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HYDROLOGICAL AND WATER RESOURCES IMPACT OF CLIMATE CHANGE

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F I R S T D R A F T

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1. PURPOSE OF THE STUDY

The purpose of this study is to make a contribution to the UNEP Study of the Implications of Climate Changes in the Mediterranean, at the request of the Intergovernmental Oceanographic Commission at Unesco, Paris. This contribution will deal with the impact of the expected climate change on hydrology and water resources. What thereby is referred to, is the concern over changes in global climate caused by rising atmospheric concentrations of carbon dioxide and other trace gases, which has increased in recent years. Our understanding of the consequences of such a change in the atmospheric concentration is today rather restrained. However, it might be expected that the regional impact of climate change on water resources may be quite serious. Since water is of paramount importance for both societal and ecological needs, there exists an urgent demand for a much more qualified knowledge of the interaction between climate change and the hydrologic cycle processes. This task is still more pressing in view of the fact that in many areas of the world water availability is only marginally adequate to meet basic human needs. Water plays an important role in societal development in the respect that it is needed for drinking purposes, but is also a necessary condition for the development of agriculture and industry. Some of the countries around the Mediterranean are already badly off, such as, for instance, Libya and Tunisia (Hinrichsen, 1986). Also world-wide occurrence of droughts, which may have been influenced by the severe El Nino event of 1982-1983, with repercussions also in the area just mentioned, has to be kept in mind when

discussing the effects on water resources due to global changes (UNEP 1987). Thus, global changes may be expected to alter precipitation patterns affecting the duration and severity of water shortages. Another consequence of the global changes - to be dealt with in the following text - is the sea level rise which may do much harm to society, in particular to communities on low-lying land.

The following report will be presented in two parts. The first one will deal with the general aspects of global change consequences for the development of the water resources sector. The second part will - with the background material presented in the first part - evaluate the effects expected in the Mediterranean area.

2. THE GLOBAL CHANGE - A RECAPITULATION

In order to give a background to the present study on some implications of the global change, very condensed information about that phenomenon will be presented below.

Dating back to the dawn of the industrial era, the concentration of several atmospheric radiatively active gases has been increasing. This radiative heating, having thus lasted at least one hundred years, has driven the atmospheric system out of equilibrium with the incoming solar energy (Kellog 1987; Titus and Seidel 1986; Unesco 1986). A new equilibrium of the climate system will be reached through warming of the surface-tropospheric system in combination with a cooling of the stratosphere. One consequence of the enhanced trapping of infrared radiation, as a result of the increase in the concentration of such gases as H_2O, CO_2 and O_3, is a much more rigorous climate system causing among other things a more intense hydrologic cycle. However, because of a nonlinear interaction

between the atmosphere, the cryosphere, the oceans and the land, the predicted surface warming is not uniform. It may vary significantly with latitude, longitude, altitude and season (Ramanathan, 1988). One striking example of this may be the observation that even if most parts of the world are becoming warmer during the 1970s and 1980s, there are some countries which do not follow this pattern. Thus, there is a newly discovered cooling trend over a large part of Europe. In Scandinavia, for instance, mean temperatures seem to have fallen by about 0.6°C when the northern hemisphere as a whole rose by 0.31°C (Gribbin, 1988).

It has just been mentioned that recent observations of climate changes refer to a period starting at the dawn of the industrial era. However, it has in fact been observed, through an investigation of the Antarctic ice core, that there is a remarkably close association between the climate and CO_2 records over the last glacial-interglacial cycle, which means about 160.000 years (Lorius et al 1988). As a supplement to this information, it could also be said that it is now quite evident that gases other than CO_2 have significantly contributed to modifications of the climate during the period just indicated.

The climate changes now referred to are closely related to the concept of a greenhouse theory, which also has necessitated a more concise verification. One fundamental problem seems to be the difficulty in studying a phenomenon that is characterized by a continuous increase of CO_2. Many model approaches performed up to now have considered a fixed increase in CO_2 instead of dealing with a transient response problem (Schneider and Thompson 1981, Barnett, 1987). This reveals that one essential task is to identify the CO_2-induced climatic "signal" relative to the background "noise" of inherent climatic variability. The transient response is then governed by a series of processes such as the time-dependent nature of the forcing and also by the heat

capacity of various thermal reservoirs - like the oceans- included in the climatic system. Moreover, a variety of thermal damping, radiative and dynamic mechanisms are involved in the response.

Anyhow, an estimation of the effects of anthropogenic increase in the atmospheric concentration of trace gases "the large-scale geophysical experiment" makes it necessary to keep to some fixed values of the temperature. Without the greenhouse effect the earth would be approximately 33°C colder than it is currently (Hansen et al 1984). It is, however, now expected that the greenhouse gases, especially CO_2, will lead to an increase in warming of between 1,5°C and 4,5°C, during the next century. These figures originate from model analyses, supposing a doubling of the atmospheric CO_2 content.

Such a global rise in the temperature - of only a few degrees- is expected to produce a series of effects in the future. For the present study, the global sea level rise is one of the most important consequences. There has not been complete consensus about the magnitude of the sea level rise, a fact that to some extent may be ascribed to the uncertainties about the order of temperature rise. Another difficulty in making prognoses of the sea level rise has to do with the fact that these prognoses may originate from evaluation of a global model, that has to account for all the important interacting elements that constitute the model. Such a model may include, for instance, the atmosphere, the oceans, the land, the glaciers in Greenland and Antarctica. In Figure 1 is shown, very schematically how such elements may interact. In particular, for a correct understanding of the sea level rise, the processes governing the thermal expansion of the sea water associated with the global warming, must be represented in an adequate manner. A concise approach to this problem would be to set up a model that could depict the three-dimensional details of oceanic temperature changes (Wigley and Raper, 1987).

