United Nations Environment Programme

Distr.
RESTRICTED

UNEP/WG.125/8
2 November 1985

ENGLISH
Original: FRENCH

Meeting of Experts on the Technical Implementation of the Protocol for the Protection of the Mediterranean Sea against Pollution from Land-based Sources

Athens, 9-13 December 1985

GUIDELINES FOR THE COMPUTATIONS CONCERNING MARINE OUTFALL SYSTEMS FOR LIQUID EFFLUENTS

In collaboration with:

WORLD HEALTH ORGANIZATION

TABLE OF CONTENTS

F O R E W O R D

In the most developed countries, in the last 10 to 20 years especially, the need has been felt to combat environmental pollution caused by the discharge into the sea of various pollutants from land-based sources. The ever increasing quantities of such pollutants discharged into the sea caused concern, which led to a number of studies with a view to defining the conditions under which wastewater containing various types of pollutants could be discharged, without excessive damage to the marine enviroment.

As concerns the wastes originating on land and discharged into the sea through coastal underwater outfall systems, the methodology for the computations concerning such outfalls has taken different forms, each giving specific answers to the problem, depending on the way it was formulated each time.

Problem One: Calculate an outfall for a given waste

The scientific rationale and the computations to be found in this document match that formulation of the problem where:

(a) the characteristics of the waste are given (flow, type and content of pollutant;

(b) the waste is to be discharged into the sea in an area encompassing well-defined sensitive zones to be protected against pollution; and/

(c) these areas are covered by standards of maximum levels of concentration for one or more of the pollutants contained in the waste.

The problem then is to define the particular features of the outfall system in such a way as to satisfy the conditions already established, i.e. to comply with the standards in force in the areas to be protected.

By taking into consideration both the quantities of the waste to be discharged and the difficulties arising from local geographical and meteorological conditions, we can select a method which would give a solution with a smaller or greater degree of accuracy in calculating pollutant concentrations at various distances around the point of discharge.

The mathematical models

For this purpose, sophisticated mathematical models have been formulated, which give the most accurate answers possible at this point in time. These models have been published and are available elsewhere, but are not included in this document. The use of such models is rarely justified in the cases that are the most frequent, because many of the parameters of the problem are very often hard to define with precision. The use of a highly accurate method is rather illusory in the majority of cases.

The method of simplified manual calculations

This is why, on the basis of theoretical equations on turbulent diffusion, which in turn are the result of certain simplifying assumptions, new approximations have led to the simplified methods and formulae described in detail in chapters 2 and 3 of this document.

The graphic method

These computation methods presuppose a certain level of knowledge of physics and mathematics, perhaps not attained by a number of technicians, who however have to deal with the problem of selecting the type of outfall system best suited to the particular case. For this reason and also because oftentimes, lower accuracy in the definition of the outfall can nevertheless give satisfactory results, it was possible - through sophisticated research - to develop a methodology which uses only plots and graphs, thus easier and faster to use.

This simplified method and the graphs that accompany it are presented in Appendix F.

It should be noted, however, that the simplicity of this method should be weighed against the fact that it has a valid application only in cases where there is a corresponding schematic simplification of the data pertaining to the marine environment under study; this should never be lost sight of when using this method.

We have three methods then, differing as to the degree of approximation, which can be used in order to solve the problem formulated as follows: Calculate the outfall system most appropriate for the discharge into the sea of a well-defined effluent.

Problem Two: Calculate the maximum receiving capacity of a coastal area

However, the problem of discharge of wastewater into a marine environment does not present itself exclusively in the formulation for which the methods reviewed above give a solution. Even if less frequently, the problem can also be formulated as follows: which is the "maximum receiving capacity" of a well-defined coastal area for a specific pollutant, e.g. urban sewage, and which is the best configuration of an outfall system to meet this maximum capacity?

In effect, there is a method to match this formulation of the problem; it is called "Scheme for the Improvement of Coastal Waters" (SAEL) and is particularly adapted to the conditions of the Mediterranean as receiving environment.

This method is interesting for two reasons:-

- By using the SAEL, a rather low expenditure scheme, one can define from the start the receiving capacity of a whole coastal area as large as one wishes. This information can be especially useful in the case of a still rather undeveloped coast, for which large scale development is envisaged. With this method, one can define from the start the best drainage and sanitation systems, and establish the best distribution of installations on land.

- The SAEL methodology is simple and uses primarily simple formulae and graphs.

This is why it was considered useful to give a brief description of the principles of SAEL in Appendix F.

Layout of the study

The chapters that follow summarise the actual state of knowledge on the most important hydrodynamic phenomena of relevance here, and aim at serving as a practical guide to those entrusted with the study of projects. Therefore, this document is not a technical treatise with the most complete and up-to-date information on the subject. It is intended for the use of technicians in the Mediterranean coastal States in the context of the UN Environment Programme, and it takes special consideration of the conditions prevailing in the Mediterranean Sea. However, much of the information contained in it can also be applied to other seas and oceans.

The contents of the study are arranged as follows:

- In the Introduction, a review of some useful concepts on the collection and treatment of effluents before discharge into the sea.

- In Chapter 1, the general guidelines for defining and delineating the problem.

- In Chapter 2, the elements most useful for the drafting of technical specifications to be used in invitations to bid or in contracts for outfall systems studies.

- In Chapter 3, the scientific rationale, both necessary for an in-depth understanding of the provisions defined in Chapter 2, and useful to the technician or the Construction Manager who is called upon to assess and use the results of the study with a view to decision taking.

- In Chapter 4, information in the field of Civil Engineering on the construction of outfall systems.

- In Appendix A, a standard model of technical specifications to be included in bids or contracts for outfall systems studies.
- In Appendix B, numerical application examples illustrating the methods described in Chapters 2 and 3.
- In Appendix C, computation formulae for sea-air heat exchanges.
- In Appendix D, revision notes on the simplified computation of dilution by graphic methods.
- In Appendix E, a precise computation method of the density of sea water.
- In Appendix F, a brief description of the methodology, based on the SAEL principle, for the computation of the receiving capacity of a coastal area.
- In Appendix G, some ideas on the establishment and implementation at national scale of a theory for the discharge of sewage into the sea.

INTRODUCTION

REVIEW OF SOME USEFUL CONCEPTS ON THE COLLECTION AND TREATMENT OF EFFLUENTS BEFORE DISCHARGE INTO THE SEA

I.1 POLLUTION CONTROL IN COASTAL WATERS

I.1.1 Two "targets" of pollution : Man and the Marine Environment

In order to understand the reasons that led to the development of a method for carrying out the computations concerning sea outfalls for liquid wastes containing pollutants, it is necessary to summarise the elements of the problem; a problem which arises from ecological and health considerations with a view to preserving a satisfactory level of quality in the coastal waters, taking into account the risks that the pollution of such waters holds in store both for the animal and plant species living in the sea, and for man through his use of the marine environment (bathing) and its products (consumption of marine animals).

I.1.2 The Standards

This distinction between the risks for the environment and those for humans should lead to the formulation of "standards" for both, expressed in maximum receiving capacity of the sea water for specific categories of pollutants most frequently discharged into the marine environment along with the sewage.

Now, the quantification of pollutant nuisance is very difficult; this is due to the type of impact that these pollutants have on the two categories of targets defined previously and to the quantified relationship between the impact of pollutants and their concentration; both of them are, by virtue of the diversity of pollutant action, phenomena which are not yet thoroughly understood.

In particular, as concerns the target "marine biocenoses", no country has, to the best of our knowledge, been able to come up with standards which incorporate quantification of such nuisance expressed in terms of "pollutant concentrations". Moreover, this is a gap which leads to the lack of regulations felt very acutely by the technicians responsible for defining sea outfall systems as a function of the provisions governing the protection of the marine environment.

Of course, qualitatively, this nuisance is a fact that cannot be denied, but because it cannot be straightjacketed into quantitative rules so as to be accepted by all participants - often antagonists - in the operation "protection of the environment", it feeds a never-ending dispute between the defenders of the sea and the technicians who must discharge wastes into it.

Fortunately, it is slightly easier to approach the other target and one must admit that men have a natural tendency to consider it as a matter of priority, since it is their own species that is affected. Even though marine pollution affects humans in various ways, very different among themselves - some of them still poorly understood - the need, felt by men as necessity, not to leave a total legal vacuum with regard to such a threatening risk, has led most countries to set down, not without a certain arbitrariness, "standards" for a number of pollutants directly affecting public health.

I.1.3 The "uses"

The risk that humans may incur from marine pollution comes primarily from two "uses" of the sea, i.e. bathing and consumption of sea products (especially if they are consumed raw), thus mainly consumption of shellfish. Therefore, the regulations are generally formulated as two series of standards concerning "bathing" and "shellfish culture" and are based on the content of sea water in pollutants to levels which are considered acceptable in terms of these two risks.

The numerical values of these standards vary from country to country; the values given in this report are those in force in the European Economic Community.

These standards, inspired by the risk of pollutants returning to humans, are in most cases the only numerical expression of the problem of waste discharge, as far as the receiving environment is concerned. However, as a second series of data and despite its essentially qualitative character, one should also take into consideration the concern to protect the marine environment and the organisms living in it.

The most frequent use of a very wide coastal area, and the most important one from an economic point of view, is fishing in the different forms it is carried out; it is thus astonishing that hardly any thought has been given to setting down standards for the quality of sea water in order to safeguard the interests ensuing from this essential economic activity.

There are several reasons for this, mainly:

1. Fishing activities extend over marine expanses that are too wide to make monitoring of the water quality feasible.

2. Pollution from land-based sources reaching marine areas far from the coast comes primarily from large rivers rather than from the dispersion of coastal effluents; obviously, the control of what rivers bring into the sea would entail control of all activities on land, and that is an enormous task.

3. With the exception of persistant toxic substances, which accumulate in living organisms and present a problem unresolved as yet, the other pollutants do not in the least affect the species taken at sea, the majority of which moreover is not consumed raw.

   This is why, as concerns sea products used for human consumption, protection is limited to the sedentary species grown in ad hoc installations near the coasts and usually consumed raw. These species are mainly shellfish and come under the "shellfish culture" use covered by quality standards. Unfortunately, such standards apply to the pollutants accumulated in the flesh of the shellfish itself. To translate these standards into standards applicable to the water used for shellfish culture is a very difficult problem indeed.

I.1.4 Marine waters, inland waters : two very different receiving environments

Thus, on the basis of the two principles of protecting humans and of safeguarding the physical environment, a methodology for the computation of acceptable wastes should be developed.

Fact one: coastal waters, as an effluent receiving medium, are governed by a totally different set of conditions than those holding for inland waters; thus the problem of discharging wastes is put under a totally different light.

Firstly, since sea water is salty, it is not taken for nourishment, at least not directly or very rarely if at all. Therefore, the protection of its quality needn't be considered from this point of view.

Secondly, the special characteristics of the marine environment, its expanse, the movements to which it is subjected make it radically different as far as pollutant dispersion is concerned from the inland waters, mainly rivers of varying dimensions.

In the first case the problem has three dimensions, in the second, most often, only one.

Because of these two essential differences, "the receiving capacity" of the marine environment is the result of conditions and characteristics totally different from those of inland watercourses. The difference is expressed in two ways: on the one hand by a much greater facility (one could almost say "accommodation") to receive wastes, but on the other by a much greater complexity.

Let us look at this "accommodating" feature of the sea first: one can state that, provided admissible flows are not exceeded, the sea can receive certain categories of pollutants, such as organic matter and some minerals which serve as nourishment for the species living in it, without any drawback and even with some benefit. Furthermore, provided that certain wastewater flow limits are respected, the sea has an enormous capacity for diluting even the undesirable pollutants, because it rapidly decreases their concentrations to under the noxiousness threshold.

If we turn now to the complex character of sea water as receiving medium, we can state that, when hydraulics specialists study the fate of pollutants discharged into the sea, they have to grapple with an environment much more difficult to express in equations than river water.

Thus, it is precisely with this aspect of the problem that we intend to deal in this document.

I.1.5 Wastewater discharge into the sea : neither the only, nor the best solution

However, to go back for a moment to what we called the "accommodating character" of the sea, and being well aware of the fact that opinions differ on the subject, we believe that it is not reasonable to take an extreme, not to say irresponsible, ecological approach which would impose "zero discharge" without any distinctions whatever. The sea offers great possibilities for absorption of wastes, while suffering little or no harm; it would therefore be absurd not to take advantage of them in the name of an obscurantist ideology and opt for highly costly solutions which generally are not feasible because the cost is prohibitive. The prohibition resulting from this impasse would more often than not lead to indifference, which would be more detrimental than the well thought out use of the receiving capacity of the sea.

Of course, this does not mean that the discharge of wastewater into the sea is the solution to adopt everywhere and at all times. It could even be humourously described as "the worst solution with the exception of all the other solutions".

Every time that coastal effluents can, from a technical and a financial point of view, find a different destination, the alternative solution is to be preferred without any hesitation, so that the liquid wastes can be reclaimed and recycled on land. It would be extremely useful to have a study presenting the appropriate methods in detail; however, this is not the object of this study.

But in the cases where, for technical or more often for financial reasons, wastewater discharge into the sea has been adopted as the only acceptable solution, this solution of "last resort" should be carefully studied; if this condition is fulfilled, it can in almost all cases be organised in such a way as to render acceptable the impact of pollutants released into the sea.

