exceeded its goals in fencing and in the construction of reservoirs and pipelines, and achieved 65–70 per cent of its programme in brush control and seeding. About 10 per cent of the rangeland was treated by combinations of ploughing, spraying, firing and seeding, in projects of between a few hundred and several thousand hectares (200000 ha subjected to sagebrush control and 100000 ha to seeding).

The main objects in range rehabilitation were to reduce the area of brush and to establish perennial grasses and replace annual cheatgrass. Brush (*Artemisia* spp.) control was by disc ploughing or by aerial spraying, but advantage was also taken of wildfires, which kill off brush. Seeding of crested wheatgrass (*Agropyron* spp.) was carried out in ploughed, and in some sprayed, areas. Seed-bed preparation was more important than brush kill in successful grass establishment, however. The natural powers of recovery of native perennial bunch grasses, much in evidence after 1968, were underestimated, and some of the reseeding may not have been necessary.

Since 1973, with the completion of the Range Rehabilitation Programme, the objective has been to develop the improvements through the management of livestock grazing as follows.

Permitted stocking rates

Under the permit system established in 1934, the forage provided increased from 255000 AUM (animal unit months, based on cow-equivalents) in 1935 to a maximum of 515000 AUM in 1958. From this time the Bureau of Land Management began to assert control over livestock use. Surveys showed that some areas should require cuts of 50 per cent in permitted use, but the main aim of the Vale Programme was to avoid this by restoring forage production. Forage production was increased from an estimated 261000 AUM in 1962 to 419000 in 1972, when for the first time estimated forage production exceeded the licensed use, to 438000 in 1975. However, parts in the south remain under-used, and to match grazing use with available forage remains a major problem.

Grazing systems

Efforts to improve livestock management generally started with the elimination of season-long grazing. Repeated seasonal grazing or rotational seasonal grazing are the normal alternatives, and both have been successful in pasture improvement. However, it is recognized that systems suited to rehabilitation of range, including year-long rest, are not necessarily the best for well-established pastures. Mature bunch grass requires yearly grazing to promote vigorous growth and to reduce fire hazard. Repeated and rotational seasonal grazing should be maintained, but there is now also a place for year-long grazing, allowing the animal to graze selectively, eliminating crowding, disease and disturbance, and reducing labour costs.

Monitoring of grazing

Many livestock management plans require certification of compliance at the end of the season. Eartagging for the permitted number of animals was introduced in 1975.

An assessment of vegetational condition was made in 1975. In untreated areas there was a lack of correlation between the densities of brush and of desirable grass. Comparison with 1963–68 suggests a small but significant increase in perennial grasses, notably in the desirable bluebunch wheatgrass, and a decline in annual cheatgrass and forbs. Study of treated areas suggests that spray-and-seed treatments were more effective than plough-and-seed, in that they left desirable native grasses. All plots showed a return of brush, many of the shrubs having established from seed in the year following treatment.

However, this is not regarded as limiting the usefulness of the treatments as long as grasses are not eliminated by overgrazing.

At least 50 per cent of the range is now in good or excellent condition, and the trend in nearly all the district is stable or improving. Plant vigour is excellent and sheet erosion and pedestalling are minor. In seeded areas, crested wheatgrass is stable or increasing in density, and bluebunch wheatgrass is stable, for it appears to reproduce vegetatively and is stimulated by grazing. Relations between crested wheatgrass and cheatgrass require further research, for cheatgrass can play a useful role in providing fodder in poor seedings, and in giving ground cover.

The Vale Programme has been highly effective from a vegetational viewpoint. Former dense and nearly pure stands of sagebrush have been converted to grassland on about 8 per cent of the district, and the additional forage has given the opportunity for flexibility in grazing use and further improvement in untreated ranges. The district now produces excess forage that provides stability against drought, and needed cover and feed for wildlife.

The estimated grazing capacity of the district has been improved from 6·9 ha/AUM in 1962 to 4·2 ha/AUM in 1975. Range treatment is still needed in the north of the area, and it is estimated that 3·2 ha/AUM will be attained eventually.

Many wildlife species have benefited from the general improvement in native range condition; for example it led to the successful reintroduction of bighorn sheep in the area. The range treatments have benefited some, such as antelope and sage grouse; others such as mule deer have been relatively unaffected, while the large areas of grass may have discouraged jackrabbits. There is now a professional wildlife manager in the programme, and knowledge of wildlife requirements has improved. There remain within the district inaccessible areas such as canyon bluffs that constitute natural refuges for rare plant and animal species. More data are required on threatened or endangered species.