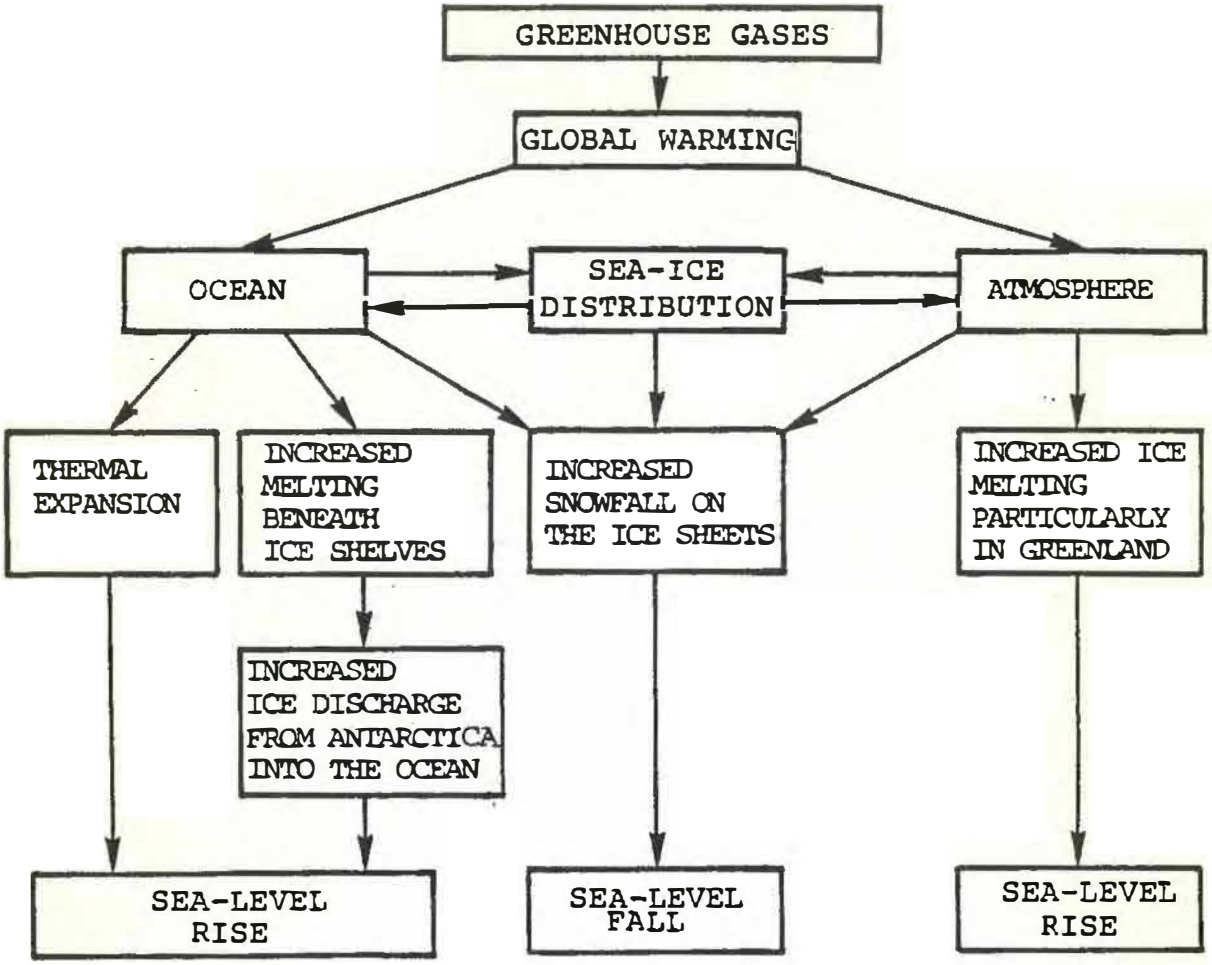


Figure 1. Effects of greenhouse gases on sea level

However, this is today not possible, mainly because of our insufficient knowledge about variations through recent decades of such parameters as temperature and other physical properties. Simple models have been set up, models that may give reasonable results because it may be expected that the main contribution of the thermal expansion of the ocean may occur at the near-surface layer.

Many scientists who have worked with the effect of ocean heat capacity upon time-dependent global warming have observed that the calculations indicate that the ocean heat capacity will produce a lag in CO_2-induced global warming of about two decades (Cess and Goldenberg, 1981). The scientists mentioned made a study of information about CO_2 content in the atmosphere between 1860 and 2025 as expected from carbon-cycle models. They found that without inclusion of the ocean heat, their models predicted that an increase in global surface temperature of 1°C, relative to 1860, will occur in 1988. However, if the ocean heat capacity is included in their model calculations, the just observed temperature increase of 1°C will be delayed until the period 2006-2012. In addition, they found that when the CO_2 content in the atmosphere is twice that of 1860, that is in 2025, the model seems to predict a global warming of 1,5°C to 1,8°C, which has to be compared to the temperature increase 3,1°C, expected to occur when the heat capacity of the ocean is neglected.

A similar study to the one mentioned was performed by Bryan and Spelman (1985). In a numerical experiment they tested the interactive behaviour of atmosphere and oceans. They found from their model that a four-fold increase in atmospheric CO_2 causes a warming sufficiently intense to produce partial collapse of the ocean's thermocline. However, in spite of this incidence the wind-driven circulation of the ocean seemed to be maintained and equally interesting was the observation that though the hydrologic processes increase in intensity there was no indication of an increased precipitation of the model ocean. Their calculations also show that the thermocline was able to sequester twice as much as normally expected. The conclusion drawn from this is a negative feedback for greenhouse warming. The scientists also discuss what possible effect this observation may have on the global carbon cycle.

Among other scientists dealing with the response of the heat capacity of the ocean, the studies by Hoffert, Callegori and Hsieh (1980)should be mentioned. They tried to apply a more realistic carbon-dioxide growth, time-depending forcing function based on historical data. The present results seem to indicate that the influence of the deep sea thermal storage could delay the full value of temperature increment about 10 to 20 years within the period 1980 to 2000, as compared to the outcome of the assumption of an equilibrium model.

Finally, let me mention the study by Henderson-Sellers (1987) where the author warns against the over-simplified model approaches of the interaction between the atmosphere and the oceans. He recommends the inclusion of a convective capability to the water column. During this, on a timescale of a century, the temperature of the surface may possibly increase by less than a factor three of earlier forecasts.

There exists, however, other difficulties that seem to play an important role in trying to calculate the exchange processes between the atmosphere and the ocean. Thus, the changes in sea-ice distribution, rainfall, winds and temperatures, as well as freshwater inflow, may each influence the density structure and the mixing rate in the upper layer of the ocean. Anyhow, Wigley and Raper (1987) made a contribution to this problem and found that one may expect a global sea level rise of 4 to 8 cm during the period 1985-2025. Thereby they assumed an induced warming by the greenhouse gases of 0,6^{o} to 1,0^{o}C. The calculations were based on a sea level rise of 2 to 5 cm during the period 1880 to 1985.

Let me conclude this part of the report by referring again to the transient character of the response to an continuously increasing global CO_2-content. The neglect of this transient behaviour of the carbon-dioxide content may make it impossible to make any

prognoses for the future. However, the problem is in fact still more difficult. Schneider and Thompson (1981) just state "The most perplexing question perhaps is whether validation of models which account for the transient response is possible before the climatic system itself tells us what its transient response will be to the actual CO_2-increase."

3. SOME SOCIETAL CONSEQUENCES OF CLIMATE CHANGES

3.1 The problem of sea level rise

Throughout geologic history we may recognize a rise and a fall of the sea level by over three hundred meters (Titus, 1985). The reasons for these changes may be attributed to changes in

- the shape and size of the ocean basins
- the amount of water in the oceans
- the average density of seawater

In addition to these changes, we have to consider the emergence and submergence of land where especially the ice ages have come to play an important role. Thus, it may be appropriate to distinguish between the "global sea level" and the "relative sea level" where by the first concept refers to the consequences of the three factors noted above and the latter expression to the appropriate consideration of emergence and submergence.

In fact, these remarks about the global and relative sea level rise have shown to have very important implications in any attempt to estimate what effects have to be expected on, for instance, in coastal regions. This problem has also been extensively studied. One need only mention the problem of uniqueness discussed in the estimation of global sea level change (Barnett, 1984; Wigley and Raper, 1987). In discussing the sea

level rise, the fact that the surface of the oceans is fairly irregular in itself may be referred to. It has been verified through satellite pictures, that the surface of the oceans departs quite markedly from that of a rotating ellipsoid with existing rises and hollows which can differ in level by up to 180 m. The reason for this has to do with variations in density inside the earth. Hollows in the water surface will be found where the density of deep lying strata is higher and rises in the water surface appear where it is lower (Pirazzoli, 1985).

To conclude the more historical introduction of sea level rise, it should be remembered that the sea level has risen and fallen with partial changes in the climate as indicated above. When glaciers were covering the northern hemisphere, there was much less water in the oceans which means that the water level was much below the present level. During the ice ages, the temperature was about 5°C colder that today and during the deglaciation period the temperature was about 1 to 2°C warmer than today. The latter period began approximately 18 000 years ago and ended about 6 000 years ago. The deglaciation led to the addition of water to the global ocean raising sea level by approximately 120 m (Peltier, 1988). This indicates a considerable rise, but during the glacial-interglacial transition phase the average rate of the eustatic sea level rise was consequently only 10 mm per year.

Leaving now these introductory comments on the sea level rise, it may be interesting to look at what sea level rises may be expected in the future. Several attempts have been made in order to make prognoses and some of them are summarized in Figure 2 (Thomas, 1986). The curves in this Figure indicate the total sea level rise which is composed of four components, viz.