I.2 COLLECTION AND TREATMENT OF SEWAGE BEFORE DISCHARGE INTO THE SEA

I.2.1 Sewerage systems

Discharge of wastewater into the sea by means of an outfall system is the last link in a chain whose first link is the source of the polluted effluent: home, industrial plant, agricultural undertaking.

Between the two ends, the chain comprises basically a sewerage system and one or more treatment plants. If there are no such plants, the sewage discharged into the sea is "raw", but we strongly advise against this option, because the savings thus realised are as nothing compared to the negative impact of certain sewage components on the marine environment.

We will not discuss sewerage systems. Their technical features are classic and well known to engineers and specialists in this field; moreover, such systems do not bear on the stage of wastewater discharge into the sea. They do however have a serious impact on the operation of treatment plants; suffice it to recall here that the operation of such plants becomes all the more efficient when the sewage reaching them for treatment is as little diluted and as "young" as possible; when, in other words, it contains the least possible products of chemical anaerobic fermentation. Sulphites are the dominant tracer for urban sewage.

From this point of view, the greatest disadvantages are:

- A sewerage system of great length and low transit speed.
- A sewerage system receiving sewage from septic tanks, where intense anaerobic reactions have already taken place.
- A warm climate, which is most often the case in the Mediterranean coastal states.

Since these unfavourable conditions cannot all be avoided, recourse should be made to equipment of reoxygenation of effluents in transit (injection of air or oxygen in rising mains or sewers) or at the head of the treatment plant.

Contrary to the sewerage system, treatment plants have an appreciable impact on the conditions of wastewater discharge into the sea, since the composition of the effluent to be released depends on the treatment it received at the plant.

We can see then why "treatment plant and sea outfall" are the two parts of a whole which cannot be taken apart and must be the object of a study covering both facets; this study must be based entirely on sea water quality standards as were established above, which have to be met in the receiving environment.

Since these standards may vary from country to country, we will not be able to give a precise quantitative reasoning or one applicable in all cases, but when it becomes necessary to give a numerical example, we shall, as a rule, refer to the standards established by the European Economic Community (EEC) which are mandatory in their application for such Mediterranean countries as France and Italy.

However, it will be very easy to adapt the computations to other standards.

I.2.2 Concept of critical pollutant

Given a series of standards for various parameters such as: microbial species, pH, hydrocarbons, detergents, dissolved oxygen, ammonia, nitrogen, pesticides, heavy metals, cyanides, nitrates, phosphates, etc. the starting point for a study on wastewater discharge into the sea consists in determining the "critical pollutant" contained in the effluent; the critical pollutant is defined by the condition that the abatement of its concentration through dispersion in the marine environment will make the concentration lower than that provided for in the standard for the appropriate use of the waters at a greater distance from the point of discharge than for all the other pollutants covered by standards contained in the liquid waste. Therefore, the distance that satisfies the requirement for the critical pollutant will be the one at which the requirements for all the other pollutants will also have been met.

Thus, the type and composition of the waste discharged play an important role in the differentiation of the problem.

The most interesting case, because by far the most frequent, is that of urban effluents, consisting primarily of domestic sewage which is quite constant in its composition.

Moreover, when the standards to be complied with in the receiving medium are those established for bathing or shellfish growing, the critical pollutant for urban wastes is almost always the microbial load measured conventionally by establishing the content in test bacteria of faecal contamination: total coliforms, faecal coliforms and faecal streptococci. Since the concentration levels of these three species in raw urban sewage are roughly constant and in constant ratio with each other, the comparison between the ratios and the established standards shows which one of the three species is the critical pollutant. On the basis of the EEC standards, it is usually the total coliforms that are the critical pollutant.

The case of industrial effluents

Everything that will be discussed further on in this document applies to the case of typical urban sewage; however, it can easily be adapted to cover other effluents, in particular industrial ones, but in that case, the range of possible critical pollutants is too large to fit into a general scientific rationale. The principle is nonetheless the same as that given above.

The establishment of the critical pollutant results from the comparison between the concentration levels of pollutants in the waste and the concentration levels meeting the standards in the receiving environment for the uses set out for it. The critical pollutant is that whose concentration falls under the accepted standard the farthest away from the discharge point. Once the critical pollutant has been determined, the scientific rationale and the computations to define the conditions for discharge apply to this parameter only.

On the basis of the above definitions, a study on discharge of wastewater into the sea comprises the following steps:

- determine the geographical location of the marine areas, in which the quality of the waste must comply with standards, within the perimeter of the possible influence of the projected discharge and deduce, under the conditions set out above, the critical pollutant.

- verify, if need be, the minimum mandatory treatment of sewage prior to discharge into the sea, encompassed in national regulations.

- if such minimal treatment is mandatory, estimate its abatement factor on the critical pollutant.

- calculate, for the critical pollutant, the needed additional abatement factor between the discharge point and the sensitive area most threatened by the discharge.

I.2.3 Classification of pollutant categories

At this point in the procedure one must look at the technical and financial optimisations of the system i.e. on the one hand, the type and the degree of sewage treatment in the plant and on the other, the technical feasibility and cost of the outfall system.

Depending on the particular case and especially for reasons of marine environment protection or, in the case where the impact on critical pollutant concentration should make it an interesting alternative for the savings thus realised, it might be justifiable to opt for a higher degree of treatment than the minimum provided for in the regulations.

This is strictly a matter to be decided on a case by case basis; no precise rule can be given for the selection of the type and degree of treatment of sewage prior to discharge into the sea. However, certain indications can be given on the pros and cons of the various treatment systems.

From the point of view of marine pollution, one should analyse the various pollutant categories contained in the wastewater and the degree to which each one is noxious for the marine environment.

Pollutants, especially those contained in urban sewage, can be distinguished into four large categories on the basis of how they act in the environment.

1. Suspended solids

It has been established that they are very harmful for the marine environment, especially if they are very small. They are the most harmful category of pollutants contained in urban sewage because:

- Suspended solids reduce the penetration of sunlight into the water. This is particularly harmful in areas where the limpidity of the environment allows certain plant species to form true "underwater meadows", as is the case of zostera and posidonia beds in the Mediterranean. Turbidity caused by suspended solids raises the lower limit of such beds.

- Suspended solids can bring about the clogging of spawning grounds, thus compromising the reproduction of many species and can, in extreme cases, lead to the disappearance of fish and filtering animals sensitive to the blocking of branchiae (gills).

- Suspended solids serve as support to many pollutants adsorbed into them. This is particularly true of bacteria and viruses carried about by small particles; this hinders the normal self-cleansing action of the marine environment.

- The settleable fraction of suspended solids accumulates, through sedimentation, on the sea bed bringing about the asphyxiation of the benthic environment, especially in areas with low rate of water renewal. In addition, sedimented pollutants, if put back in suspension because of heavy swells, may affect water quality in a sensitive area.

2. Organic matter

Since almost all types of organic matter are biodegradable, which is also the case of urban sewage, they can be accommodated well by the marine environment; they bring to it the nourishment needed by living organisms and thus help replenish, to a certain extent, the quantities caught in fishing.

The risk for adverse impact appears only when either of the following two specific conditions is present:

- content or renewal of dissolved oxygen is inadequate to ensure biodegradation.

- the water is stagnant or insufficiently renewed.

Both situations are found either in enclosed coastal bays, where currents do not penetrate and where it would be counter-indicated to install an outfall system, or under the layer of density discontinuity or "thermocline". The latter is a frequent occurrence in the Mediterranean in the summer season.

In both cases, biodegradation of organic matter is inhibited by inadequate oxygen renewal resulting in a decrease of oxygenated compounds (sulphates, nitrates, phosphates). Thus all conditions for a dystrophic imbalance of the plant environment are assembled (eutrophication).

For this reason, if poor renewal of the waters at a certain depth from the surface is expected, a situation which is quite frequent in the summer in tideless seas, it is not advisable to discharge effluents at a certain depth because of the risk that the rising plume might be trapped under the thermocline. We will come back to this important matter later on in this study.

3. Toxic substances

They are of either inorganic or organic origin and frequently non-degradable retaining in time their toxic properties. Many heavy metals fall in this category. Urban sewage contains few such substances. When industrial effluents contain toxic substances in quantities large enough to create an unacceptable risk for the environment, then their elimination or the adequate abatement of their concentration before discharge cannot be expected to come from a treatment plant designed primarily for urban sewage. This operation should be carried out as a preliminary treatment of the effluent at the industrial plant, through the care and under the responsibility of the firm producing such toxic substances, and always by using the process recommended for the specific toxic substance to be eliminated.

4. Pathogenic micro-organisms

Their enormous variety and the extreme difficulty of the operation make it impossible systematically to detect and count them in any type of effluent. Since they most frequently move through the digestive tract, the probability of their presence and, to a certain extent, their concentration in an effluent are considered to be linked with the presence and the quantity of organic discharge, more specifically of human origin. Of this group, the intestinal coliform bacteria have been chosen as indicators, because they can easily be detected and counted. However, it should be kept in mind that these intestinal bacteria are not pathogenic organisms and are used only as probability indicators for the presence of pathogens; moreover, that the quantitative link between coliforms and pathogens, on which such studies are based, is extremely chancy.

The only thing measured by the counting of test germs of faecal contamination is the number of people whose sewage is discharged into the sea. In regulations worldwide however, no better indicator for possibly dangerous microbial pollution was found than these three families of test bacteria of faecal contamination.

I.2.4 What type of treatment before discharge into the sea?

Since this is the case and if we leave aside the persistent toxic substances, which constitute a source of exceptional pollution which should receive specific treatment and come under special regulations in the context of polluting industries, it is now time to ask the following question: how can one classify the other three pollutant categories in terms of noxiousness for the marine environment?

The main difference between the sea and inland waters (rivers, lakes) as receiving environments is the great tolerance, not to say a certain kind of appetite on the part of the sea for organic matter. This means that there is very little need for biological treatment of the discharge, since the essential objective of such treatment is to eliminate organic matter.

For the abovementioned reasons, suspended solids is the number one enemy of the marine environment. This is why some countries prohibit any kind of discharge without preliminary partial elimination of suspended solids. In France for instance, after preliminary treatment (screening and removal of sand and grease) it is mandatory to eliminate before discharge 90% of the suspended settleable solids (or 50 to 60% of the total suspended solids - MEST - for urban sewage).

These regulations are based on the fact that such results lie within the scope of the physical process of simple gravitational settling. If better results are desired - up to 90% of MEST - one must use a physico-chemical process of coagulation - flocculation of the various colloidal substances by means of flocculation catalysts such as lime, ferric chloride, aluminium sulphate, polyelectrolytes.

Biological processes (bacterial beds, biological discs, activated sludge, bacterial filters) give, to be sure, results at least as good on MES; they are not recommended however, unless most of the organic matter must be eliminated, but such a requirement would be exceptional before effluents are discharged into the sea. On the other hand, the biological processes present the following disadvantages:

- imbalance in the chain of treatment which takes long to correct, in the case of sudden variations in the load and flow rate of sewage coming into the treatment plant.

- decreased performance of the system when effluent septicity is high.

The first disadvantage is felt acutely in coastal tourist towns, where the fluctuations in the number of users are very pronounced on weekends and at the beginning and end of the holiday season.

The second disadvantage is a frequent occurrence in warm climates and where there is a long transit time of wastes in the sewerage system.

Since the object of this document is to study the phase of discharge into the sea and not the previous phases, we will not discuss sewage treatment further. But because the final composition of wastewater depends on the treatment it received before discharge and because treatment has important repercussions on discharge conditions, it was thought useful to touch upon certain specific aspects of sewage treatment prior to wastewater discharge into the marine environment.

We must bear in mind that, under normal local conditions, the marine environment is less demanding than inland waters; moreover that suspended solids are its main enemy and therefore that the physical treatment of simple settling which removes the settleable solids is always desirable and often sufficient. However, the small colloidal substances, which are the most noxious, cannot be removed except by a physico-chemical settling process of coagulation - flocculation, but the cost of sewage treatment is then higher.

I.2.5 Can one disinfect sewage before discharge into the sea?

In our discussion of treatment processes we did not include the elimination of micro-organisms. The reason is that the various methods are comparable and none is very effective when it comes to micro-organism elimination, since the abatement of concentration one strives for, between raw sewage and the standards covering "bathing waters" and "shellfish growing waters", is in the range of 10^5- 10^6; thus a factor of 10 - an order of magnitude possible for a treatment plant - is a negligible contribution to abatement and moreover one on which we cannot even count absolutely.

Now, since microbial pollution is in most cases the critical pollutant for the sensitive areas, the first thing that comes to mind in order to simplify the problem of discharge is to destroy the bacteria before the effluent enters the outfall pipe which in that case could be shorter and less costly. Furthermore, one can argue that the process already exists on paper; it is sewage "disinfection".

Here we must make the distinction between natural and chemical disinfection processes.

Chemical disinfection

The reasons why chemical disinfection is not as a rule desirable are numerous and relate to several complex fields.

This isn't the place to enter into a lengthy discussion on the disadvantages of chemical disinfection - a topic for another study; however, the unfavourable judgment we must pass on such processes, which in most cases are based on the bactericidal properties of an oxidising agent (chlorine, bromine, ozone), makes it imperative that we give forthwith certain explanations and justifications for our views.