The programme nominated fifty-five tracts for recreational purposes, principally canyon and waterside sites for family camping, picnicking, hunter camping and scenic qualities, and about half of these have been completed. Other areas included archaeological sites, wilderness areas and nature preserves. Archaeological surveys now precede developments such as reservoir construction.

Lack of water of good quality limits agricultural and industrial development in the Vale district. The catchment properties of the rangelands are accordingly of the first importance, although run-off is estimated at only 133 million m^3 annually, and 75 per cent of the irrigation water must be supplied from the Snake River. With rangeland deterioration and erosion, sediment loads in the Malheur River system had attained 5000 ppm. Erosion control is a major aim of the programme: gullies are now healing with sagebrush and perennial grasses in their floors, while sheet erosion is minor.

Cost–benefit analysis of the programme poses difficulties in that only 10 per cent of the area was treated, while the remainder has benefited indirectly from management made possible by the availability of the treated areas. Forage removed is not the only criterion; for instance, managed grazing may increase subsequent forage production. Estimated costs of the programme to the Bureau of Land Management are U.S.$20 million, including U.S.$8 million for roads and recreational developments. Range improvement and maintenance costs, discounted to 1962, are estimated as U.S.$9·2 million, and the estimated value of increased forage is U.S.$8·6 million or U.S.$4·3 million, depending on whether the value of an AUM is taken as U.S.$3 or U.S.$1·5. The former gives a ratio of benefit to costs of 0·9.

Lessons learned

The programme has demonstrated the great importance of favourable public opinion and the need for effective publicity. At first, stockmen resented measures to regulate use of the range, and there was some doubt as to whether the Bureau of Land Management could carry the programme through, and concern about some technical measures, such as the seeding of crested wheatgrass, which were relatively unknown. The ranchers wanted greater emphasis on increased numbers of watering points. Early demonstrations of success in range treatment were an important factor in winning round the ranchers.

The programme has demonstrated the possibility of range improvement through rehabilitative treatment of selected sites combined with livestock management on untreated areas. It also exemplifies the possibility of maintaining such improvements through livestock management. The study emphasizes that the stage of rehabilitation of rangeland may require different management from that of maintaining rangeland in good condition. Whereas year-long and seasonal deferment may suit the establishment of pastures, repeated seasonal grazing systems and even year-long grazing may be needed to maintain the vigour of perennial grasses once condition has been restored.

The study draws attention to the possibilities of using fire as a management tool in range improvement. Wildfires seem to be as effective as the more expensive forms of land treatment in increasing forage production, and expenditure on fire suppression may be unwarranted. There is a need to manage forage and fuel as an integrated system.

The programme has demonstrated that rehabilitation of 10 per cent of the range can result in rapid improvement of untreated areas through the opportunities given for improved grazing management. Untreated areas must therefore be included in the programme. Priorities in rangeland improvement should be based on their potential for increased production rather than on their present degree of degradation.

Improvements such as fences, gates and watering points should be sited in accord with management needs, and not merely on the basis of engineering convenience.

There is a need for improved methods of determining range condition and trend. These should be applicable to large managerial units, should provide accurate and pertinent data, and should be usable by non-research personnel.

The study demonstrates the possibility of combining the grazing of domestic animals with successful wildlife management, by improving vegetational habitats through the grazing system so as to increase cover and feed for wildlife. Nevertheless, there is a need for more information on wildlife populations, on the ideal habitats for the various wildlife species, and on how these may be brought about through land management. More knowledge is also needed on the impact of various land treatments on wildlife species.

The study exemplifies the growing importance of multiple land use in rangelands, and the increasing pressure from wildlife and recreational interests. It demonstrates that these uses can generally be reconciled, but that there is need for education to obtain acceptance of this principle among users, and for greater responsibility, particularly by visitors. Programmes of rangeland improvement should recognize the need to integrate the various land uses, and should secure the participation of various interests on advisory committees. The case study demonstrates the need for publicity, education and demonstration tours to gain public support and community participation in land-improvement schemes.

8 Conclusions from the case studies

Introduction

The varied evidence of the case studies demonstrates that many parts of the world's drylands have experienced, and are continuing to undergo, changes towards more desertic conditions, whereby the productivity of natural or managed ecosystems is lowered, with adverse effects on the livelihood of their human populations. Many of the changes can be traced over centuries, but often there has been a noticeable acceleration of desertification in recent decades, at times associated with human tragedy. The extent of the problem, the aspects common to many areas, the different experiences in combating desertification revealed in the case studies, and the interdependence of world communities in and outside the drylands, quite apart from moral obligations, justify the call for international co-operation in countering desertification.