- thermal expansion of the oceans
- melting of glaciers and small ice caps

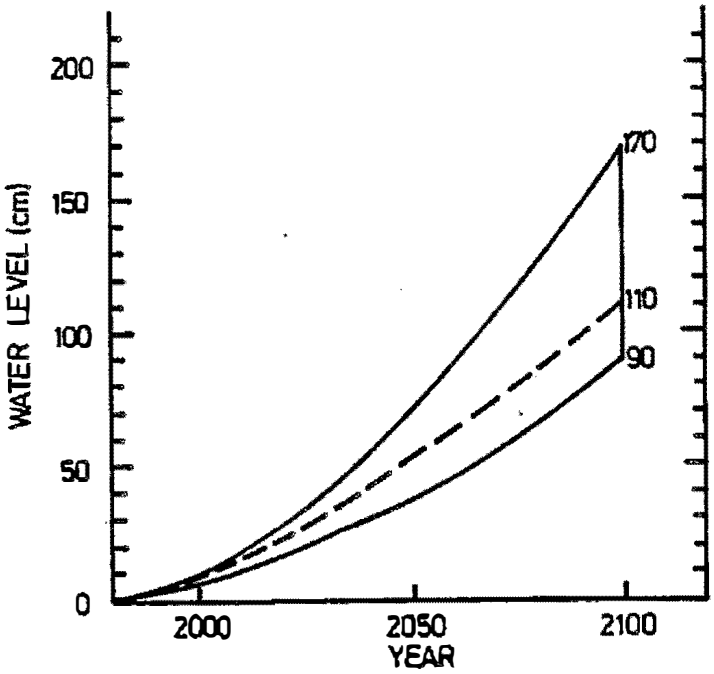


Figure 2. Expected total sea levelrise

- melting from the Greenland ice sheets
- increased ice discharge from Antarctica

Moreover, it is assumed as a basis for preparing the curves shown that the earth-surface temperature increases by an average of 3°C by the year 2050 and that it will remain constant after that time. This is, of course, a restriction to accept an arbitrary termination of the activity of the greenhouse gases after that time.

The curves in Figure 2 may need some more comments that have to do with the rate at which the sea level rises. The first comment is due to the interaction between the atmosphere and the oceans. This problem has already been dealt with (Schneider and Thompson, 1981). If there is a lag of several decades between the CO_2 doubling and climate warming, because of a diffusion of heat into the deep oceans, the temperature prior to the year 2100 will be lower than assumed (Thomas, 1986). This will consequently indicate a lower sea level rise.

The second comment to be made is that the increase in sea level will be very gradual for the first few decades. After these the rate probably will increase progressively. Such an increase will not likely be unambiguously detected until the year 2020 or later.

The third comment may be that there seems to be only a small net contribution to the sea level rise during the next century from the ice in Antarctica. However, if climate warming is sustained, the melting ice may come to play a decisive role in sea level rise on a global scale. In fact, under these circumstances a several metre increase could be expected during the following centuries.

The rise of the sea level may have a lot of consequences particularly to low-lying areas in the world. Problems associated with this will be discussed later on in the text.

3.2 Effects of sea level rise

The rise of the sea level may result in the following effects (Titus, 1986)

- coastal erosion
- increased salinity in estuaries and aquifers

- inundation
- flooding and storm drainage
- submergence of coastal wetlands

In this subchapter only consequences of erosion and increased salinity will be dealt with.

3.2.1 Erosion

Erosion is a wellknown problem all over the world and it has been noted that erosion is increasing on a global scale (Paskoff, 1985). Thus, erosion is a normal phenomenon at sandy coasts. To some extent damage to beaches may be calculated by semi-theoretical relations where the most used formula is the one known as Bruun's rule (Bruun 1962). The relation between sea level rise and the rate of erosion is based on the assumption of an equilibrium beach profile. It has to be pointed out that the term "equilibrium profile" is a statistical average profile that is maintaining its form apart from small fluctuations, including seasonal effects at a particular water level. The Bruun concept of an equilibrium profile is schematically shown in Figure 3. Mathematically the Bruun rule may be expressed as

$$S = \frac{h' \cdot L}{h} = \frac{h' \cdot L}{h_D + D} \qquad (1)$$

where

S = the shoreline recession
h' = sea level rise
L = the "active" portion of the profile participating in the adjustment
h = the vertical distance over which the adjustment occurs
h_D = average height of the sand dunes

If the profile may be considered to be in equilibrium then the

distance L can be calculated according to the relation (Dean, 1977).

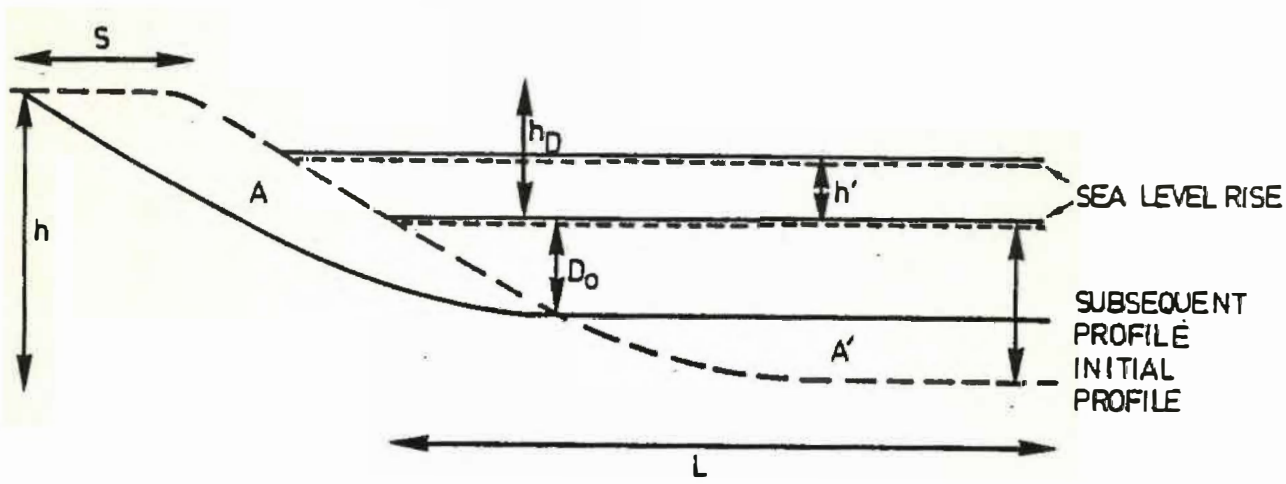


Figure 3. Shore erosion following a rise in sea level according to the Bruun rule

$$L = (D/A)^{3/2} \qquad (2)$$

where A is a parameter that depends on the grain size of the bottom material D_{50}.

If, for instance, D_{50} could be assigned the value 0,2 mm, then, according to Moore (1982), A is equal to 0,1 m/s which leads to L = 465 m. If we look at the situation where a sea level rise of 1 m could be expected and h_o and D are 2 m and 6 m respectively, we find that

$$S = \frac{1 \cdot 465}{2-6} = 60 \text{ m}$$

This means that with the assumption made the recession of the shoreline will be 60 m.

From mass conservation the volume A is equal to A' (Figure 3) and by integration along the contour of the shoreline, the eroded area A may be calculated. This in turn gives the possibility to calculate the eroded volume for each meter of the shore. The total volume of material to refill is then also possible to calculate.

3.2.2 Salt water intrusion in coastal regions

The sea level rise will not only have a major impact on coastal erosion, and flooding but also on saltwater intrusion. In a report from the US Environmental Protection Agency (Hull and Titus, 1986) it is said that "no one had estimated the saltwater intrusion expected to result from an accelerating rise in sea level due to the greenhouse effect". However, so much can be said that excessive concentrations of sea water at water intakes would create public health risks, increase the cost of water treatment, and damage plumbing and machinery. Moreover, an increased salinity of intruding water could also upset the ecology of the coastal area.

Like erosion, salt water intrusion is in no way a new problem. One need only mention the activities within the "salt water

intrusion meetings" held since 1968 in order to organize an international co-operation in the field, thereby recognizing the importance of that subject from a theoretical as well as practical point of view. Moreover, the important contribution Unesco has made in order to analyse the extremely serious problem of the adverse effects of saltwater intrusion on groundwater in coastal areas (Custodo and Bruggeman 1987) should also be mentioned. Today there exists also a very clear understanding of the consequences of the over-exploitation of groundwater from coastal wells all over the world. An interesting parallel to this extreme withdrawal of water from wells, is the effects of salinization in arid and semi-arid irrigation projects, which causes severe problems to water supply just by groundwater extraction. In both examples, it has proved to be extremely difficult to renovate such salt contaminated wells.