Keeping in mind what was said previously about the chancy character of the use of test germs as indicators of microbial contamination, we must extend the restriction to the even more chancy character of the value of those same germs used as "indicators of the effectiveness" of disinfection treatment. This has to do with the fact that the destruction capacity of chemical oxidising agents - most frequently chlorine - is not the same on all germs, and that many pathogens, especially the viruses and many bacteria, have a much greater resistance than the test germs. Since in practice disinfection effectiveness can only be measured on the test germs, one has to be satisfied with only a semblance of safety which in reality is none at all.

There are additional reasons for which this process is counter-indicated, namely:

- effluents contain nitrogen compounds, especially ammonia, binding a large portion of chlorine in compounds such as chloramines, which are less bactericidal than chlorine, but toxic for marine fauna even in concentrations as low as 0,02 mg/litre.

- disinfection equipment is delicate in its operation, gets deregulated easily and since its constant monitoring is not always assured, one cannot rely on the continuity of the operation and thus on the system's efficiency. Now, any interruption would result in non-compliance with the microbial standards in the areas to be protected.

- Finally, the installation and operation costs of a chemical disinfection system, in need of constant and very careful monitoring, are high and in many cases prohibitive.

Summing up, we can say that the disadvantages of this type of treatment, whose effectiveness on the dangerous germs is neither guaranteed, nor controllable in practice, outweigh the advantages which only the assured continuity of operation would procure; but such is not the case.

Disinfection through natural processes

However, if the credibility of chemical disinfection is low, a natural process such as the use of solar radiation in a system of tanks is a lot more effective, because it has a relatively homogeneous impact on all the species of germs and its continuity is assured. Whether we are talking about a complete system of tanks for the treatment of raw sewage which guarantees the sedimentation of suspended solids (MES); the biodegradation of oxidisable matter and microbial disinfection; or about this last phase only in tertiary tank treatment, downstream from a classic treatment plant, this process is both low-cost and reliable and should be opted for in all cases were it is technically feasible. The main prerequisites are the following:-

- a flat and rather waterproof area, 1 to 2 hectares per 1000 inhabitants, in order that the waste remain in the tanks between 6 weeks and 3 months.

- a warm and sunny climate.

Since both of these conditions are easily found in many regions around the Mediterranean, the complete or partial treatment of wastes by using a tank system should be considered everywhere that the local situation permits.

The greatest advantage is that the waste thus treated is decontaminated and of a very low noxiousness; it can therefore be discharged at a small distance from the marine areas to be protected. Large savings are possible on the total outlay for a classic sea outfall system.

In effect, the effluent coming out of the system can easily meet the required standards for bathing waters of about 10^2 to 10^3 total coliforms per 100 millilitres.

However, it is not possible to resort to this method in all cases; it may be that for various reasons the site does not lend itself, or that the available area is not large enough, especially in the case of big cities. The solution then would be to obtain an abatement factor of the microbial load of between 10^4 and 10^5, through a different process, for the effluent between the treatment plant outlet and the quality of the sea water in a bathing area. The abatement factor rises to 10^6 if the area under consideration is a shellfish growing one.

For the reasons indicated above, it is very rarely advisable to resort to chemical disinfection; it is always preferable to try and obtain the desired result through dilution, because in that case one is certain that it applies uniformly to all germ species. The solution then would be to discharge the effluent at a certain distance from the sensitive areas; this would guarantee both an adequate hydraulic dilution and sufficient transit time; thus, concerning the germs, their own decay would be added to the dilution, given the self-cleansing capacity of the marine environment.

Both effects are equivalent to a dilution and the final abatement factor is the sum of the two. The method that takes greatest advantage of both is therefore the discharge of waste water into the sea through an outfall system of appropriate length.

The following chapters deal with computation methods concerning sea outfall systems.

CHAPTER I

GUIDELINES

By prolonging a sanitation sewerage system with a sea outfall, we not only put some distance between the discharge and the frequented areas, but in addition take advantage of the hydrodynamic mechanisms facilitating effluent dispersion. The first problem is to control these mechanisms and primarily the circulations of sea water masses.

Unfortunately, sea water is in constant search of an equilibrium which it never achieves because it is continuously affected by sea-air interactions. Oceanography is thus the reflection of meteorology and it is only measurements spread over a long period of time covering all the main meteorological situations that can furnish the required data.

Similarly, the study must cover a marine area large enough to allow a "bird's-eye-view" of the likely sites for the installation of a sea outfall. In no case must one - even if considerations alien to the marine environment should incite in that direction - first pick a site for the outfall and then organise the field investigations uniquely as a function of this choice.

The plan of the outfall must derive from the study of the marine environment and not vice versa.

Taking into account the average speeds of currents most frequent at sea and the time scale of bacterial decay, we conclude that the area to be investigated should range between 10 and 20 km^2 and the follow-up time of the fate of the effluent between 3 and 10 hours.

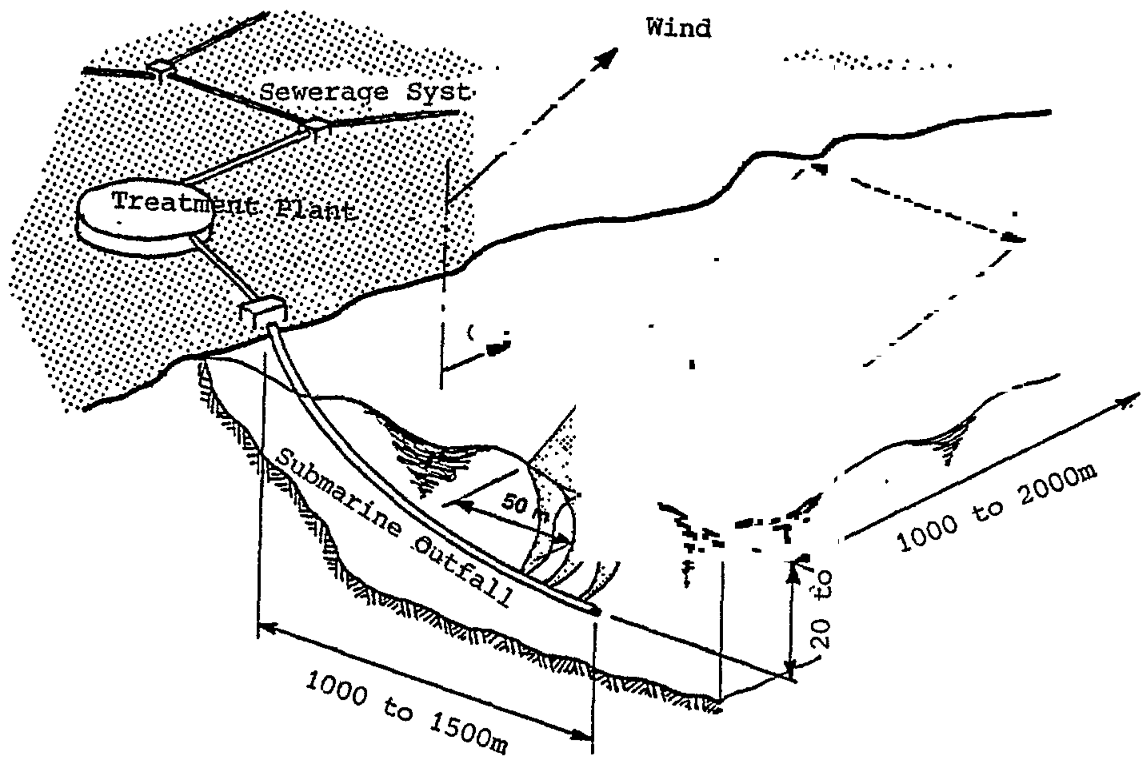


Figure 1: Schematic spread of effluent discharged into the sea

Until proven otherwise, the marine environment should at first be thought of as made up of a series of liquid layers, horizontally homogeneous, but vertically independent because of different densities. Consequently, studies and measurements should be carried out in sufficiently deep zones, where a thermocline can occur, or near the mouth of rivers.

1.1 GENERAL INFORMATION ON FIELD MEASUREMENTS

Because of the complex character of oceanic movements, especially near the coasts due to the thrust on the shore, the low depths and the ensuing friction, it is hardly ever possible in practice to obtain the required data without carrying out measurements at sea. But the sea is an aggressive and moving environment: the work is difficult, the loss or deterioration of measuring equipment frequent. Thus, one must allocate funds commensurate both with the difficulty of the task and the interest of the data sought. Similarly, the time allotted is considerable: well over a year between the decision to carry out the study and the availability of data which have been processed with a view to decision taking on the sea outfall. Indeed, it is necessary that field measurements cover all periods critical for the impact of discharged effluents: mainly and almost in every case the summer season. One must also provide for gaps in the recording, due to the inevitable failures of the recording equipment immersed in the sea water and take into account the variability of the phenomena to be measured.

A reasonable length for the phase of operations at sea to complete measurements would be between 3 and 6 months, depending on the size of the project, the type of the sensitive areas to be protected from pollution and the complexity of the topography. The summer season must be covered because the most critical cases of pollution occur as a rule when the waters are calm, the volume of discharge flow increased because of tourist influx, water temperature favourable to the growth of all biological species and especially because bathing water quality should mainly be monitored during the bathing season*. In the shellfish growing areas one must also study the risks of pollution during the periods of intensive harvest.

Measurements should cover a period which is sufficiently long in order to observe all winds of dominant direction and intensity and to increase the probability of observing important exceptional phenomena, such as thermocline tilting, internal waves, etc.

If one limits oneself - as one is often tempted to do for reasons of economy or urgency - to a field study of inadequate duration, then one runs the serious risk of basing one's conclusions on incomplete data.

The marine area to be investigated cannot be covered only by batch. topical measurements, even if in sufficient number. The only valid strategy consists in combining continuous measurements by means of fixed recording instruments with several charts of current trajectories (on the basis of data on prevailing currents) which are followed by a dye tracer or better yet by a set of drogues. This method is interesting, not costly, and at the present time the best. In the future however, new measurement techniques either airborne or through the use of satellites might furnish new solutions.

---

* Attention, from this last condition it follows that consultations and all preparatory work must be carried out at a time of the year which would allow measurements at sea to begin before the onset of the summer season.

Sea water is never homogeneous and density differences, even if slight, play a fundamental role. Even the fifth decimal of the number measuring this density is important**. For instance, a temperature variation of 1 degree centigrade changes sea water density by 0,00025 or 250g/m^3. Such a small difference is enough however to ensure the buoyancy of the layers of sea water one on another and practically to stop any vertical exchange. The effect of salinity is more pronounced yet.

The density stratification of sea water has the following two consequences:

- Field measurements are absolutely necessary to get information on it.

- Measurements of currents must be carried out at various depths and always through the use of several current meters on the same vertical. The measurement of density is deduced from the twin measurements of temperature and salinity, both fundamental parameters in all oceanographic studies. All current meters should be fitted with the appropriate sensors and since all models on the market come equipped with them, one should avoid taking only the temperature readings: the savings are negligible but never justified since the operation is totally discredited.

One can also use temperature and conductivity chains; this is a recording device fitted upon demand with 5 or 11 sensors staggered on it.

Diffusion due to the turbulence of sea water flow depends primarily on the horizontal shear between liquid layers moved by different velocities. Shear intensity is linked to friction, in other words to the wind and the rugosity of the sea bed. The parameters measuring diffusion are not physical constants, they vary in time and space. Thus, the corresponding measurements must be repeated several times. Only a very strict protocol for the experiments will allow correct interpretation of such measurements which can be carried out by using a dye tracer or better yet a set of drogues.

To determine experimentally the vertical turbulent diffusion is a difficult problem, which has not found a satisfactory solution as yet. The best approach is to carry out sophisticated simulation computations of turbulence.

Field measurements concerning bacterial decay are possible but the operation is complex, costly and generally not very reliable, unless carried out by experienced specialists using sophisticated equipment. The reasons for the lack of precision and the variability of the phenomena to be measured are such that valid results are obtained only by a series of one hundred samples and frequently many more than that. Therefore, it is in most cases preferable to forego any such measurements and to use instead the published values of the parameter T_{90}, especially since these values vary very little from one point of the globe to another.

For measurements at sea to be effective, one needs a painstaking preparation of each cruise and equipment that is carefully verified and calibrated. The operations plan to be established in advance ought to be precise to the minute, taking into consideration the difficulties of marine work and the time for manoeuvering. For optimum results, the number of measurements should be increased many times over.

** See Appendix E

Some gross errors, committed occasionally, ought to be avoided, mainly:

- Measuring the temperature of sea water at different depths by pumping it onto the operations vessel. A chart produced thus will give a vertical profile of temperature of no value whatsoever, since the precision sought is to the tenth of one degree.

- Measuring the surface velocity of a wind generated current with a current meter immersed to a depth of about -2m. The true surface velocity is often 2 to 10 times higher.

- Measuring turbulent diffusion while crossing over the area marked by the dye with the operations vessel because this interferes with the course of the dye. This disadvantage is more acutely felt when using the experimental method of a radioactive tracer, since measurements must be carried out in the marked off area.

- Using teledetection methods without simultaneously controlling at sea all the parameters measured and without taking into consideration the degree to which the radiation used penetrates into the sea water.

- Trying to establish the law governing effluent dilution by inferring it from a small experimental flow marked by a tracer. This inference is totally unacceptable, because the law of dilution depends essentially on flow and this means that measurements should be carried out in an environment which complies with all laws of similarity, the basis for all scale models.

- Linking the configuration of currents to a specific meteorological situation without taking into account the considerable inertia in current response after a wind regime has been established.