Despite differences in the human and natural environments depicted, the case studies afford some useful general conclusions on the nature of desertification. Environmental and human factors can generally be distinguished, but the two are generally inseparable through linked cause and effect, an important point in the design of combative measures. Contributory causes can be roughly identified with three overlapping and interacting phenomena: a limiting, rigorous and uncertain climate; biophysical systems that are subject to alternating stress and abundance through the vagaries of climate and at the same time to pressures of exploitation by man; and the human populations of the drylands, with their quest for food and shelter, their conflicts between and within livelihood and cultural systems, and their subjection to internal pressures of growth, movement and change as well as to external economic, social and political forces.

Climate and desertification

The case studies yield no evidence of a general secular decline in rainfall as a cause of desertification, but many of them indicate the importance of drought or of long periods of below-average rainfall, as in India and in the Sahel zone of the Republic of Niger. The decisiveness of a particular climatic fluctuation may not be measured simply by its duration or magnitude in physical terms, but by its interaction with biophysical and human livelihood systems, and accordingly on the status and resilience of those systems at the time of crisis. In this respect, each climatic event and each region is in some degree unique with regard to desertification.

Droughts are seen to be periods of stress which may reduce managed ecosystems to lower planes of productivity, and under land-use pressure their impact may extend over periods which far outlast the triggering climatic event. For this reason, forecasts of dryland production based on past performances are suspect as a basis for development. Sometimes drought brings complete social collapse, as among pastoralists in northern Niger after 1973.

The critical importance of periods of above-average rainfall is also demonstrated in the case studies. Where these extend over several years they may result in an extension of cultivation into areas of high climatic risk or on to marginal and vulnerable lands, such that livelihood systems are precariously balanced and vulnerable to ensuing drought. In this way both phases of the rainfall cycle contribute to desertification, as shown in the Sahel. The period of higher rainfall after a drought is a vital time of recovery for impoverished desert ecosystems and a time for lightened environmental pressure and careful management to allow regeneration, not for an immediate resumption of full exploitation.

It is the fluctuations of desert rainfall that determine alternate surplus and scarcity in the drylands, and with them the main problem facing management for sustained productivity. The case studies collectively, including the Israel case study which describes experiments with cloud seeding, contain no general promise that modification of climate by man or the seasonal prediction of rainfall will play an important part in combating desertification in the near future. However, they do demonstrate that existing records make it possible to calculate the probability of receiving rainfall of a given effectiveness. This affords a better basis for the estimate of climatic risk and potential in planning than optimism based on a recollection of the last exceptionally wet season. It can also assist estimates of the need for fodder reserves, drought insurance, and emergency relief organizations.

The emphasis on effective rainfall is important. Dryland productivity depends on plant growth and on the balance between water available from the soil and water losses above and below ground. Man can change this balance adversely, as in southern Tunisia where accelerated soil erosion has been estimated as equivalent to a loss of 5 mm of available soil water. Such changes probably far outweigh those induced indirectly through changed surface albedo or dust in the atmosphere. On the credit side is man's amelioration of local climate, as in the cases of Turkmenistan and the Golodnaya Steppe, where drying winds have been checked and the atmosphere over irrigated surfaces rendered less parching.

Desertification in dryland pastoral systems

Several case studies consider desertification in relation to extensive livestock rearing in arid lands, ranging from traditional subsistence economies in Niger to commercial ventures linked with external markets, as in the United States and Australia. All place stress on the native vegetation as the fundamental resource and on the need to conserve it, but most tell a story of animal husbandry at the expense of the pastures. The studies show a common history of degradation, with increasing erosion by wind and water following destruction of the perennial vegetation and trampling of the surface. Failure of perennial plants to regenerate under grazing, and increasing dependence on annual pastures, leads to marked fluctuations in carrying capacity between drier and wetter seasons, as reflected in pasture condition and stock-carrying capacities.

The case studies of desert pasture lands are particularly valuable for providing evidence of the onset of desertification. They show that its advance is piecemeal and not linear, reflecting inequalities of land-use pressure and local differences in the inherent vulnerability of the drylands. In this way they demonstrate that the extension of desert conditions is attained mainly through degradation of land that has previously enjoyed a higher status, including land that has formerly been regarded as lying outside the desert. The insidiousness of the desertification process resides in this fact, and recognition of the nature of its dynamics must affect estimates of where the threat is greatest and where the efforts to counter it should be concentrated.