Quantitative observations of salt water depth in coastal porous aquifers were made already at the beginning of our century. From these observations, a formula was deduced for salt water intrusion, a relationship now known as the Ghyben-Herzberg formula, see also Figure 4, namely

$$(h_f + z)\gamma_f = z\ \gamma_s$$

$$z = \frac{\gamma_f}{\gamma_s - \gamma_f} h_f = \alpha h_f \qquad (3)$$

where

h_f = fresh water head (water table elevation over mean sea level)

z = depth of the interface below mean sea level

$_f$ = fresh water density = 1000 kg/m^3

$_s$ = salt water density = 1025 kg/m^3

$\alpha = \gamma_f / (\gamma_s - \gamma_f) = 40$

The Ghyben-Herzberg formula is a hydrostatic approach, with in fact some severe limitations (Custodio and Bruggeman, 1987).

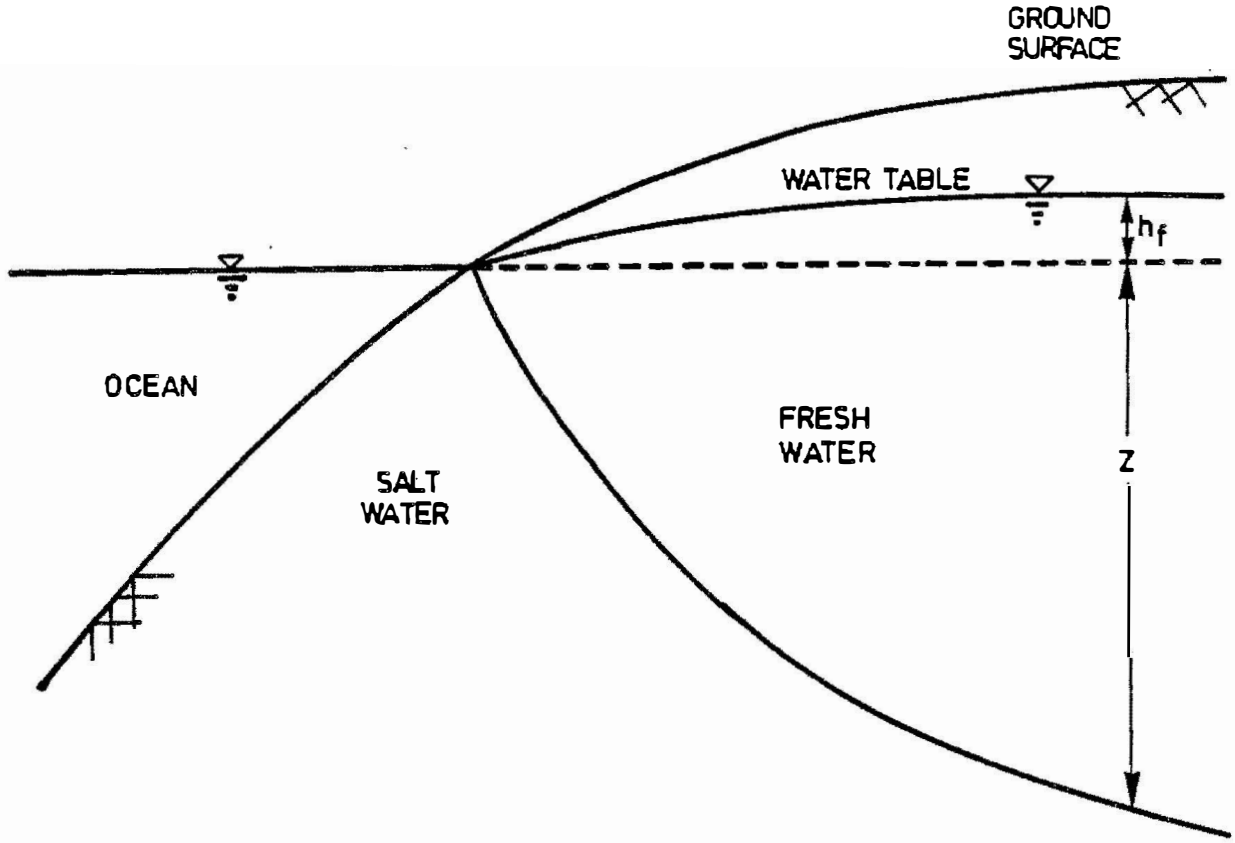


Figure 4. Explanation of the Ghyben-Herzberg principle

There have been many attempts to find more appropriate approaches to the salt water intrusion problem than those presented by Ghyben-Herzberg, mainly in order to correspond to the dynamic processes that are in fact, involved. In order to account for the

mixing of fresh and salt water, mainly through microscopic and macroscopic dispersion, a new relationship has been deduced, replacing the older formula. According to the new hypothesis salt water is dragged along with fresh water towards the sea. In order to conserve the salt water balance this implies a small landward salt water flow in a coastal groundwater aquifer under equilibrium. Some considerations then lead to the so-called Hubbert's formula

$$z = \frac{\gamma_f}{\gamma_s - \gamma_f} h_f - \frac{\gamma_s}{\gamma_s - \gamma_f} h_s = \alpha h_f - (1+\alpha)h_s$$

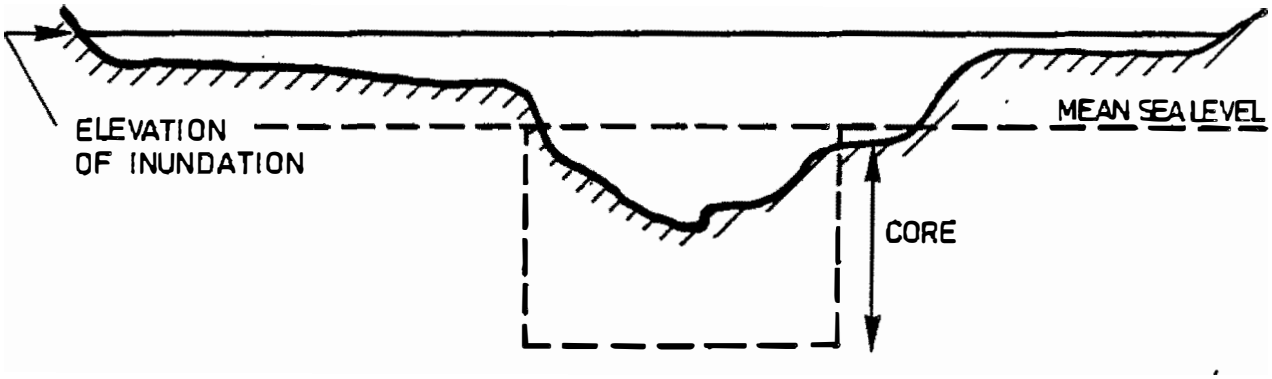
$$= \alpha (h_f - h_s) - h_s \qquad (4)$$

With reference to to Figure 4, a sea level rise may lead to a landward moving of the salt water wedge. The hydrostatic formula will then lead to an increase in the groundwater table indicating a decrease in water availability. However, the only portion of an aquifer likely to be salty is the part below sea level. In coastal aquifers the fresh water floats on top of the heavier salt water.

There is an apparent risk that saltwater and freshwater mix, thereby causing contamination of the freshwater in the well. Heavy withdrawal from wells also cause the equilibrium saltwater line to move far inland. In many cases, there is a hydraulic connection between wells and adjacent rivers. If there is extensive pumping from wells it may happen that the wells are recharged by the nearby rivers. As a consequence, the wells will be contaminated by salty water through infiltration into the aquifer. It has proved to be very difficult to wash away salt from such aquifers.