- Measuring the diffusion coefficient by using a dye tracer, while assuming an instantaneous size of the patch at its origin; this is not really the case given the <u>modus operandi</u>.

1.2 <u>ENVIRONMENTAL STUDIES</u>

The engineer, who because of existing regulations must protect the marine environment, ought not to consider only the direct impact of pollution on Man, but ought also to take into consideration the very serious effects of effluents on the species living in the sea.

In the first phase, one can concentrate on the effects on the flora covering the sea bed and on the fauna living on it or hidden at small depths under it in the sand or mud. The sedentary character of the epiflora (algae fixed on the soil) and of the macrobenthos (organisms larger than 1mm living on the sea bed) makes them accurate witnesses of the state of the marine environment. They "integrate" or "average" the variability of local living conditions, the physico-chemical qualities of both the water and the sediments.

1.3 DILUTION STUDIES AND SEA OUTFALL PROJECTS

The study of the marine environment, which precedes the installation of a sea outfall system, consists in computing the effluent dilutions and residual concentrations at every point in the impact area, starting with each possible discharge point. A point of discharge will be acceptable if the ensuing pollutant concentrations are compatible with the standards of water quality for the sensitive areas to be protected against pollution (bathing areas, shellfish growing areas, etc.).

As a rule, the method consists in applying this computation to several discharge points, starting with the one presenting the greatest advantages and moving down the list, taking into account parameters such as economy, ease, proximity to a treatment plant existing or planned. The process stops as soon as one finds a point satisfying the conditions of acceptability set out above.

Such a computation of effluent dilution and residual concentration is only feasible - for certain phases of dispersion and if one wants the best approximation possible - by means of mathematical models which although complex are not yet perfected. Nevertheless, the application of the simplified methods described in Chapter 3 offers an adequate approach for a solution in the most frequent cases, provided that the hydraulic mechanisms involved and the limitations on the validity of the formulae due to the simplifying assumptions are thoroughly understood.

1.3.1 Phases in the course of the effluent

The final concentrations of pollutants, which we want to achieve at every point within the impact area of the effluent discharged, are the direct result of the combination of the partial dilutions computed during each of the phases which can be distinguished in the transfer of the effluent. These phases are in most cases three:

(1) Rising phase from the discharge point on the sea bed toward the surface.

(2) Phase of horizontal transport by the currents from the level reached in the previous phase.

In the case of persistent pollutants total dispersion is the result of the above two phases exclusively.

(3) For non persistent pollutants (detergents or other biodegradable matter, bacteria, etc.) the law of decay as a function of time forms the basis for the calculation of an abatement factor equivalent to dilution.

Total dilution is the sum of the three partial dilutions. More detailed information on these computations is given in Chapters 2 and 3.

However, it might be useful to give now certain orders of magnitude in order to illustrate the relative importance of each of these three phases in terms of its contribution to the total dilution.

In effect, because the computations for each phase are different and because precision is obtained in each by the use of models of a different level of sophistication, it is important to realise the varying degrees of interest in obtaining precise results for each phase, depending on its importance for the final dilution.

The following table gives an idea of the relative importance of each phase for the abatement of concentration of test germs (a parameter of critical pollution in almost all cases of urban effluents).

Concentration of total coliforms in 100ml of urban effluent European guide standard* for the quality of "bathing waters" expressed in total coliforms in 100ml of water			10^8 5.10^2
Total dilution needed			2.10^5
Abatement (equivalent to dilution) obtained by biological or physico-chemical treatment excluding disinfection			1 to 20
First Phase Rising Plume	Dilution by turbulent diffusion	with diffuser without diffuser	2 to 100** 10 to 1000**
Second Phase Horizontal transport for 1000m	Dilution by vertical and horizontal diffusion		5 to 20***
Third Phase Bacterial Decay	Equivalent to dilution	after 3h after 6-8h after 10-15h	10 100 1000

* Mandatory standard in force in the countries of the European Economic Community (Directive of 8 Dec. 1975) with which all new discharges must comply.

** Increases roughly by the power of 3/2 of the depth.

*** Increases with the movement of the sea surface.

We can see then that:

- The first phase will give considerable dilution if the depth is sufficient and the sea outfall is equipped with an efficient diffuser. The calculation of the corresponding dilution is simple and the level of precision high.

- The dilution equivalent resulting from the third phase increases with time at a slightly lower rate than it would according to an exponential law. For a common type of sea outfall, the order of magnitude can reach 100. The calculation is very simple on the basis of the value adopted for T_{90}; the precision is a function of the accuracy of this value which is not normally measured at sea.

- Compared to the dilution obtained in phases one and three, routinely of the order of 10^4, the contribution of phase two is always small. Now, it is precisely this phase for which the computation is both complex and very imprecise. Thus it is often acceptable to forego the calculation and adopt a priori a conservative average value, because even a not so small error will have a very small impact on the final result.

However, one should keep in mind that, if in a particular case one must absolutely obtain a more precise value for the dilution coefficient, the problem can only be approached through sophisticated mathematical methods (see Chapter 3), since physical measurements such as simulation by tracers are of no help at all.

The grave error which is at times committed is to allocate to such a simulation - which is costly - a large part of the total funds committed to the study, while the result is totally devoid of sense, since the dilution measured on a small experimental discharge can neither be applied as is, nor extrapolated through a computation, to the considerably larger flow of discharge in the system under consideration. This basic impossibility has to do with the fact that there is no law of similarity linking dilution due to turbulent diffusion with flow.

On the other hand, the tempting solution to reduce bacterial concentration in sewage through chemical disinfection after treatment is almost always to be avoided for all the reasons given in the Introduction.

1.3.2 What to measure at sea and why?

From the above one could come to the conclusion that, in order to determine the concentrations resulting from effluent discharge in the impact area, very few field measurements are needed.

Indeed:

- With the exception of effluent trapping because of stratification, dilution in the rising plume depends only on depth, sea outfall design and the characteristics of the effluent discharged.

- Bacterial decay will more often than not be calculated on the basis of a classic T_{90} value adopted a priori.

- Finally, we have seen that the phase of horizontal convection:

  (a) cannot be directly measured at sea, and

  (b) that it does not often pay to use sophisticated models, both because they lack in precision and because generally this phase of transport brings a small contribution to the final dilution.

However, a study for the installation of a marine outfall system must of necessity include field measurements for the reasons and objectives defined further on, which are substantially different in the case of a sea with tides from what they are in the Mediterranean. The latter is presented now in comparison and contrast with areas subject to considerable tidal range.

1.3.2.1 Tidal seas

In this type of receiving environment, tides play a predominant role.

Field investigations on the direction and velocity of currents in the various tidal phases and for different tidal coefficients form the basis for the acquisition of data needed for the selection of discharge conditions.

The main part of the field study will consist in establishing a map of currents by traditional means (recording current meters, dye tracers and floats). Obviously the study must also include, obtained by the same means, one or several values (for different meteorological situations) for the coefficient of transversal horizontal diffusion Ky. In order to carry out field measurements of the diffusion coefficients one can use several methods: dye tracers, radioactive isotopes, drogues which have to be accompanied by aerial photography. However, when carrying out this type of measurement one must not forget that the coefficients do not have an absolute value at a given point and that they vary considerably depending on the meteorological conditions and the state of the sea. It is therefore necessary to perform these measurements in that local situation, which through other means has been established as the most unfavourable for pollutant dispersion.

More difficult, but useful - if one can determine it - is "drift", i.e. displacement of water molecules as a result of several tidal cycles. It can provide interesting information on the long-term course of certain persistent pollutants which remain noxious even after very strong dilution.

Information on marine circulations obtained in this manner will be useful in establishing the most unfavourable conditions of currents from the point of view of pollution risks for sensitive areas. This "most unfavourable situation" will give the time of transport to be introduced into the computation of test germ decay.

The vertical profile chart of temperature and salinity which can be easily incorporated in the field study will give useful information in certain cases, but especially where it is feasible to plan a sea outfall at considerable depth.

1.3.2.2 Tideless seas (Mediterranean)

The main differences with the previous case are the following:

(a) The absence of tidal currents causes marine circulation to be influenced mainly by winds.

Currents are a lot less regular than those to which tides confer a periodic character. In addition, because they are generated at the sea-air interface, they do not affect the masses of sea water below the surface, except through the combined effect of viscosity and turbulence, i.e. in a delayed and irregular manner, thus giving rise to strong vertical velocity and direction gradients. The chart of currents will take the form less of a general map and more that of a series of configurations corresponding to that of the winds.

(b) The strong summer sunshine, of nychthemeral rhythm, gives rise to intermittent heating, decreasing as one goes down in depth; that translates into a vertical heat gradient with lesser or greater level differences; this is the phenomenon called "thermocline".

Because a thermocline can trap the effluent plume at intermediate levels, when the discharge is at a depth of more than 20m, field charting of the configuration of currents through readings at various depths on the same vertical must also be accompanied in the summer season by several vertical temperature profiles; the latter will illustrate thermocline development in terms of the meteorological conditions.

Field measurements will thus provide all the elements necessary in order to establish the most unfavourable situation as far as the pollution risk for the most threatened sensitive areas is concerned. This situation may be either a fast beating down current, or a period of great calm, which does not promote turbulent diffusion, or even effluent trapping by the thermocline followed by a strong land wind which does away with the thermocline and carries the pollution toward the sensitive areas.

This is the general concept and some guidelines concerning the preliminary field investigations at sea, an operation essential for the selection both of the discharge point and of the design characteristics of the marine outfall system, in all cases where sewage flow is considerable.

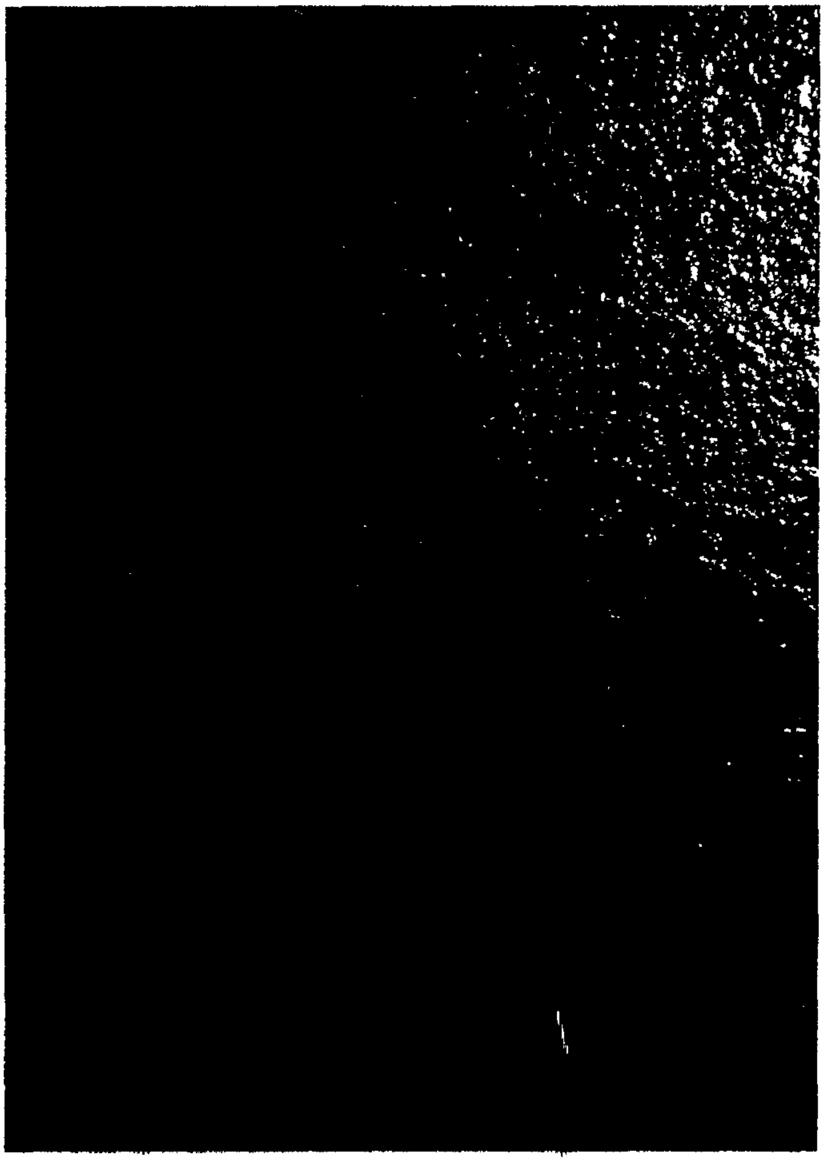
Obviously, the larger the outfall, the more detailed the studies.

For very small projects it might even be sufficient to use only the approximate indications resulting from a general study covering a considerable stretch of coastline such as the "Scheme for the improvement of coastal waters", the principle of which is given in Appendix G at the end of this document.

1.4 COST OF THE FIELD MEASUREMENTS

It is very unfortunate that quite often a study for the installation of a marine outfall system misses its objective totally or in part either because, if it is poorly designed, it is not cost effective, or because inadequate funds were allocated to this "accessory", considered as such that is by the Construction Manager, in other words as a more or less useless source of expenditure or as a regrettable waste of time. This is why frequently any solution is considered good provided it keeps the cost down: fixing from the start the scope of the operation in a very miserly way; setting a low ceiling on expenditure ne varietur; or most often selecting that firm whose proposal is characterised either by the greatest parsimony - which is a clue that unreliable methods will be resorted to - or by certain appealing "extras" that add nothing to the value of the results.