Several case studies demonstrate the critical importance of occasional periods of effective rainfall for the maintenance of the important perennial pasture components in rangelands. Settings as varied as Niger and western Australia indicate that pastoralists are much too concerned with dry periods and the provision of watering points to tide livestock over drought, and insufficiently concerned with systems of deferred grazing to allow the regeneration and reseeding of perennial edible shrubs after rain. In effect, most livestock losses have resulted from starvation due to destruction of pastures, rather than from thirst.

In some pastoral settings improvement of rangelands is feasible through the planting and seeding of native forage species, as in India, Iran and the U.S.S.R., but where labour costs are high in relation to returns, as in Australia, the only measure available to the grazier is ecological rangeland mangement, that incorporates the maintenance of stocking rates consistent with fodder resources, employing rotational grazing supported by sufficient watering points to equalize pressure, and deferring grazing to allow the recovery of perennial species after the occasional effective rains. Even in advanced technologies, more research is called for into the productivity, phenology and grazing performance of native pastures to support such management. Where rangeland pastures are under control and where pastures are fenced and adequately watered, as in Australia and the United States, their management poses few problems. However, in many of the countries studied, pastures are owned communally while rights to water and livestock are under private ownership, and here considerable reform is indicated, involving methods of control compatible with the use of pastures by family and larger social groups.

Where ecological management is the main approach to the improvement of degraded rangelands it must be accepted that the process will be slow and gradual. Several case studies agree in pointing out that the least-degraded rangelands should be the first to come under such treatment. Management measures must be adapted to the existing systems of range ownership or use, and will have to be diffuse rather than intensive where rangelands are used collectively, with emphasis on production per livestock unit rather than per hectare.

Several case studies indicate the need for grazing strategies to cope with the fluctuating production of semi-desert rangelands. Possibilities include the complementary use of rangelands, as between wet- and dry-season pastures in Niger, or between oasis feed crops and adjoining steppes in Tunisia. Other proposals, as from the Sahel zone, suggest a commercial linkage between livestock breeders in the drier parts and those concerned with fattening of stock for nearby markets in wetter areas. Other possible stabilizing measures include the establishment of drought rangeland reserves and fodder banks, and the provision of supplementary feed concentrates, including agricultural by-products. Several proposals stress the need for the maintenance of a migratory pastoral element for the flexible use of rangelands, despite the widespread and apparently irreversible tendency for the sedentarization of nomads, through support for modern systems of transhumance, as practised in Turkmenistan, compatible with the provision of modern social and technological services.

The concept of an optimum stocking rate presents difficulties where the productivity of pastures fluctuates so markedly between seasons and where it would generally not be economic to stock at rates set by the driest years. Many of the studies illustrate the inherent difficulty of reducing stock numbers, at the onset of drought, from levels attained in foregoing wetter years, and the social and economic forces that hinder this. However, stocking rates on desert pastures must generally be low, as revealed by assessments in these studies which range from 3·6 to more than 50 ha per sheep. In most studies a lowering of grazing pressure is called for, particularly in critical regeneration periods. Nevertheless, as pointed out in the Iran and Niger studies, it is inconceivable that measures proposed to combat desertification should undermine the only livelihood, and to this extent blanket recommendations for reduction in stock numbers without compensatory measures may be unacceptable.

In the Australian study area a redeployment of livestock over available pastures would suffice, and in Turkmenistan and Niger a better network of managed watering points would bring into fuller use pastures that are commonly inaccessible. The Indian study stresses the importance of improved quality and productivity of livestock to offset smaller numbers. Where the grazing animals are seen as the main resource and the essential means of response to good seasons, proposals for de-stocking must be linked with alternative strategies. The introduction of a stronger commercial element into traditional pastoral systems, through linkage with land-use systems and markets outside the arid zone, is proposed in the Niger study. The Australian and United States case studies depict the advantage of leasing pastures under government control (e.g. the Bureau of Land Management, U.S.A.) thus providing a legal basis for inducing better management of pastures. There is general agreement on the ultimate aim, namely optimum sustained production consistent with the conservation of the pasture resource.

Problems arising from the introduction of permanent central water points into traditional pastoral systems are exemplified by the Niger case study, where this led to an imbalance between numbers of stock watered and the carrying capacity of adjacent rangelands, and to localized desertification through the heavy concentration of stock around water points through long drought periods. In Niger particularly, the improvement of existing seasonal water supplies might well have fostered a more extensive and balanced exploitation of the pastures.

Several case studies point to the steady encroachment of arable farming into rangelands, particularly during periods of above-average rainfall, as for example in Rajasthan (India), Tunisia and Niger. This has contributed to high stocking rates on the remaining available pastures. Much of this movement, which has been linked with and facilitated by the mechanization of agriculture, must be seen as inevitable and irreversible, given the higher economic returns and greater food production from farming. In marginal climates and on unsuitable terrain however, dryland agriculture may introduce undue social and economic risks and lead to extreme environmental degradation, and in these areas existing pastoral systems should be supported by subsidies and if necessary by protective legislation.