Studies have been made in order to make prognoses about salt-water intrusion (Hull and Titus, 1986). These are based on fundamental equations, considering also the special geometry

caused by inundation of river reaches, cf. Figure 5. The basic equations describing saltwater intrusion are



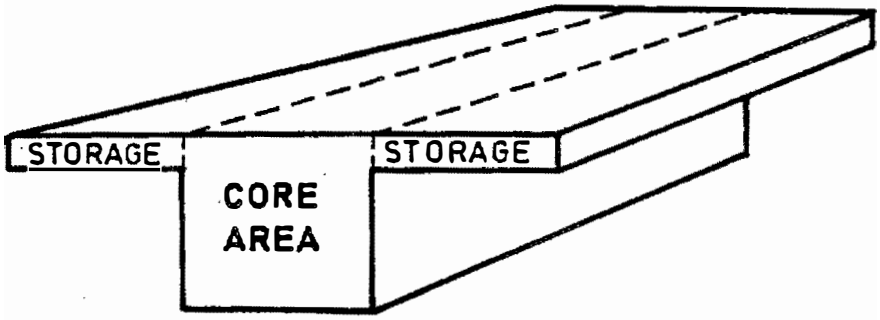


Figure 5. Increase in width resulting from sea level rise and a schematic sketch of the geometry

the continuity equation

$$b \frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \qquad (5)$$

the longitudinal momentum equation

$$\frac{\partial Q}{\partial t} + \frac{\partial (QU)}{\partial x} + gA \frac{\partial h}{\partial x} + g \frac{Ad_c \cdot \partial \zeta}{\rho \ \partial x} + \\ + g \frac{Q|Q|}{AC^2 \cdot R_n} = 0 \qquad (6)$$

the salt balance equation

$$\frac{\partial (A_t S)}{\partial t} + \frac{\partial (QS)}{\partial x} = \frac{\partial}{\partial x} (A_t \ E \frac{\partial s}{\partial x}) \qquad (7)$$

the equation of state, i.e. the relation between density, salinity and temperature

$$\rho = \alpha_T + \beta_T \cdot S \qquad (8)$$

where

- b = total surface width
- h = depth from water surface to horizontal datum
- Q = cross-sectional discharge
- q = lateral inflow per unit length
- U = longitudinal velocity averaged over the cross section of the core area
- A = core area
- g = acceleration of gravity
- d_c = distance from the water surface to the centroid of cross section
- ρ = mass density of water
- R_h = hydraulic radius of core area, including that of storage areas
- s = salinity averaged over the total cross section
- E = the longitudinal dispersion coefficient

The quantities mentioned are functions of longitudinal location (x), and time (t). The coefficient α_T an β_T depend only on temperature.

In order to use the theoretical approach above for prognoses, one has to start from information already known about the salinity content of a great number of wells in the region in question. The model just described, has been applied for saltwater intrusion in the Delaware Estuary in order to calculate effects of a sea level rise (Hull and Titus, 1986).

3.3 Influences on the hydrologic cycle

The sea level rise is only one of the important consequences of the global climate change. Another one, also with far reaching societal implications is the changes in the hydrologic cycle processes with further repercussions on the water resources. When we talk about consequences for the hydrological cycle we mean changes in the elements that interact within the hydrologic cycle, cf. Figure 7. Such important elements are primarily: precipitation, evapotranspiration, infiltration, surface run-off, and soil moisture content.

For the study of changes in the hydrologic cycle various global circulation models have been used. Wellknown today are the so called General Circulation Models (GCMS) that have come into use through the rapid development of computer hardware and software (Manabe and Stouffer, 1980). The global models describe the physical part of the climate system. However, we have already reported on how, for instance, insufficient knowledge about heat exchange between the atmosphere and the oceans may lead to conclusions that may be questioned. Another part of the hydrologic cycle that is not quite well covered by the model, is the role of vegetation as well as soil moisture. This is in fact not so

surprising, because transport processes through the unsaturated and saturated zones are as yet, so well understood in hydrology. These rather simple remarks are however extremely important for the reliability of the global models and as a general opinion it may be said that they are rather crude.

Some of the studies performed using these global models have, however, given some indication of changes in precipitation and evaporation that may be used as a first estimation of the changes in question. As one example a study of Mitchell (1983) may be mentioned. As result of his study he gives maps showing, for instance, simulated values of total precipitation, evaporation and soil moisture on a global scale. In another study, Wilson and Mitchell (1987) have made a doubled CO_2 climate sensitivity experiment with a global climate model including a simple ocean. The model used is an atmospheric general circulation model coupled to a 50 m oceanic mixed layer and an energy-balance sea-ice model. The prescribed heat convergence in the ocean ensured that sea temperatures as well as seasonal variation of ice were in close agreement with observations. The results presented comprise a series of maps showing soil moisture content, precipitation changes for a doubled CO_2 content, etc. The authors also add some important comments from which may be concluded that, for instance, the representation of cloud is extremely crude. Moreover, they point out that the dynamics of sea ice and changes in ocean dynamics are not taken into account. As a final conclusion the authors claim that "they consider themselves still some way from predicting the magnitude and distribution of climate change due to increased atmospheric CO_2 with the accuracy required for climatic impact studies". And they add that studies like the one presented should be considered more as a sensitivity study and not as a forecast.

A somewhat older study may also be mentioned (Washington and Meehl, 1984). This study makes use of a simplified ocean model, a

simple slab of 50 m depth. Seasonal heat storage and release is included in the slab but not heat transport in the ocean. Also in this case a series of maps showing hydrological parameters are shown with comments on their reliability.

3.3.1 Impacts on water resources

Looking at the impact on available water resources due to the global change, it is certainly a useful approach, as has been indicated earlier in the text, to consider at first how the hydrological cycle processes are affected by the climate change. The idea behind this round about way will be explained schematically from Figure 6. This Figure wants to show how climatological

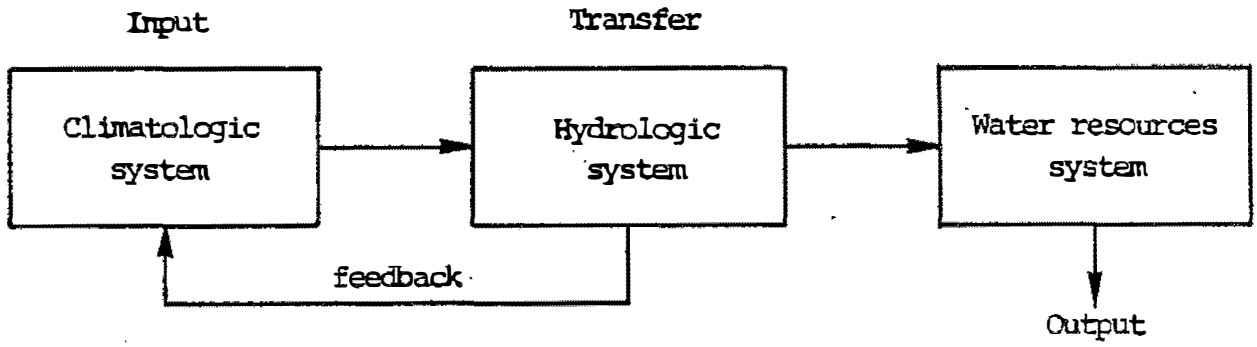


Figure 6. Interaction between climatologic, hydrologic, and water resources systems

variables may make an input in the hydrological system. The output from this transfer or throughput system then makes the input to the water resources system, the output of which hopefully will indicate what changes are to be expected from variations in the climatological variables. If not for other reasons such as an interacting process makes clear that there is a conceptual distinction between what we call hydrology and water resources. This fact has been still more clear over the years, since water resource activities more and more have been dependent on knowledge that has been drawn from other disciplines such as economics and civil engineering. Moreover, as is pointed out by Beran (1986), "while all natural water is of hydrological interest, only water that is available at the time and place required and in suitable quantity and quality, is of water resources interest".