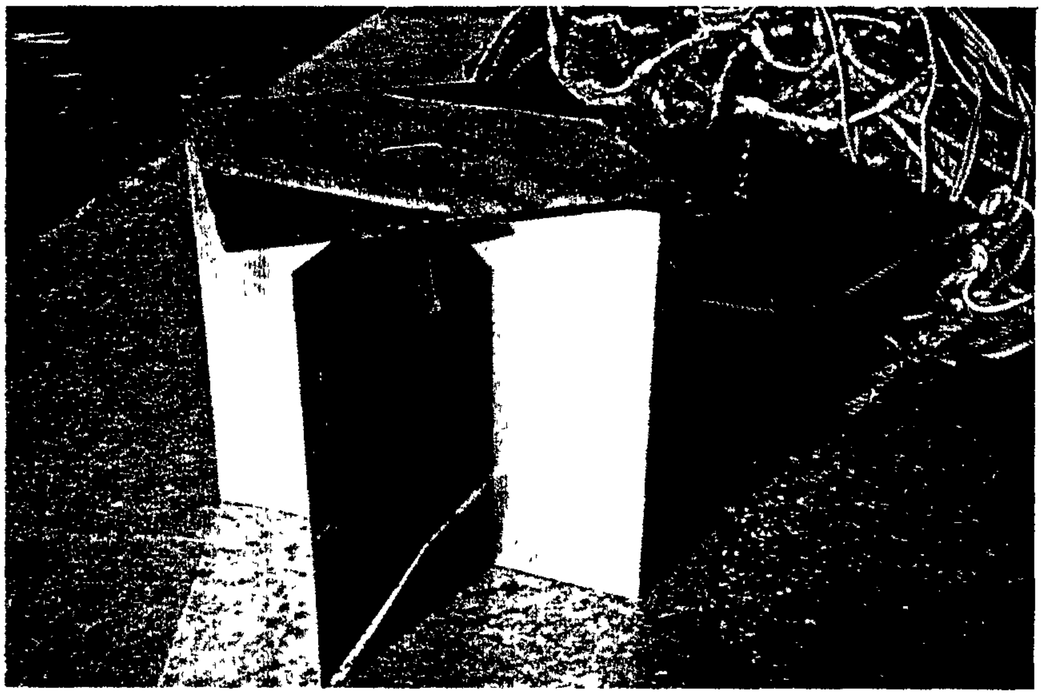
Let us be honest: if the supposed technical justification of a project, whose characteristics have been decided in advance - serves no other purpose but compliance with regulations and completion of a file submitted to the authorities for consultation or approval; if these authorities do not always have the possibility or the courage to ask for and get technical justifications worth their salt, then it would be best to be honest and not spend money on a study; because if the study is poor (and conceived in that spirit it will most certainly be inadequate) that money will have been thrown out of the window.



Eddy diffusivity measurements at sea using dye (Rhodamine) or a large number of buoys. The white strip is 10 metres long

Flow is from top to bottom of the photograph. Note the pronounced dissimmetry of the dye mark induced by shearing flow. (Differences of celerity with depth resulting from wind effects)

Buoy with a drag



Now, what is the expenditure for a solid study on the installation of a new outfall, given on the one hand the absolute technical necessity for such a study and on the other the total cost of a sewage disposal system?

Obviously the cost of the study varies with the point of discharge; it varies very little in terms of the flow of discharge. It varies from about 0,5% of the total cost for an urban centre of 500,000 people to 3% for 10,000; thus one cannot overstress the point that those in charge of technical control should recommend, if not require, good, solid studies.

Moreover, from a good study two things can result: savings on the total expenditure, which generally exceeds the cost of the study and at least a certain guarantee against the technical uncertainties and risks.

In effect, the installation of a submarine outfall system is in any case a costly and risky operation. In addition to the essential aspect of environment protection against pollution - which is the main object to this study - other aspects of the construction of the outfall will be highlighted by the study on the installation of a sea outfall. Thus, the type and the profile of the sea bed, the area available on land for the construction works are factors which will have an impact on the construction and installation techniques and will affect the selection of the installation site. Protection of the works from wave action, the risks presented by a sandy beach to which the sea can cause accretion or erosion are all problems to be studied thoroughly.

One must also convince the Construction Manager that a sea outfall system must be constantly monitored and almost always, after a certain period of time, fortified with protective works. Unfortunately, many outfalls are damaged in their portion lying in the "surf zone". This happens because in most cases:

(a) no good study for the protection of the outfall exists, and

(b) there is a lack of maintenance of the protective works.

Chapter 4 of this study gives some indications on these civil engineering matters.

CHAPTER 2

PROTOCOL OF STUDY OF THE MARINE ENVIRONMENT WITH A VIEW TO INSTALLING AN OUTFALL SYSTEM

We have just given the main reasons why such a study must be carried out: its main purpose is to furnish the local environmental data that will determine the characteristics of the proposed sea outfall system.

We must now define the how. This is the object of the present chapter; its scope has on purpose been limited to include only such information as is necessary and sufficient for the drafting of the protocol of investigations and field measurements. This protocol will be the basis for the technical mission entrusted to the person appointed to carry out the preliminary study.

The Chapter is supplemented - in Appendix A at the end of this document - by a standard model of technical specifications to be used in connection with Consulting services or for the drafting of contracts for the study.

The data presented here will be supplemented in Chapter 3 - entitled "Behaviour of effluents discharged into the marine environment" - by technical explanations and comments which will shed more light on all facets of the case and will lead to a better understanding of the subject if one wishes it; they will also, to a certain degree, help in interpreting correctly and analysing effectively the data furnished by the study, in view to decision taking on the characteristics of the sea outfall system.

This two-step presentation aims at separating, thus making them more directly and more easily available, the data which are of interest to two different groups of users with different objectives and perhaps also different degrees of technical knowledge.

2.1 PRELIMINARY DATA

The study of the marine environment under consideration will illustrate the behaviour of the effluent to be discharged into the sea; however, before proceeding in this direction, one must determine certain preliminary elements which will define:

- the effluent characteristics: flow, degree of treatment, physico-chemical and microbiological composition.

- the known features of the receiving environment: geography, bathymetry, general currents, tides, winds (meteorological statistics), use of the sea, quality standards in the areas to be protected against pollution, type of sea bed (possibly granulometric analysis).

Depending on the particular case, such data will either be furnished - in more or less complete form - to the person responsible for the study or, if not available, that person will be asked to provide all such information.

It should be noted that the type and degree of effluent treatment prior to discharge will be in certain cases (and the best ones to be sure) not a preliminary element of the study of sewage dispersion in the environment but will result from it.

In particular, in the case of an effluent such as urban sewage - for which existing regulations provide for mandatory sedimentation to eliminate the majority of the settleable suspended solids - the environmental study might prove the need for a higher degree of treatment.

To avoid unpleasant surprises, observed frequently, it is always very important to know the exact type of effluent pollutant loads. Certain industries may release into the sewerage system toxic substances which are practically non-degradable or capable of chemical reactions in the sea water, while hospitals and slaughter-houses increase the risks of bacterial contamination. Regardless of whether there is or is not a sewage treatment plant, the impact of all such substances should be carefully looked into.

It is only then, and on the basis of the data thus gathered that measurements at sea can begin.

2.2 GUIDELINES FOR FIELD MEASUREMENTS

The field study must provide all data needed to establish the total dilution of pollutants between the point of injection into the sea and the various sensitive areas, whose waters are covered by quality standards and which are likely to be affected by the pollution discharged.

The phases of effluent dispersion defined in the previous chapter lead to the establishment of the following list of elements to be measured or monitored in the field, all essential for the computation of dilution and for the establishment of the pollution map before the outfall system becomes operational:

(a) Temperature and salinity of the sea and their variations depending on depth.

(b) Map of the topography of the sea bed.

(c) Surface currents and currents of the surface layer in conjunction with tides and winds.

(d) Turbulent diffusion coefficients.

(e) Currents at depths where the effluent is likely to be trapped by the thermocline.

(f) Initial state of the benthic flora and fauna and of the various types of sediments (mud, sand, gravel, etc.)

(a) and (b) do not present any difficultiès. The others are dealt with further on.

To carry out such measurements, one must keep in mind two things:

- The variability of marine circulations highly dependent on meteorological conditions.

- The risks of marine work.

Strictly speaking, the survey of the parameters measured at sea should cover the annual season cycle. If the argument against such a practice is cost, one may point out both the price of a sea outfall system as well as that of a treatment plant and the risks incurred if the project proves inadequate.

In the climatic conditions prevailing in the Mediterranean, the most critical period for pollution coincides in most cases with the summer season. Indeed, it is then that winds and currents are extremely light and it is in the summer that heat stratification of the water may occur; this means that contaminant disperson will be the poorest.

On the other hand, measurements at sea are difficult and subject to many accidents. Risks for equipment include: Corrosion, water tightness, alternating stresses due to the swell, deterioration caused by the users of the sea. All of the above can cause interruptions in measurements.

Experience has shown that field measurements should be carried out during a period lasting as a minimum 5 to 6 months, provided the summer season is included.

Two types of measurements are possible:

- Permanent measurements with the equipment recording continuously, but the results are restricted to specific points.

- Measurements covering a marine area but which at the present time are intermittent since they require the intervention of human operators.

The two methods should be combined: the first gives a statistical basis and the second allows a large scale and detailed investigation of the marine area under consideration.

We should stress the importance of carrying out perfectly simultaneous measurements in a medium which is in constant search of equilibrium. Let us emphasize that:

- To install a current meter while ignoring whether it is submerged above or below a stratification limits the scope of the data obtained.

- To measure temperature but not salinity means obtaining the fourth decimal of density while ignoring everything of the third.

- To assess the parameters of turbulent diffusion by means of a dye without simultaneously measuring the vertical distribution of velocities and without monitoring the presence or absence of stratification means ignoring the links between these magnitudes and makes any transposition of the data to other flow conditions impossible.

2.3 MEASUREMENTS BY MEANS OF CONTINUOUSLY RECORDING EQUIPMENT

Continuous recording of several parameters is now possible thanks to more sophisticated electronic equipment. Without mentioning all the latest equipment available, we can state that there are two types of instruments giving an answer to the problem: current meters and measurement chains of temperature and conductivity (from which salinity can be deduced).

The classic type of current meters can be fitted upon demand with supplementary sensors for the measurement of conductivity and pressure; they must always be used. Even if not very accurate, the pressure sensor will furnish the time in relation to tide and at the very least the exact depth of instrument submersion. This will do away with any possible confusion if several instruments are used at the same time.

Not so well known are measurement chains for temperature and conductivity which are made by certain manufacturers. This type of instrument is made up of a cable on which are distributed 6 temperature and 6 conductivity leads. The case, similar to that of a current meter, records at predetermined intervals (every 10, 20, 30...mn) the readings from the 12 leads.

All those instruments record the results directly onto magnetic tape of the mini-cassette type; the data can later be automatically processed on computer (fig. 3). In this way one can obtain: the laws governing the evolution in time of the magnitudes measured, the rose of currents, a spectrum analysis of the components of velocity due to tide, the component of velocity in a given direction etc.

These various instruments are installed in the sea down the length of cables stretched between a mooring buoy and a float submerged under the surface layer (fig. 2). Several instruments can be attached on the same cable if necessary. A tender buoy equipped with a light signals the installation to seamen. The installation is difficult and should be left to specialists. The weight of the mooring buoy must be sufficient to ward against any risk of dragging, the attachments well adapted to resist stress and corrosion. To install and remove the equipment one needs a boat fitted with a cargo boom or a winch, since the mass to be manipulated can reach several hundred kilograms.