Desertification in dryland cropping systems

Although the area under rain-fed crops in drylands is much less than that used by pastoralists, the population supported by farming is far greater, and with it the human consequences of desertification. Several case studies illustrate the inexorable extension of cropland in the last decades, because of its promise of higher returns, the pressure of population growth or external economic forces. As with pastoral systems, preceding runs of wetter years may have contributed to an unbalanced development revealed in drought disaster, as indicated in the Niger case study.

The case studies present a common picture of desertification in many dryland cropping regions, notably where arable farming has extended into excessively drought-prone areas or on erodible soils or terrain. Degradational processes include deterioration of the structure of topsoils through overcropping and loss of organic matter, compounded by consequent accelerated wind and water erosion. As the top few centimetres of dryland soils contain the most significant concentration of nutrients, accelerated erosion results in a sharp decline in crop yields. The soil-moisture reserve is critically diminished through enhanced run-off where soil crusting occurs, or with the exposure of relatively impervious subsoil. A major form of erosion is wind-drifting of light sandy soils, which are otherwise suited to dryland cropping, as in the Indian and Tunisian areas, resulting in the growth of fence-line hummocks and of coppice dunes, and consequent reduction in the area of potential cropland. Severe gullying of footslopes has had similar consequences in certain of the case-study areas.

Many dryland farming practices designed to conserve moisture, such as clean fallowing, incidentally increase vulnerability to erosion by wind and water. The sequence of impoverishment can be rapid. Much of the remedy lies in removing marginal land from cultivation and in the introduction of improved farming practices, such as the planting of leguminous crops in cereal rotations, strip cropping, and contour ploughing and furrowing, as suggested in the Tunisian study. However, such improvements may be thwarted by conditions of land tenure, as in the communal settlements of the Chilean study, where fragmentation and uneconomic subdivision of holdings have occurred, or by inability to purchase fertilizers, through poverty, as in India. Clearly the solutions are not only technological, but also involve social and economic reform, and assistance to farming communities through co-operative management, marketing and purchasing arrangements as shown in the Israel case study.

Several studies, notably those from India and Tunisia, demonstrate the importance of supplementing limited soil-water wherever possible, through additional irrigation, water-harvesting from small catchment areas, contour furrowing, and the use of subsoil barriers in highly pervious soils.

Some technological innovations in dryland farming appear to have had harmful consequences and to have intensified desertification. The recent spread of arable farming in the drylands has been facilitated by the mechanization of agriculture, which must be seen as inevitable and generally advantageous, particularly in India where preparation of land in the critical period at the onset of the monsoonal rains is facilitated by tractor ploughing. Nevertheless, the introduction of the heavy steel plough in place of the lighter wooden plough has been blamed for the comminution and erosion of dryland soils in this area, and illustrates the need for careful adaptation of technology to local conditions of land use. There is a general need for the design of cheap agricultural implements suitable for light tillage, to reduce soil disturbance and consequent erosion in traditional cropping systems. As suggested by the Negev study, deep ploughing and intensive cultivation brings little advantage in terms of crop yields under these conditions.

The low response of dryland crop yields to inputs such as fertilizers and labour is exemplified by the Indian and Israel case studies. In some cases this may be an argument for improving facilities for long-term credit, to allow the dryland farmer to compensate for high environmental risk; elsewhere it suggests that economies of scale may be critical, as allowed by mechanization, and supports the case for changes in land tenure where this has prevented the necessary amalgamation of holdings. Experience from the Negev suggests that scope for technological and other improvements in dry farming will be greater in the semi-arid areas. In regions receiving as little as 150 mm annual rainfall, the traditional crop–fallow systems are likely to remain the most efficient, and improvements must be sought within this framework, through the selection of quicker-maturing and drought-resistant varieties, by planting alternative crops when seasonal rains are delayed, as in India, and through measures to reduce wind and water erosion and conserve soil moisture, such as strip cropping and contour furrowing.

Post-harvest losses of grain crops are serious in many of the study areas. The planning and implementation of rodent-control measures and supportive research are well exemplified in the Indian case study, and the education of the farmer in the use of chemical treatments to prevent losses through fungal and insect attack should be given high priority.