In order to reveal possible impacts on the hydrological cycle, one could use the interaction systems shown in Figure 6. The most straight-forward procedure would then be at first to look at the interplay between the meteorological and the hydrological systems. However, we certainly do not have sufficient understanding of this interaction, which has been pointed out several times, cf. for instance EOS (1988). In general, it could be said that the GCMs are not yet so fully developed that they can be used as input to the hydrological system. It should, however, be stressed that the global circulation models cannot be developed without very efficient co-operation between meteorologists and hydrologists.

In this situation it seems plausible to adopt another approach, namely to start from the hydrological system itself, assuming certain fixed input values to the system. This could, for instance, mean that we test the response of the hydrological system for fixed changes in precipitation etc. However, this would mean that the hydrological system itself is known. The most

basic illustration of this system would then be the hydrological cycle process which schematically can be expressed as in Figure 7 (Lindh 1979). The mathematical background of this cycle process is the water balance equation (Sokolov and Chapman 1974).

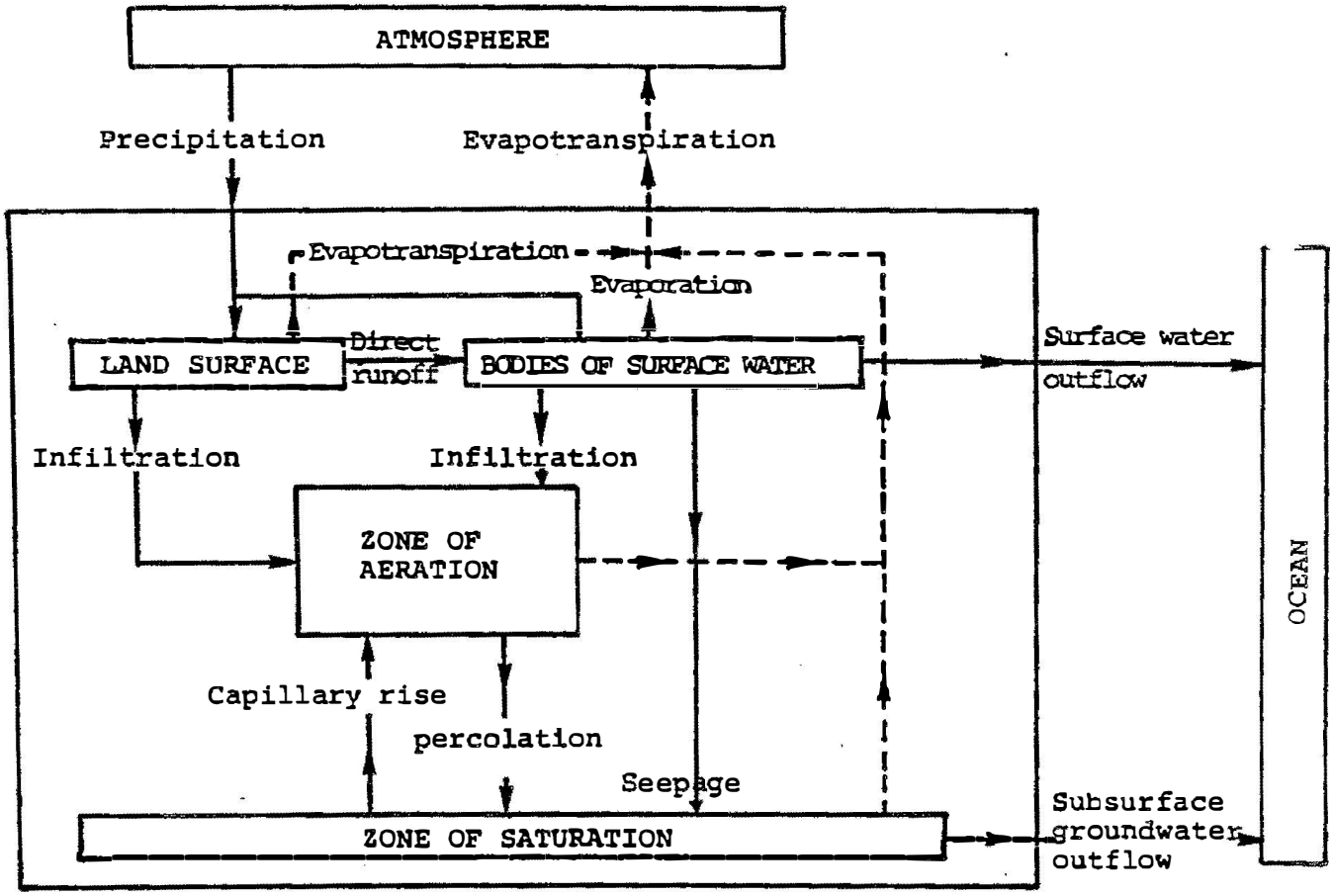


Figure 7. Schematic illustration of the hydrological cycle

$$P = Q + E \tag{9}$$

where

P = precipitation

Q = runoff

E = evapotranspiration

This equation may, of course, be subdivided in order to depict partial processes.

A study of the available literature concerned with consequences of the global change impact on the hydrological system, seems to confirm that the water balance model implies a practical method of approaching the actual problem. A series of interesting papers have been published that show how the water balance model can be used for climate impact assessment. I would like to mention some of them below.

Let me start with a study of the Sacramento Basin published by Gleick (1986, 1987a, 1987b). In the first of the three papers Gleick makes use of a modified water-balance method in order to evaluate the regional hydrological impacts of global changes. He starts his study be quoting a statement by the U.S. National Academy of Science from 1979 which reads "At present we cannot simulate accurately the details of regional climate and thus cannot predict the locations and intensities of regional climate changes with confidence. This situation may be expected to improve gradually as greater scientific understanding is acquired" Gleick's comment on this - in 1986 - is that the situation is only marginally better today. And he expresses the view that even current climatic assessments are limited to a few global consequences such as changes in average or zonal temperatures and precipitation. But this is not sufficient knowledge if the intention is to determine a regional or national policy. He also stresses that the use of general circulation models (GCMS)

is of limited value because of its complexity and because the resolution of these models is coarse compared to hydrological events. However, he admit that the models per se may indicate important changes in, for instance, precipitation. One such indication is the suggestion that there will be a major reduction in summer soil moisture patterns in the middle latitudes which may be a consequence of a northward shift in the mid-latitude rain belt and an earlier onset of winter snowmelt and spring runoff (Manable and Wetherald, 1986). Very important is also the general statement that relatively small changes in regional precipitation and evaporation patterns might result in a significant change in regional availability. In this paper on the usefulness of modified water balance models, Gleick points out that once a region has been characterized by water balances the effects of climatic change may be evaluated in three ways, namely

- After having verified the accuracy of the model by using long-term historical data it would be possible to use historical data to evaluate the effects of historical fluctuations in precipitation and temperatures on historical runoff and soil moisture.

- After the sensitivity of runoff and soil moisture to theoretical changes in the magnitude and temporal distribution of precipitation and temperature has been determined, it would be possible to assess a wide range of hypothetical climatic changes in order to evaluate the hydrological sensitivity of the watershed.

- By incorporating even rough regionally-disaggregated changes in temperature and precipitation predicted by general circulation models, a first estimate can be made of the impacts of future predicted climatic change on regional hydrology.

After his paper emphasizing the advantages of the modified water balance model in the study of climatic impacts Gleick (1987a, 1987b) applies his ideas on the Sacramento Basin California, USA. For this basin he developed a water balance model and as input to this model he used eighteen widely-varying climate-change scenarios designed to evaluate the impacts of global climatic changes on runoff and soil moisture in the Sacramento Basin. Four particularly important and consistent changes were observed

- large decreases in summer soil-moisture levels for all scenarios

- decrease in summer runoff for all scenarios

- major-shifts in timing of average monthly runoff throughout the year

- large increase in winter runoff volumes for almost al of the scenarios

The conclusion made by Gleick is that the changes just noted may have serious implications for many aspects of water resources if they materialize.