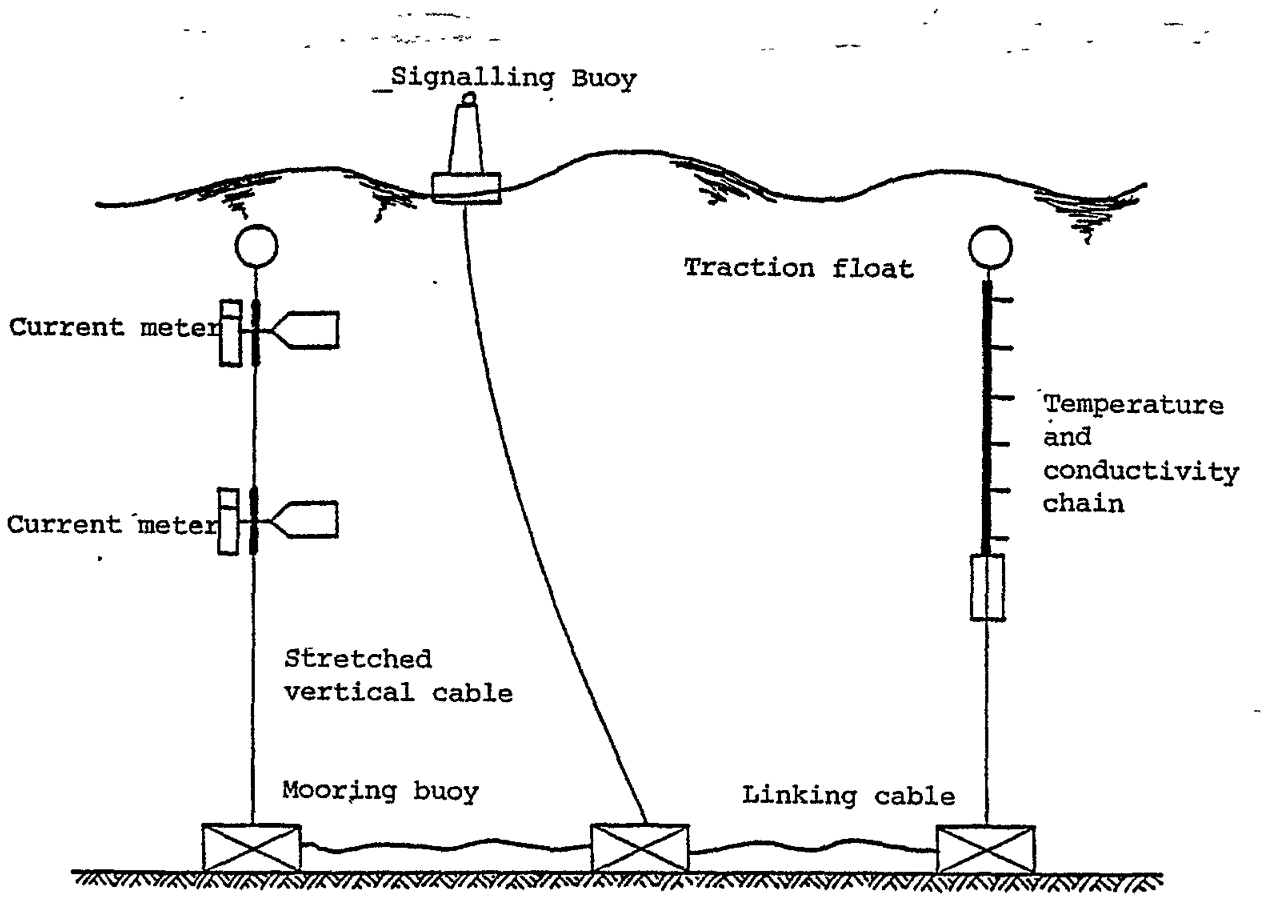


Figure 2: Schematic representation of installation of current meters and temperature and conductivity chains

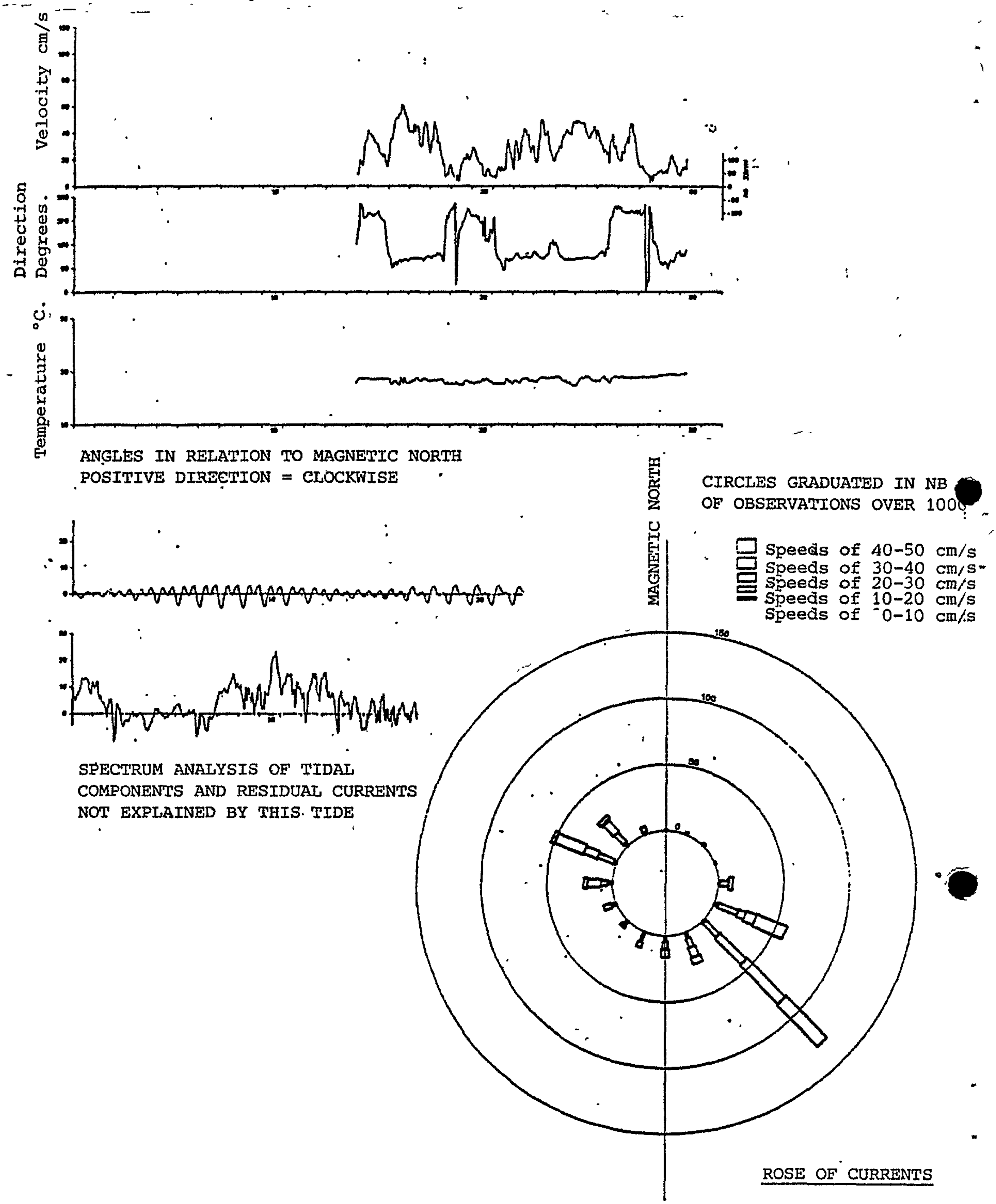


Figure 3: Example of automatic processing of data relating to currents
(CORMORAN PROGRAMME)

If an accident should occur, the cable linking the mooring buoys facilitates recuperation, by dragging, of the instruments fallen to the sea bed.

Even if the self-recording equipment can function up to several months, it should be checked out more frequently (once a month or once every two months), in order to prevent some very real mishaps: uncertainty as to the life of electric batteries, instruments jammed by premature growth of algae or animal species (fouling) etc.

With the exception of areas where depth does not exceed 10m, it is always useful to install several current meters on the same vertical. The cost of using an additional instrument is practically negligible if compared to the total cost of the field study.

The installation of a temperature and conductivity chain is especially necessary in cases where there is good reason to expect heat/salinity stratifications. This is the case in depths exceeding 20 or 30m and near the mouths of rivers. However, given the importance of the phenomena relating to density in the structure of oceanic circulations, it is advisable systematically to measure these parameters.

2.3.1 Organisation of the continuous measurement campaign

Maintaining continuous measuring equipment at the same spot for a long time (at least 5 to 6 months) makes, as a rule, problematic for reasons of time and money the solution of installing such equipment at different spots in turn. Since on the other hand, the most useful solution would be to install from the beginning such instruments at close proximity to the future effluent injection point, the first difficulty we find ourselves confronted with is precisely selecting this point which in turn would mean that the problem had already been solved.

If on the one hand, as explained above, one must not sidetrack the environmental study from its objective by making it confirm the merits of a particular discharge point selected in advance on non-technical grounds (mainly expediency), it is equally important on the other hand to pare down the list of possible sites through preliminary research and rough estimates. The latter could be based on the results of the simplified computations given in this chapter, computations into which one can introduce at this stage estimates for the values of the parameters to be accurately defined through field measurements.

In addition, by taking into account environmental factors such as the location of urban areas and of the effluent treatment plant (existing or planned), the morphology of the shore and of the sea bed, the general current picture, the benthic flora and the sensitive zones to be protected against pollution, we can obtain from this initial paring down one or several (depending on the case) possible discharge areas.

The installation of the fixed verticals on which the instruments are attached will be made in terms of the discharge area one considers in advance as the most suitable. Where several areas appear promising, it would be desirable to install a more or less complete set of instruments simultaneously in each of the areas. If this is not feasible, assuming that the second best site is not too far from the first, perhaps one could carry out a shorter and possibly simplified measurement campaign at this alternate site; one could then transpose the results obtained at the first site by comparing them with the batch measurements of the first campaign, the latter having normally covered an area wide enough to include all the various discharge points under consideration.

On the other hand, it would most definitely not be a good solution, if one had to give up the installation of the sea outfall system at the site where instrument measurements had been carried out and decided to install it at a different site without proceeding to any measurements there. This would be deciding in the dark after having spent money for nothing.

Having come to a decision on the point(s) of instrument location, both the choice of sensors and the installation and use of equipment will follow the principles outlined in paragraph 2.3 above.

Depending on the case and in terms of the particular characteristics of a discharge site, it may be considered necessary to carry out continuous measurements (generally for a shorter period of time) at one or several additional points in the effluent dispersion area. This decision is to be made on a case by case basis.

2.4 BATCH MEASUREMENTS

Measurements carried out through the use of current meters form a data base indispensable because of its continuity in time but inevitably limited in terms of space; obviously it is not feasible to install the very high number of instruments required to cover (by measuring all the necessary parameters) the vast marine area of effluent dispersion. Thus one needs to carry out the investigation through other means, primarily batch measurements.

There are several different such techniques. Those useful to us here are mainly:

- Study of currents by using either dye tracers or drogues, the latter being better for measuring currents at a determined depth.

- One can use the same method and add radioactive tracers to measure diffusion coefficients; in this case however aerial vertical photography must accompany the procedure.

- Instantaneous measurement of both salinity and temperature with an instrument such as a reversing thermometer. Simultaneous measurements at various depths on a vertical will give a chart of temperature profiles establishing the density gradients (picnoclines) characteristic of stratifications affecting dispersion dynamics in several ways.

- This measurement can be accompanied (if one uses the appropriate sensors) by the measurement of several other parameters to be selected on a case by case basis to cover specific needs. In addition to temperature, multi-parameter leads can measure salinity, pH, dissolved oxygen, turbidity, content in chlorine, lead or copper ions, etc.

- Instantaneous plotting of the vertical profile of the horizontal current velocities at a certain point.

- Finally, even if very complex and in almost all cases counter-indicated in the context of a field study at a particular site, let us mention pour mémoire research into the law governing decay or transformation of a non-conservative pollutant (biodegradable matter, bacteria, etc.).

2.5 COLLECTING DATA ON CURRENTS

2.5.1 By drogues

The measurements which are the most important for us here are those leading to the establishment of a chart of currents which will transport the effluent away from the point of discharge, under various tidal situations and meteorological configurations (wind), among which one must identify the most unfavourable conditions for the protection of the sensitive areas against pollution.

In order to accomplish this, the best and least costly technique is the use of drogues. It has the advantage (especially over the other methods of following the trajectories of water masses, such as tracers dissolved in the mass, dye or radioactive materials) of ensuring the separation of currents to well determined depths corresponding to the drogue levels. The slight error resulting from the impact of the surface current and of the wind on the floating crew is largely made up by the advantage just cited.

This procedure is relatively easy to put into effect if one is methodical and careful. It is based on the principle of following the drogue trajectories either by topographical surveying or other more sophisticated techniques. The drogues consist of a crosspiece of light aluminium sheet called "drogue" and a float.

The difficulty from the point of view of mechanics is to obtain a contraption which does not catch the wind at all, but which maximises the hydrodynamic movement of the drogue. In this connection, the crosspiece is an effective solution. The balance of forces acting on the crew requires that the weight and the thrust are preponderant over the entrainment of the drogues, otherwise the linking cable will slant too much.

A practical realisation of this principle consists of a circular plate of 40 to 50cm in diameter, cut into plywood of 10mm thickness. The drogue will be of aluminium sheet 0,1mm in thickness, approximately 50cm in height and 50cm in width.

There are some limitations concerning the effectiveness of this system. If the dimensions of the drogue are 50 x 50cm, this type of float can only be used in depths not greater than 5 to 6m; this is sufficient in practice if one is interested in the transport of effluents risen to the surface.

For field measurements, 10 t0 20 floats should be used simultaneously: the operating cost of an additional float is negligible if compared to the cost of the field study. To cover a rather large marine area, the floats will be placed in the water in sets, distributed along a line roughly perpendicular to the current. In order to get solid information on the vertical distribution of velocities, each set will consist of several floats, the drogues of which will be submerged at different depths. A drogueless float will give the accurate surface velocity.

One will carefully mark the successive positions of the floats in time and space every 20 to 40 minutes if possible; the length of time between two sightings does not have to obey a strict operating rule. Following the floats in space can be carried out either by topographical survey from the shore, or by another radio-localisation system. In practice, one takes a reading of the boat passing near the float, since the latter is seldom visible from the shore. Radio link between the operator on the boat and the surveyors on the shore is indispensable.

Because the floats do not catch the wind, looking for them at sea is oftentimes difficult. To solve this problem, one can add some floats fitted with flags whose only purpose is to help locate the floats used for measurements. Some floats are inevitably lost, thus the initial number of floats should be adequate. The results are then plotted in graph form as trajectories and average velocities computed (See Fig. 4).

There are other more sophisticated solutions, such as floats with radar reflectors, radio transmitter floats or aerial photography. Regardless of the cost effectiveness of each solution, the disadvantages are either that the floats catch the wind or that there is difficulty in marking each float accurately. In addition, aerial photography requires that there appear on each negative fixed points carefully positioned within an established system of co-ordinates.