The Tunisian study shows how climatic risk can be estimated in terms of the probability of receiving effective rainfall for crop production. This suggests a strategic means of delimiting potentially 'safe' arable areas in the plans for land use that are indicated in most of the studies. The need for spreading out the risks also calls for a closer linkage of dryland cultivation with neighbouring animal-based systems, through the growing of forage crops, the grazing of stubble and fallow, and the use of animal manures, such as existed traditionally in Niger before the recent drought. As shown in several studies, the collapse of crop-based systems tends to contribute to the failure of pastoral systems in the same region.

Irrigation and desertification

The case studies provide abundant evidence of the widespread occurrence of soil salinization in irrigated areas, with subsequent loss of productivity. This is due to evaporation and capillary action from raised water-tables and the presence of increasingly saline shallow ground water through inadequate drainage, the introduction of salts from irrigation waters, inadequate provision of water for the leaching of accumulated salts from root zones, inefficient application of irrigation water, inadequate preparation of irrigated lands, and the employment of inappropriate cropping systems.

The case studies from China and the U.S.S.R. show that integrated regional development based on irrigation can effectively counteract desertification, checking physical degradation, raising productivity, and supporting a larger population with improved living standards by relieving the chief factor limiting life in arid lands, namely water shortage. As pointed out in the Turkmenistan study, this makes it possible to tap the natural advantages which might otherwise remain unused, such as sunshine, warmth and soil fertility. In the Golodnaya Steppe, more than 90 per cent of all production and 95 per cent of rural employment now stem directly from irrigation. Irrigation can also play a part in sustaining other elements of a dryland economy, for example in supporting livestock-raising in Tunisia and Turkmenistan. The availability of surplus water, including tail-water from irrigation, can be an important factor in the success of measures to combat desertification, as in the revegetation of sand dunes, the provision of tree shelter belts, and the agricultural reclamation of *gobi* surfaces in the Chinese study of the Turfan oasis.

The case studies confirm that the reclamation of waterlogged and salt-affected soils is generally feasible, given adequate drainage and leaching and appropriate cropping systems. However, the problems of soil fertility for the optimum growth of a variety of crops must still be solved after the process of reclamation is completed. There is a general need to optimize the balance of all agricultural inputs if maximum productivity is to be obtained.

Large investments in hydrotechnical projects can pay off only where they are supported by other appropriate inputs, including technology and skills in management and application, and form part of integrated regional development. This is exemplified by the U.S.S.R. case studies. Lack of such supports has certainly contributed to problems described in the Iraq and Pakistan case studies. The physical and socio-economic conditions that have contributed to success should also be borne in mind, however, lest it be concluded that irrigation is an ever-available and unfailing remedy for desertification. These include the existence, in the U.S.S.R. case studies, of uplands with snow-fed water resources adjacent to desert basins. The successes in the U.S.S.R. are the outcome of developments over two generations, and the harnessing of water resources under different physical and socio-economic conditions—as in the African Sahel—may take a comparable time.

The case studies of irrigated farming illustrate the importance of an understanding of the regional water and salinity regimes and of the local water needs of crops as determined by climate and soils. In both the Pakistan and Iraq case-study areas these investigations were carried out only as part of large-scale rehabilitation schemes after problems of waterlogging and salinization had become severe, but they are in fact fundamental to the successful design and operation of irrigation schemes from the outset, and particularly for the provision of adequate drainage systems.

The Pakistan and Iraq case studies identify several factors essential for the successful operation of irrigation schemes, including the design of irrigation and drainage systems, control of irrigation schedules and water application, and appropriate land subdivision and preparation.

The U.S.S.R. studies are helpful in presenting the environmental consequences of the introduction of irrigation as expressions, both adverse and beneficial, of a dynamic complex, which call for constant readjustment. For example they have had to overcome sand drifting caused by canal construction, and soil salinization where drainage proved inadequate. This emphasizes the importance of constant monitoring and continuing research during the operation of irrigation schemes in order to observe changes in ground-water patterns and quality, the functioning of tube-wells where these are installed, changes in crop productivity, and indicators of social and economic well-being. The Pakistan case study in particular stresses the need for long-term data and the importance of continuing research into all aspects of irrigation management. This emphasis on monitoring is a valuable lesson for all concerned with the management of dryland livelihood systems in the face of desertification, although the more fundamental transformation of the environment under irrigation makes it particularly relevant in that particular country.

Several case studies point to the importance of pilot irrigation projects as a means of adapting general principles to particular regional environments. These act as a preliminary test-operating phase before costly irrigation developments are undertaken, as sites for monitoring changes resulting from the operation of the scheme, and subsequently serve as demonstration projects to assist extension services to ensure the application of appropriate technology by land users.