In a series of papers by Bultot and Dupriez (1976a, 1976b) they consider a conceptual, hydrological model for an average-sized catchment. This model is a complete description of the hydrological system including transport process as well as the storing of water at various positions in the system, cf. Figure 8. It aims to calculate the outflow of such a model for given inputs. With this model, data from the period 1966-1972 has been used to determine the parameters used in the model description. The model has also been used to foresee the outflow of the system. As a complement to these studies, Bultot, Dupriez and Gellens (1988) have made a special study of the estimated annual

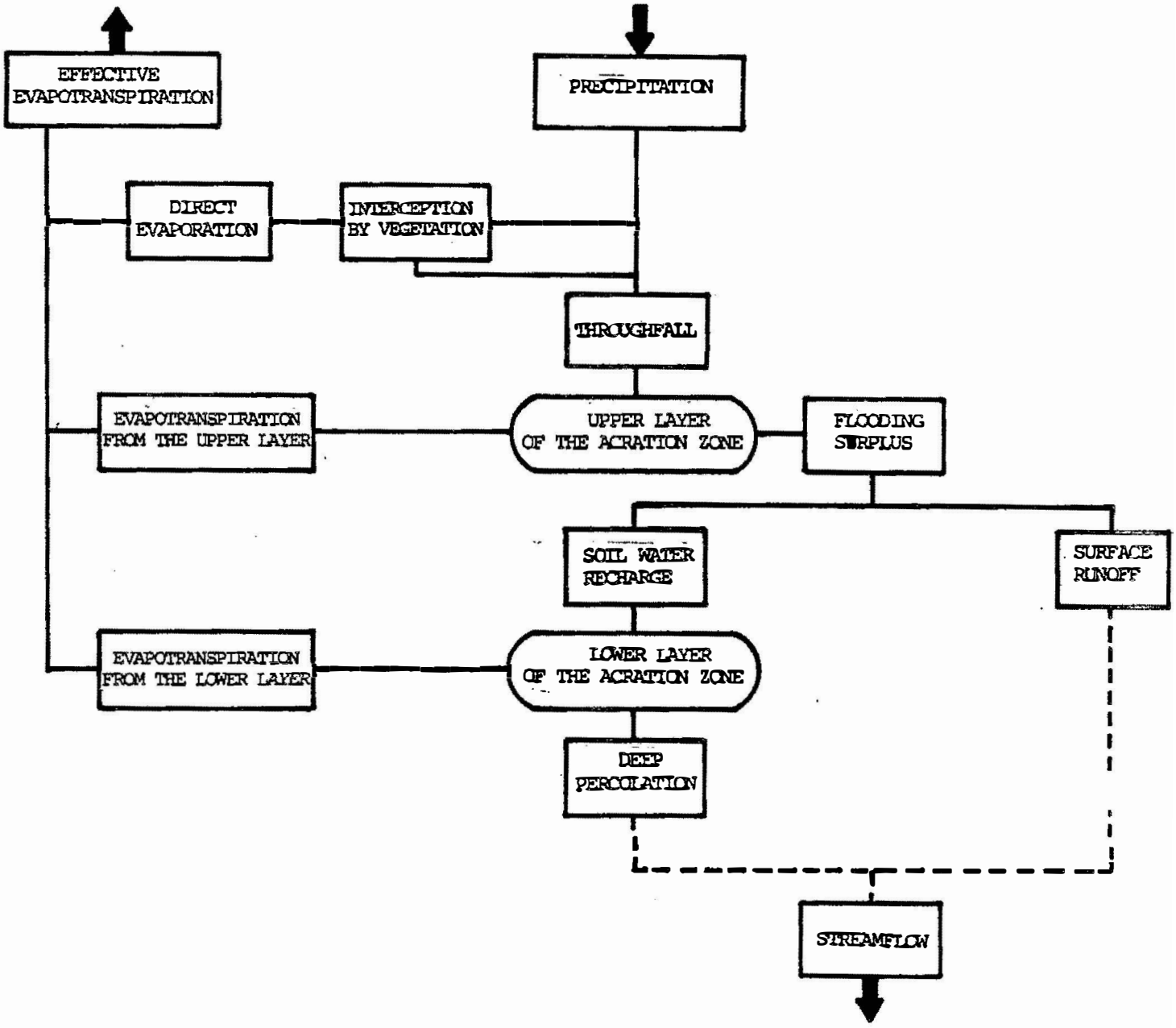


Figure 8. Flow chart of the upper part of the IRMB model

regime on energy-balance components, evapotranspiration and soil moisture for a drainage basin in the case of a CO_2-doubling. This study was a preliminary step to a more detailed impact analysis dealing with three Belgian river catchments with very different features.

In a study by Aston (1984) particular interest has been devoted to the role of vegetation and evapotranspiration when developing the special hydrologic model called SHOLSIM. It simulates a large catchment area with a number of varying land uses. Four computer simulations were undertaken in order to illustrate the maximum effect the CO_2 enrichment can have on large-scale catchment hydrology. Some results seem to be very encouraging for the part of Australia studied.

For instance, Aston points out that there may be agricultural land which at present is marginal due to water shortage but where it will be possible to increase production considerably. Moreover there are urban areas where the water supply will be significantly increased leading to greater domestic and industrial development. This could apparently be done along with the expansion of irrigated agriculture. Such prognoses, if they are correct, will certainly create another attitude to planning and development, especially as increased water availability may aggravate salinity and soil erosion as well as floods.

Not precisely thought of as a contribution to the consequences of climate changes but a good study of modelling catchment response, is the paper by Ward (1984). The paper contains a rigorous process-based catchment model. As input variables, precipitation and potential evapotranspiration are used. Output consists of hourly or daily values of actual evapotranspiration, soil moisture status and streamflow.

Over the years, a series of conceptual and physically-based models have appeared. One very much detailed and thoroughly worked through model is the one by Abbott et al (1986). The model is called "SHE" and is a physically-based, distributed system and it is produced jointly by the Danish Hydraulic Institute, the British Institute of Hydrology and SOGREAH (France). The model consists of different components:

- the ARAME component which coordinates the parallel running of other components
- the interception and evapotranspiration component
- the overland and channel flow component
- unsaturated zone component
- saturated zone component
- snowmelt component

According to the scientists involved in the project, it is relatively easy to add some components to the model.

Wigley and Jones (1985) made a special study of the hydrologic cycle response to changes in precipitation and direct CO_2 effects on streamflow. They also start by considering the fundamental water balance operation, valid for small non-evaporative losses, namely

$$Q = P - E$$

where Q is runoff and P and e precipitation and evaporation respectively. The runoff coefficient k is related to Q and P through

$$Q = k \quad P$$

In order to estimate changes in runoff due to changes in precipi-

tation and evapotranspiration, the authors denote the change in precipitation from P_o till P_1 as

$$P_1 = a\ P_o$$

Changes in evapotranspiration will occur for two reasons. One is due to a climatic change, the other though direct CO_2-induced change in vegetation. The authors now claim - after some arguing - that runoff is always more sensitive to precipitation changes than to evapotranspiration changes, particularly for higher values of the runoff coefficient. They also state that precipitation changes have an amplifying effect on runoff, especially in arid regions where the runoff coefficient is small. A list of runoff ratios for selected major rivers in the world show that these values range from 0,1 or less for rivers flowing through arid regions up to more than 0,6 for some tropical rivers. From the list it is evident that in temperated latitudes runoff coefficients around 0,4 are fairly typical. An interesting Figure in Wigley and Jones' paper is reproduced here, cf. Figure 9. From this Figure we may see that when a = 0 there is no direct effect. When a = 1 the direct effect corresponds to a maximum. Changes in evapotranspiration due to climatic changes can also be read off since the range a = 0 to a = 1 in fact corresponds to a range of reductions in evapotranspiration from 0 to 30%.