On the other hand, the precision required for such measurements is fully attained by the simpler and less costly solution given above.

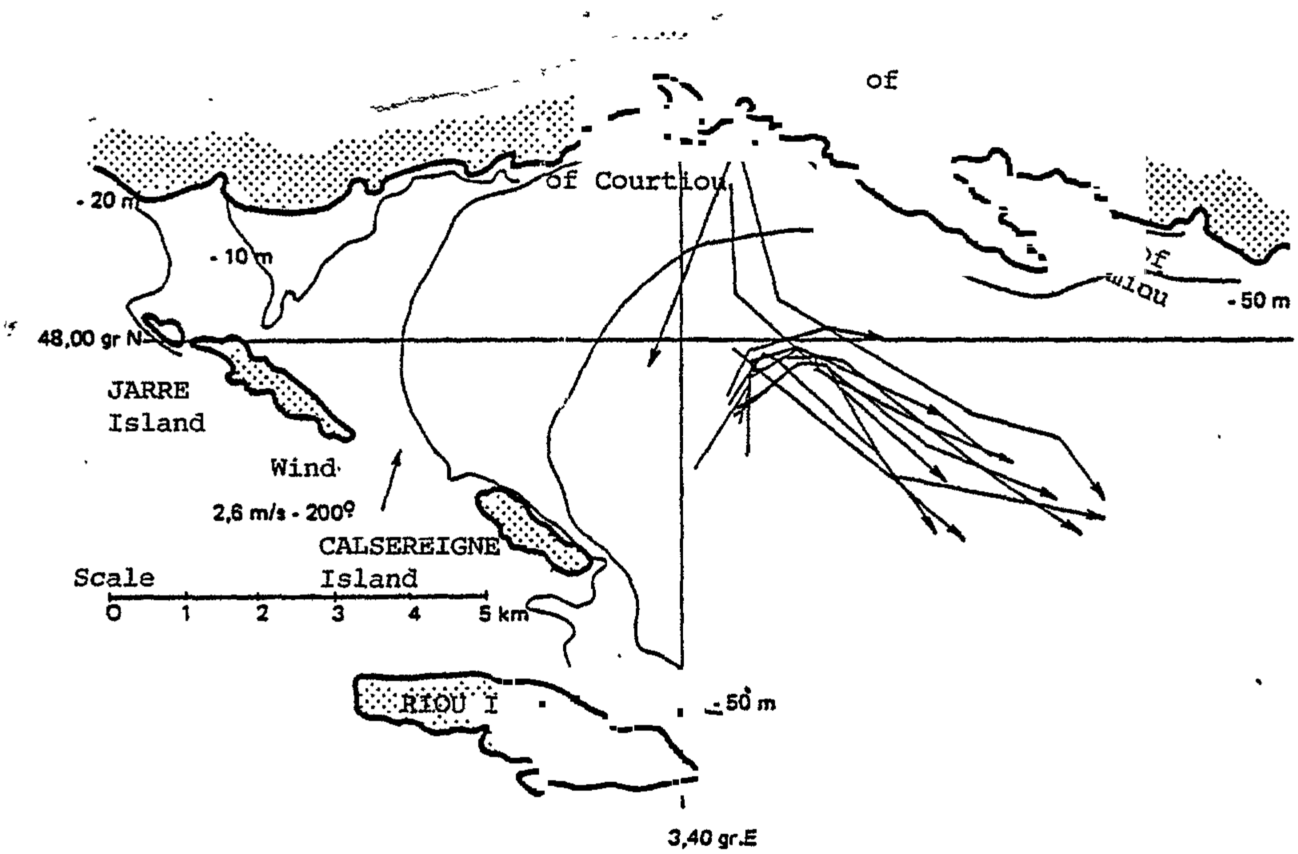


Figure 4: Trajectories followed by means of floats

2.5.2 Use of dye tracers for the collection of data on currents

We have already seen the use of dye tracers to measure surface currents. Rhodamine is the one most frequently used.

We counsel against the use of this method because it is not suited to the problem for the following reasons: the vertical dispersion of the tracer through diffusion does not allow the differentiation of the currents at various depths. Furthermore, the horizontal dispersion of the dye which makes the surface of the patch larger with time hampers precision in marking its displacement, especially if the current measured is weak. In sum, floats are definitely preferable.

2.5.3 Currents at the level of effluent trapping

We have stated that batch measurements of currents (floats) cannot be carried out if the depth exceeds a few metres. However, information on currents at greater depths is essential if there is a risk of effluent trapping in a stratified environment.

Indeed, it is very important to know in such cases whether the effluents which will degrade poorly because of dearth of oxygen are likely to be carried out to the open sea by the currents prevailing at the level of effluent trapping, or on the contrary whether they will accumulate on the spot because of either absence of currents or their rotating character.

One should first determine the depth at which effluent trapping is likely to occur by a computation on the basis of the vertical density profile. After this has been accomplished, the only way to obtain data on the currents at that level is through continuous recordings by means of a fixed current meter. The continuity of operation is also essential in order to illustrate either the permanent presence of currents facilitating effluent removal, or the risk of stagnation due to very weak currents or those of a rotating character. This situation is quite frequent in the Mediterranean below a certain depth.

Based on the analysis of the rose of currents established on the basis of measurements, one can judge how severe and how frequent the case of effluent trapping will be.

2.5.4 Surface currents measured by current meters

In relation to surface currents, on which information is essential because they move the effluents not trapped by a stratification, their continuous measurement is most frequently obtained by using a current meter submerged, for practical and safety reasons, at least 2 metres below the surface (and of necessity deeper in tidal seas). We have seen that at that depth the current, if it is caused by the wind, can be approximately 5 times weaker than on the surface layer proper. It is thus necessary to determine, by simultaneous measurements with current meters and surface floats, the corrective factor to apply to the data recorded, in order to obtain velocities on the surface.

2.6 ESTABLISHING THE VALUES OF THE DIFFUSION COEFFICIENTS

The relatively simple methods which can be used at a site to compute experimentally the coefficient of horizontal diffusion perpendicular to current direction cannot be used to measure the vertical diffusion coefficient. Experimental studies on the latter use more complex methods which can hardly be incorporated into a routine study of sewage discharge into the sea.

However vertical diffusion is an important phenomenon in the pollution dispersion process since, under certain environmental conditions (absence of stratification), it increases the volume of pollutant dispersion and hence its dilution faster than horizontal diffusion.

Therefore, regardless of whether simple manual methods or computer programs are used for the computation of dilution during horizontal transport, one must introduce a value for the vertical diffusion coefficient. In practice, one generally takes a value deduced from that measured (or simply estimated) for the horizontal diffusion coefficient. According to the Taylor-Elder studies, the vertical coefficient K_z varies greatly with distance from the surface of the sea (see figure 13, p.76) and its average value (see graph at the end) is approximately 1/3 of the horizontal coefficient K_y. In the computations therefore, the value for K_z must be chosen on the basis of the thickness of the layer under consideration and of its level in relation to the surface.

Since, as we have indicated in Chapter 1, measuring K_y in the field is not really useful, because on the one hand it varies greatly with time and on the other it makes a small contribution to the total effluent dilution, one can in many cases omit field measurements and adopt a value proposed by Taylor-Elder such as:

$$K_y = \alpha H u^*$$

A more precise definition can be found in paragraph 3.9; a computation graph is at the end of the document.

As concerns the coefficient of horizontal diffusion parallel to current direction, it plays no role in the case of a continuous discharge, such as the one issuing from a sea outfall, as will be shown in paragraph 3.6.3. However, it should be understood that one makes the implicit assumption that the marine current is constant and this means that K_x can no longer be ignored in the case of tidal seas, since this assumption can no longer be verified.

2.6.1 Field measurement of horizontal diffusion coefficients K_y and K_x

The fact that they are very variable in space and time has the following two consequences:

- On the one hand, the need to carry out many measurements in different meteorological situations, since one cannot know in advance the situation(s) most unfavourable for effluent dispersion;

- On the other hand, the need to carry out such measurements in conditions as closely resembling those of permanent flow as possible. This means that the measurement should be carried out in a relatively short span of time (between 1h and 1h 30 mn) and that is feasible.

For the interpretation and possible extrapolation of the results, one must simultaneously measure the vertical profile of velocities and at the same time establish the presence or absence of a density stratification of the waters.

A simple principle on which to base measurements is the recording, through aerial photography, of the development with time of either a patch of marker substance or better yet a set of drogues. This second solution concerns only a single horizontal layer defined by the submersion depth of the drogues. Thus one can eliminate both the impact of the horizontal shear of the flow and the interaction with vertical diffusion. In addition, more information can be collected with the floats than with the dye. In effect, one can evaluate the co-ordinates concerning each float, whereas the dye gives only the total width on each photograph.

In order to overcome this problem, attempts were made to establish the distribution of concentrations in the dye through a photodensimetric analysis of the photographs of the patch of marker substance; however, the semblance of precision of this method (i.e. the large number of definition points) is deceiving, because it is biased (since the patch varies in thickness) on account of the identity of response of different concentrations distributed over layers of varying thickness; in other words, there is no absolute correspondence between tracer concentration and optical density of the negative.

Interpretation of results is only possible if initial conditions are perfectly well known. Indeed, the equation of diffusion (3.12) cannot have a simple solution (3.13) unless the injection of the dye is both topical and instantaneous, i.e. unless its total mass is concentrated at one point at the initial time. To approach this condition one can break from a distance a glass container holding the dye. This condition is less strict with floats, because the first photograph taken from the air will give an exact image of the initial conditions. It is advisable to use 15 to 20 floats and to put them in the water in as restrained a circle as possible, a few metres only in diameter.

If a dye is used, one should make sure, and this is a trial and error process, that the density of the solution matches that of sea water as closely as possible. For instance, Rhodamine B in commercial acetic solution, whose density is approximately 1.11 must only be used if diluted with alcohol.

The patch of dye or the "patch" of floats will then be photographed vertically every 5 to 10 minutes. A strict chronology is not necessary. On the contrary, it is indispensable to know the exact time that each photograph was taken. To accomplish this, one should use an aerial photogrammetric chamber with incorporated stopwatch which eliminates any ambiguity.

The overflight should be very low in order to obtain as large a picture of the patch as possible. Precise marking with respect to a system of geographic co-ordinates is totally useless; on the other hand it is essential to plot the negatives to a scale, since the altitude of the flight is not precise enough to evaluate this scale. A practical and effective solution is to let float in the sea a piece of wood of known length, say 10 metres.

In the case of a patch of dye, the value of the transversal diffusion parameter K_y can be calculated by using the following expression (derived from 3.13):

$$K_y = \frac{y_{i+1}^2 / t_{i+1} - y_i^2 / t_i}{4 \operatorname{Log}(t_i / t_{i+1})} \qquad (2.1)$$

or also by using the following general formula adjusted by a method of least squares:

$$y^2 / t = 4 k_y \operatorname{Log} t + b \qquad (2.2)$$

where (for both (2.1) and (2.2):

t = duration of the development of the patch in the sea from injection onwards,

y = half-width of the stain (direction perpendicular to the flow) taken on the section of maximum width,

b = numerical constant,

i = serial number of aerial photograph under consideration.

If the measurements are carried out with a set of floats, one should mark on each photograph the relative co-ordinates of each float in an arbitrary system of co-ordinates. Then one shall evaluate the centre of gravity of the floats and the standard deviations, both in the direction of the flow and perpendicular to it.

Thus one has:

$$\sigma_x^2 = 2 K_x t + \sigma_{x_o}$$
$$\sigma_y^2 = 2 k_y t + \sigma_{y_o} \qquad (2.3)$$

where σ_x is the standard deviation in the direction x at time t and σ_{x_o} the same value at the time considered as initial (first photograph). If a desk computer is available, one can find the system of principal axes minimising σ_y.

In practice, such measurements are more complex than it first appears. Natural currents may indeed vary widely in direction and intensity, while the measurement is in progress, causing unpredictable changes in the patch and confusing the evaluation of principal directions. The only way of handling this is to repeat the measurements many times over.

2.7 MEASUREMENT OF VARIOUS PARAMETERS

There are several types of equipment available for the field measurement of various physical and physico-chemical parameters; such instruments are the leads called "multi-parameter", which (for a reduced volume) can be used directly in the field to collect data on temperature, salinity, pH, dissolved oxygen, turbidity, ion content for chlorine, lead, copper, etc. Frequently their range is limited because of the restricted length of the linking cable between the sensor and the measurement case, since this length affects the precision of the measurement. However, this is not a major disadvantage in coastal waters.

Of the classical instruments of oceanography use can be made of sample jars and reversing thermometers. This latter instrument is a high precision mercury thermometer. One submerges it vertically to the desired depth and after thermic balance, one tips the holder of the sample jar to which the thermometer is attached, by means of a carrier, i.e. a fly-weight which slides on the lowering cable. The tipping cuts off the column of mercury at a pre-determined point because of constriction of the thermometer tube. The mercury thus isolated flows towards another small receptacle at the opposite end of the tube. Although isolated, this column of mercury undergoes a certain expansion because of the temperature difference between the point of measurement, at a certain depth below the surface, and the atmosphere at the time of reading. Thus a second regular thermometer is incorporated into this instrument to permit the calculation of the correction required. The precision attained is of the order of 1/100 of one degree.