In many areas subject to irrigation, as exemplified in the case studies, there is an important need to introduce methods of irrigation suited to the use of marginally saline water, to select and develop salt-tolerant crops, and to study the effect of salinity on crop yields. The Indian experience also points to the importance of selective and partial irrigation in areas of scarce water resources, through the identification of critical periods of water stress and the development of techniques for increasing production through the partial irrigation of larger areas, instead of intensive irrigation aimed at higher yields from smaller cropped areas.

Irrigation supports the most intensive production and densest settlement pattern within arid regions and commonly involves a fundamental transformation of the way of life of human populations. All the case studies indicate that the consequent social problems are likely to prove more intractable than the purely physical problems. This calls for the highest level of support through farmer-training and the promotion of social services. Many studies agree on the need for more adequate training and extension schemes, for assistance to farmers through co-operative purchasing and marketing arrangements, and for adequate social services to irrigation settlements, including water supplies, sanitation and health, housing, schools and civic amenities. In many cases there is need for a more diversified economic base in irrigated areas with ancillary agricultural projects and agriculture-based industries to counter potential unemployment.

Desertification and man

General reviews of the problem of desertification tend to emphasize its physical environmental aspects, perhaps because generalizations are most readily made in that sector. However, it is mainly the demographic, social, political and economic aspects that convey uniqueness; the case studies are particularly valuable in presenting these parameters. They also demonstrate clearly the indivisibility of the physical and social factors in desertification, and the need to reconcile environmental and socio-economic considerations in combative measures. In many cases it is suggested that the human factors in desertification may well prove to be more intractable in the long term. Several studies refer to traditional strategies for coping with the constraints and uncertainties imposed by the desert environment. Most involve spreading out the risks, by a low intensity of land use, mobility and flexibility, using a wide resource base and by social interdependence. At the same time the consensus from the studies must be that desertification is largely man-made, and that man in the drylands has not been the passive victim of adverse environmental deterioration. The search for causes is complicated by our ignorance concerning the degree of disturbance of dryland ecosystems under human land use that is consistent with sustained productivity, and by the background of climatic fluctuations that hinders comparisons in the long term. The case studies do however indicate that the rate of environmental degradation in the drylands, defined as desertification, has quickened over recent decades, and with it the vulnerability of their populations. This calls for urgent analysis of the human factors.

Some of the causes of environmental instability undoubtedly lie within the dryland societies themselves, notably population growth as a determinant of increasing pressure on the environment. In several areas, notably those of the Indian and Chilean studies, the present population structure suggests that the rates of population increase, reflective of diminished mortality in societies where high birth rates contributed towards survival, will continue for some decades. Pressure of numbers on resources has generally been reinforced by rising expectations in living standards, and by increasing technological means of attaining these in the short term. It is directly shown in increases in the area of arable lands and in livestock numbers, and in the removal of trees and shrubs from uplands and desert plains to meet an increasing demand for fuel and timber.

In some cases problems have arisen from growing competition between livelihood systems for scarce resources, notably between farmers and herders as in Niger, Tunisia and Israel. Disharmony may have arisen from the internal social pressures already described, or from external pulls such as those of markets outside the area with the growing commercialization of dryland livelihood systems. There may also have been a breakdown of the social and political frameworks which sustained earlier relationships, as between farmers and nomads in the Sahel zone of Niger. The Tunisian case study, with its recommendation supporting the livestock industry against the encroachment of arable farming, indicates the need to restore these balances in many regions.

Several studies discuss problems of nomadic societies under desertification and present a picture of the progressive decline of nomadism and increasing sedentarization, whether as part of planned social reconstruction as in Turkmenistan or as an aftermath of drought disaster as in Niger. Nomadism is shown to be a successful traditional adaptation to desert conditions, but it poses problems related to the provision of modern social services such as health and education. On a small scale in Rajasthan it is an obstacle to the rational management of pastures, in Tunisia it is the victim of farming encroachment, while in Niger it is undergoing important voluntary changes following virtual collapse in the recent major drought. The case of nomadism exemplifies the general problem, implicit in most of the studies, of reconciling the need for change with respect for existing social systems.

Measures to combat desertification should attack the urgent social and economic problems facing populations in the study areas. In particular, they should bring about a significant increase in incomes, create employment and lead to increased productivity. In most areas there is an urgent need for the widening and diversification of the economic base and for the provision of alternative means of livelihood, for example through the development of agriculture-based and craft-based industries, and through mining and tourism. Investment in the interest of gradual social developments, in contrast to shorter-term technological measures, may bring few immediate returns, and it is suggested that part of the revenues from mining and similar developments should be reinvested in the interest of longer-term social and economic improvement, particularly towards the rehabilitation and further development of renewable resources with the ultimate objective of higher and sustained productivity. Ideally, measures to combat desertification should be part of country-wide plans for long-term development.