Wigley and Jones show how the curves can be used in order to calculate changes in future runoff due to changes in precipitation and evapotranspiration when a certain value of runoff is given for a catchment area. As a conclusion, one may say that Wigley and Jones' studies make it possible to make a first estimate of annual mean runoff changes for any river where the runoff ratio is known. Moreover, it would be possible to identify regions that will most likely will show large runoff changes due to increasing CO_2.

A special study applied to American conditions is presented by Rind (1988). This study uses results from the Goddard Institute

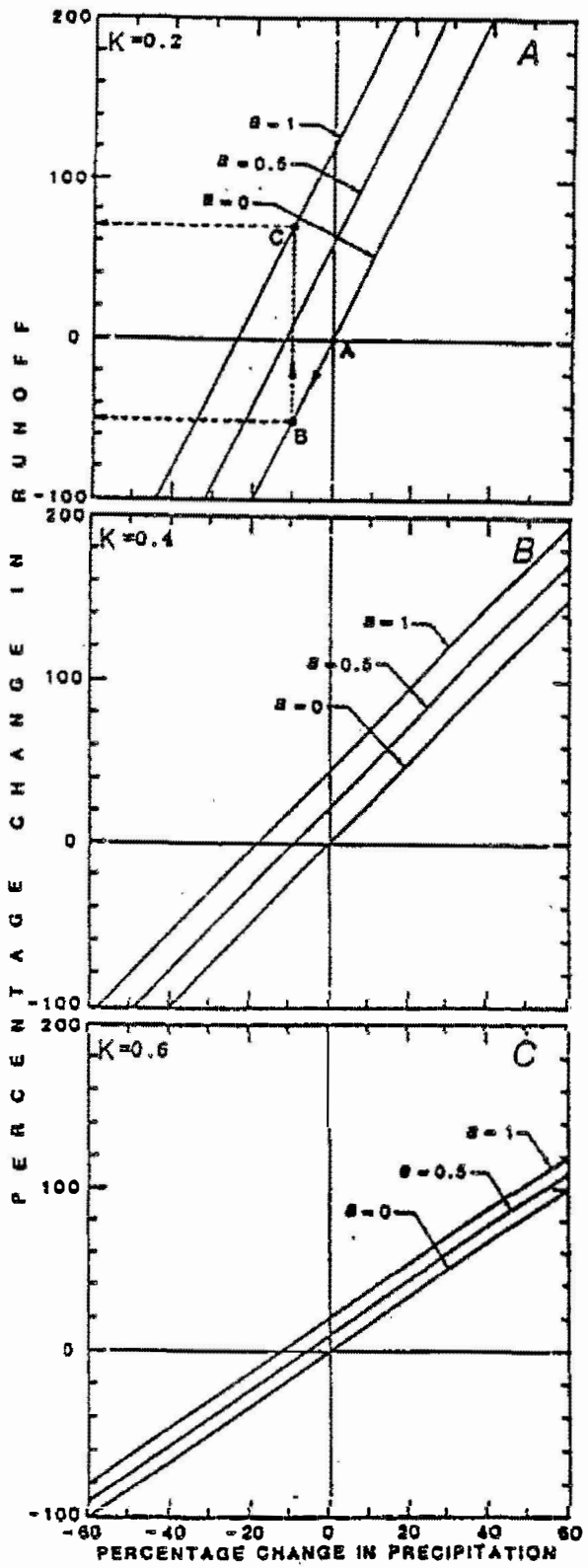


Figure 9.

Runoff changes due to changes in precipitation (P) and evapotranspiration (E)

a = 0 corresponds to no change in E

a = 1 corresponds to 30% reduction in E (maximum direct CO_2 effect

Three values of runoff coefficient K is shown.

Precipitation change alone is determined by a = 0.

Thus, the line AB shows the effect of a 10% reduction in P.

The line BC correponds to a range of E reduction from 0% (point B) to 30% (point C).

(According to Wigley and Jones, 1985).

for Space Studies' (GISS) general circulation model to investigate the consistency of changes in water availability over the United States. At the same time, the author provides the reader with a critical survey of global models in general. From the result derived by the model it can be mentioned that the climate of the northern and western regions of the United States and southwestern Canada will become wetter, particularly in winter and spring. There is a tendency that the southern and eastern parts will become drier. A series of other results and findings are also presented. The paper concludes with the comment that "it is unlikely that climate simulations of sufficient length to differentiate signal from noise will be made in the near future". The author thinks that at least a decade is needed to develop better ground hydrology and ocean models in order to fit in the global circulation models. And he adds "From this perspective, "consensus" results from current GCMs may represent risky projections of future water availability. Nevertheless, the problem is of such great importance, and the planning of water resources needs such a long lead time, that every attempt should be made to reduce the uncertainties as quickly as possible".

Recently a quite another approach in studying details of a general circulation model was published by Koster, Eagleson, and Broecker (1988). The main problem was to investigate what lateral distances the water vapor generally travels while in the atmosphere. Or, stated in another way, the problem is to answer what fraction of the precipitation in a given region is derived from water evaporating from the region itself? It is quite evident that an answer to these questions cannot be given by direct measurements in nature. The method used in this study was to incorporate in the GISS model a tracer water istope model. The three most important water isotopes have the same chemical properties as normal water but have slightly different physical properties, due to their higher mass. The two physical properties affecting water isotope transport are vapor pressure and

molecular diffusitivity. The tracer water model was especially applied to determine the evaporative sources of precipitation falling on representative regions in the Northern Hemisphere for the CGM climate. A very intresting result of the MIT study was that there seems to be a larger degree of water recycling over mid-latitude continental regions than is generally estimated in the literature.

A study by Shukla (1982) indicates the importance of the influence of land-surface evapotranspiration on the earth's climate. A numerical model of the atmosphere has been used to show the the global fields of rainfall, temperature, and motion strongly dependent on the land-surface evapotranspiration. The short paper includes a series of maps showing simulated precipitation, surface temperature and surface pressure on a global scale.

Last but not least the study of Olejnik (1988) may be mentioned. His studies are based on several models presented earlier in the literature. A series of maps are presented showing variations in the hydrological parameters studied for Europe.

3.3.2 Consequences of runoff in urban areas

Possible effects on the hydrologic system due to climate changes have been discussed earlier in this text but excluding effects in urbanized areas. The sea level rise may cause inundations which in turn may render gravity drainage systems, useless or even require that they must be shut off in order to prevent sea water from backing up into the community (Titus, Kuo and Gibbs, 1985). Increased precipitation may increase flood frequencies. It is difficult to know if this would mean more frequent storms or more rainfall during the same number of storms. In order to meet an increased precipitation larger pipes or wider drainage channels may be used. Where drainage systems already are in place, a

supplement pipe system can be installed or older pipes may be replaced with layer ones. It is also important to know the communities that rely on gravity drainage systems, have to shift to forced drainage when the sea level rises. That is because pipes must have sufficient elevation, adequate cover and be above sea level themselves. When force drainage is already used, larger pumps may be necessary to work against the higher tailwater. Moreover, a larger capacity is certainly needed to handle more water because less water is taken care of by natural drainage. One more interesting aspect in managing urban and suburban drainage is to use more detention basins. Such basins are already used in order to control surface runoff. They can now be applied when the capacity of the drainage systems decreases, when sea level rises or when precipitation increases.

In some parts of the world one is already prepared for encountering the situation just dealt with.

One example may be taken from the City of Charleston where seventy percent of the existing storm water drainage facilities were undersized. The total cost for construction of the recommended improvements was estimated to be approximately 135 million dollars (Laroache, and Webb 1985). One way of meeting the new requirements because of increased precipitation was to change the type of design storm. Just in the City Charleston they have changed from a 5-year storm to a 10-year return frequency. In fact calculations for reconstruction of the storm water drainage system is perhaps not so difficult. The difficulty lies in making decisions and creating consensus about new plans and being aware of the increased cost of replacing or supplementing the system. This can be expensive but is anyhow a better alternative than waiting too long. One may express it also in the way that the sea level rise and increased precipitation may involve a degree of uncertainty. One way to reduce this uncertainty is to plan for potential future changes (Waddell, 1985).