A feature of most dryland communities is a high level of out-migration among the work force. Resulting social stresses are exemplified in the Chilean case study, but generally, as emphasized in the Iranian and Israel studies, out-migration should be viewed as a rational means of supplementing local resources. While measures may be needed to prevent the devitalization of dryland communities through excessive migration, the migrants should not be regarded as refugees defeated by the desert, but should be assisted in their accommodation and effective integration at the receiving centres.

Most case studies stress the importance of participation by the communities affected in formulating and carrying out measures to combat desertification. To this end there is a need to determine how desertification is perceived by people in the areas concerned, and how it is seen to threaten their values and objectives. Mass-education programmes are called for in many areas to acquaint local populations with the nature, causes and long-term consequences of desertification, and to ensure an understanding co-operation in carrying out control programmes.

Experience from the case studies suggests that the recommendations most likely to be adopted and carried through are those that respect existing sound practices and knowledge based on indigenous experience. Extreme measures are in any case inadvisable in what are generally seen as sensitive and fragile environments, in a human as well as a physical sense. In many traditional communities technological and social innovations will be opposed by custom and by social barriers—the Indian case study for example mentions caste and religious barriers—and change will necessarily be gradual, as education and demonstration programmes overcome problems of illiteracy and prejudice. In other areas, such as Chile, fundamental problems of land tenure must be surmounted before proposed agricultural improvements become feasible. As with the physical environment, the progress of social and economic programmes to combat desertification must be monitored, and there is a need to establish critical indicators for this purpose.

Several case studies point to the adverse environmental impacts of human settlements as factors in desertification, and to the need for improved design of housing and settlements to reduce that impact, and also to reduce the stress imposed on the inhabitants by the desert climate. In several resettlement schemes, in irrigation areas and in sedentarization projects, the need for housing designs to be culturally acceptable has been clearly demonstrated.

The need for alternative energy sources for dryland communities is apparent from several of the studies. In Niger, Tunisia and India for example, they are needed to reduce pressure on woody vegetation as the main source of fuel for cooking and heating. In Tunisia and Iran, as in other Arab countries, the increasing use of oil for heating has already relieved the pressure of fuel-gathering from rangelands. In the Negev, solar energy is being harnessed both on a domestic scale and as a source of power in large desalination plants, while in India the use of solar energy for cooking remains in the pioneer stage and warrants support by promotional and educational programmes, together with measures to foster the wider use of biogas. Cheap electric power is essential to reduce pumping costs and to promote the exploitation of ground water for small-scale irrigation in the Indian case-study area. In many areas, however, fuel wood will remain the most economical source of power in the foreseeable future, and there is a need for afforestation programmes and managed wood lots, which link directly with measures for fixing sand dunes and preventing the drifting of sandy soils. Considerable progress has already been made with the selection of suitable tree species and methods of establishment and sand stabilization. The main outstanding problems, apart from the financial ones, are the social difficulties involved in the communal management of wood lots and the enforcement of conservational practices.

Relief measures will continue to be necessary at times of stress, but should wherever possible be combined with programmes for longer-term development. In India for example, current expenditure on famine relief in the arid and semi-arid areas commonly exceeds investment in development. Many relief programmes have an undue emphasis on the wage components, leaving inadequate amounts for related capital investments, and so restricting the productivity of the programmes. Advantage must be taken of crisis conditions, as in the post-drought period in Niger, to set in progress desired long-term social and economic changes. Some studies mention a danger that relief and drought insurance may be used to bolster environmentally unsound systems of land use, and so hinder the achievement of the necessary diversity and flexibility of dryland livelihood systems, as a measure against inevitable environmental risks.

The case studies confirm the fact that dryland communities are generally disadvantaged relative to those outside the drylands, and that within the drylands the rural, more remote and nomadic elements are disadvantaged relative to the settled and urban communities. The drylands are not only rigorous and high-risk environments, they also tend to be geographically remote from centres of government and administration and from sources of capital and technology, and consequently to suffer from lack of political and economic influence. The Tunisian and Iranian case studies call for closer economic integration of livelihood systems, in and outside the arid portions of the countries, as a means of increasing stability through interdependence. They stress that the desert margins are equally part of the national patrimony and hence of its responsibility, and ask that national programmes to counter desertification should seek to redress economic, cultural and political discrimination wherever these exist. On a world scale, the combined evidence of the case studies can leave no doubt that the same holds true for the international community.