Another instrument which is sturdy, inexpensive and easy to use is the bathythermograph, still used by some. However it is of low precision and has been superseded.

All of the above instruments, with the exception of the reversing thermometer, need frequent calibration in order to retain their effectiveness and accuracy.

2.8 EXPERIMENTAL STUDIES ON THE LAW OF BACTERIAL DECAY AT SEA

We have already stated that this type of measurement is difficult and should not be carried out because of the high risk of error.

However, for information purposes we will give here the outlines of the method used in such measurements. One should be dealing with a discharge of urban sewage, non-disinfected and of sufficient flow.

Such measurements are of a statistical nature, because of:

(a) the type of the phenomenon measured;

(b) the way in which the test germs are counted; and

(c) the risks due to water turbulence and to the sample taking procedure. One must take a very high number of samples at sea and carry out many analyses in the laboratory. 100 is a minimum.

The principle on which this type of measurement is based consists in comparing, in the same mass of water, the evolution in time of the quantity of the test germs with that of a persistent tracer; such a method eliminates the factor of hydraulic dilution. The most suitable tracer to measure this dilution in the case of fresh water discharge is salinity of the mixture.

The precision needed in salinity measurements requires the use of a laboratory electromagnetic salinometer (brine gauge). For bacterial counting the classic 3-tube method is totally inadequate. One should use instead either membrane cultures or the very recently developed system of honeycombed plates miniaturising the tube method; this method is cost effective, leaves no margin for errors and allows multiplication of the experiments. However, the MacCrady tables, which (on the basis of Poisson's statistical law) furnish the most probable number of germs (NPP), should be redone. To our knowledge there exist no tables for measurements in which 20 or 30 tubes are used.

In practice, one "marks", by means of a drogue, a mass of water at the outlet of a marine outfall. One follows the mass for as long as possible (4 to 5 hours being a minimum) and certainly for a time exceeding the T_{90} one is looking for (see paragraph 3.10.2). One carries out 4 to 5 samplings graduated in time and consisting of several samples each. One repeats with several "marked" water masses, in order that the results be statistically significant. Let d be the hydraulic dilution and N the number of bacteria counted at point of time t; the computation of T_{90} will be carried out by using the following formula:

$$\text{Log}\ (d_i N_i/d_o N_o) = -2{,}3\ (t_i - t_o) / T_{90}$$

There is always a great spread in the results. One should verify the possibility of adjusting them to a log-normal law (equation 3.34).

A condition for these measurements is the careful assessment of the maximum salinity of sea water which is the basis for the computation of dilution. To determine this, the samplings of sea water should be carried out at various depths and outside the effluent plume.

2.9 HEALTH STATE OF THE LIVING MARINE ENVIRONMENT *

When one considers the installation of a new marine outfall system in order to discharge to the sea an effluent which will bring pollution to the environment, it is important to carry out, in addition to the preliminary hydraulic study which we have just discussed, a biological study which will shed light on the health state of the living marine environment before the outfall is put into operation.

This study is interesting for two reasons:

1. It shows the pre-existing state of balance/imbalance of the species living in the impact area of the future discharge; furthermore, it enables one to judge how threatening for the living species the new aggression brought about by the pollution will be.

   The conclusion arising from such a clinical study can be either a well founded case against the installation of a new outfall at a certain site whose biological balance is already precarious, or specific recommendations concerning the biological aspect of the problem in terms of preliminary waste water treatment (suspended solids, nutrients, specific toxic substances, etc.).

2. It establishes the initial point for the health state of the living marine environment, condition sine qua non for future comparisons, on the basis of which possible changes due to the sea outfall when operational may be followed up.

A complete study of the state of the marine environment using the most up-to-date knowledge of the science of ecology is a considerable task requiring a lot of time and money.

In connection with the outfall feasibility study and in the context of the considerations limited to the two aspects defined above, it is both necessary and possible to carry out a study limited in scope, but amply sufficient in terms of giving a rough idea of the health state of the marine environment.

In this context, one focuses essentially on certain standard species characteristic of the benthic flora and fauna; they are followed up in time in order to show the evolution of the environment under the impact of the pollutants discharged; this evolution is then analysed and defined initially as follows:

- through cartography (mapping) of the populations present in the area and likely to be affected by the discharge;

- through a more in-depth study and later follow up of selected sites.

2.9.1 Mapping of benthic polulations

One should not forget that a considerable portion of the French coastal environment has already been mapped and that because of this the cartography proposed here may be a complement or carried out for verification purposes.

---

* This paragraph was written by G. Bellan, Senior Research Scientist of CNRS, Marine Station of Endoume, Marseille.

Indeed, as a basis for the mapping one can use the maps of the Service Hydrographique de la Marine, which furnish a lot of data, not only on topography but on sediments as well.

The area to be mapped will depend directly on the area likely to be affected by the masses of polluted water and will be established as a result of studies on currents carried out previously.

The operator or the team entrusted with benthic cartography must clearly be competent, because it is from their level of competence that will ensue not only the reliability of the results but also the speed of the operation (and hence savings in the cost).

For a cartographic operation one needs a boat (a trawler is usually adequate) fitted with an electric winch, a cargo boom or a rig, and capable of correct positioning. One must use sturdy dredging equipment (e.g. a Charcot dredge) to allow for scoops of 20 to 50 dm^3 of sediment to be dredged out each time. When the sediment (dredgings) has reached the boat, the first thing to note is the nature of the sediment which will be classified in a preliminary way as mud, sandy mud, muddy sand, sand, gravel, etc.

Approximately one litre of sediment should be reserved for later granulometric analysis. One should also note other characteristics of the sea bed: whether it is rocky, concretioned, with water plant communities (Posidonia beds, zostera beds) or with laminaria.

The sediment not reserved for granulometric analysis will be sifted through a "mason" sieve (mesh side between 1mm and 1,5mm) to determine on the spot the type of the population itself, that is, the type of large communities (biocenoses) to which the population belongs. One will carefully study the facies (when one species or a very small number of animal or plant species are quantitatively predominant). Attributing a population to one or another population grouping (biocenosis, facies, etc.) poses for the most part no problem in the French coastal waters and especially in the Mediterranean. One will take care to follow the correct procedure and preserve individual examples of species which may be important but are difficult to determine.
All essential data (nature of substratum and of population(s)), will be exactly marked on the map at the topographical site of the dredging.

Then, one must trace the boundaries of the population groupings (biocenosis, facies) defined previously, while paying special attention to the exact nature of the margins of contact between two groupings; such margins are likely to be modified after the sea outfall has become operational.

This preliminary cartographic study will:

1. considerably limit the network of stations to be studied in detail later;

2. facilitate the location of such stations;

3. form the basis for later monitoring, on a large scale and at lower cost, the transformations due to the sea outfall (and also the possible modifications to be brought to it).

2.9.2 Baseline study and follow-up of selected stations

2.9.2.1 Establishing the network

Essentially one must define the location of a number of stations, whose distance from one another will be computed on the basis of their distance from the discharge point. This enables one to define the radials which form a true network if the sea outfall is a large one. The distance of the stations will be between 200 and 500 metres.

Preliminary population mapping considerably reduces the number of stations. In addition to the station located on the axis of the outfall and a few dozen metres away from it, one can select a point within each large type of population and facies and, for sensitive communities, at the boundary between two of them. A station must be located at the centre of sedimentation (or storage) areas defined by the current study.

2.9.2.2 Sampling and analysis of data

It is assumed here that the samples are taken from loose sub-strata. A brief methodological survey concerning solid sub-strata is given further on.

Samplings are carried out preferably with a Van Veen or Smith-McIntyre bucket or a modified Briba and Reys "Orange Peel". Sediment collection is carried out on a surface ranging from 0,3 to 0,5m^2, allowing for 3 to 5 "bucket thrusts". An additional sampling will provide sediment for granulometric analysis (notably mud content, Ø of particles $< 63\ \mu$) and also for chemical analysis of the sediment, which will include at least a quantitative analysis of organic carbon.

The sediment should be carefully sifted through a 1mm mesh and the residue left on the sieve fixed with neutralised formol. The animal and plant material gathered will be sorted out in the laboratory. It should be identified and counted to a taxonomic level as advanced as possible (Mollusca, Polychaeta and Crustacea to the species level). Data on specific composition, on absolute and relative abundance (dominance) and on rank as a function of dominance should be established. In order to interpret the population structure, which will furnish at a later stage clues about population dynamics, one should without fail take into consideration the results of the following analyses:

1. Similitude measures for all stations, taken in pairs, on the basis of the Sanders affinity index and the grid diagram.

2. Diversity index for each sampling. The diversity index to use preferably is the Shannon-Weaver as follows:

$$H' = -\sum_{i=1}^{i=S} Pi \log(Pi)^{*}$$

---

* $Pi = \dfrac{\text{Number of individuals of species } i}{\text{Total number of individuals, all species commingled}}$

S = Total number of species counted (1, 2, 3..., i, ... s)

3. The Sanders rarefaction curve, which allows one to add up dominances for each species as a function of their rank of abundance in the samples.

On solid substrata, 5 sample takings of $400cm^2$ per station located within a homogeneous algal or animal population should be carried out. The procedure is complete scraping, down to the substratum, of all living organisms in this area measuring $400cm^2$. Processing of specimens and interpretation of results follow exactly the procedure outlined above.

2.9.2.3 Follow-up

Follow-up studies for all stations should be carried out two years after the sea outfall has become operational, the sole exception being the station near the outfall for which the time is shortened to one year. Subsequent follow-up studies can be carried out periodically every 4 or 5 years, unless the type of effluents discharged were to change drastically. Monitoring should cover primarily:

- Sediment content in mud and organic matter;

- Evolution of: the similitude coefficients between stations according to Sanders, the Shannon-Weaver diversity indices and the Sanders rarefaction curve for each station.

The evolution of these rather complex data will give a clear idea of the evolution of the marine environment and will suggest possible changes or improvements in the sea outfall system.

In order to determine the "state of health" of a community or ecosystem it is sometimes suggested (and on occasion even practised) to use the appearance, disappearance, or quantitative evolution of a small number of species which are typical or indicative and which, either individually or grouped together could furnish a summary result of sufficient precision at lower cost. Such a method can in effect give interesting results but requires great caution and a high level of competence. Obviously, the selection of species will be determined by environmental factors: geographic location, depth, type of substratum etc. and it is the task of a specialist to draw up (on the basis of these parameters) the list of species to be monitored.

It is very difficult to draw up in advance a list of species, with the exception of course of the Polychaeta Capitella Capitata and Scolelepis fuliginosa which multiply rapidly in environments with considerable organic pollution, but cannot always tolerate an equal amount of typical chemical pollution (heavy metals, pesticides), nor can they survive in very low salinity environments.

However, in the North-Western Mediterranean on loose substrata one could follow up the appearance, disappearance and quantitative evolution of the following species (in addition to those referred to above):

Polychaeta: Lumbrineris Latreilli, Staurocephalus rudolphii, all species belonging to the Cirratulidae and capitellidae families,

Mollusca : Dentalium rubescens, Nucula turgida, Corbula gibba, Myrtea spinifera, Tellina distorta, Thyasira flexuosa, and

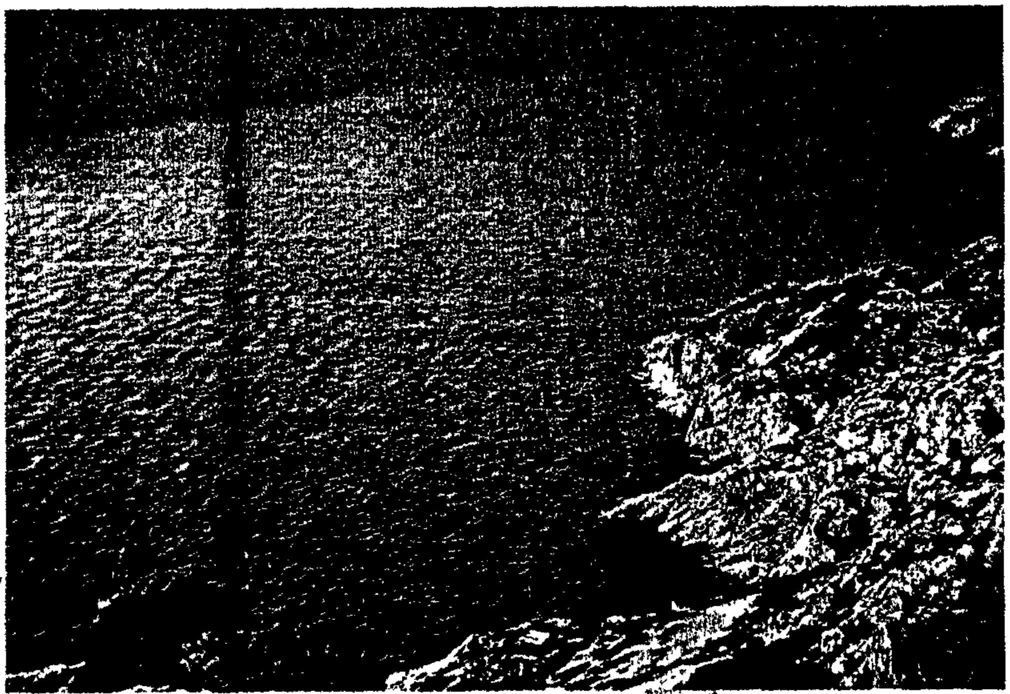
Crustacea : Eupagurus prideauxi and Macropipus depurator.

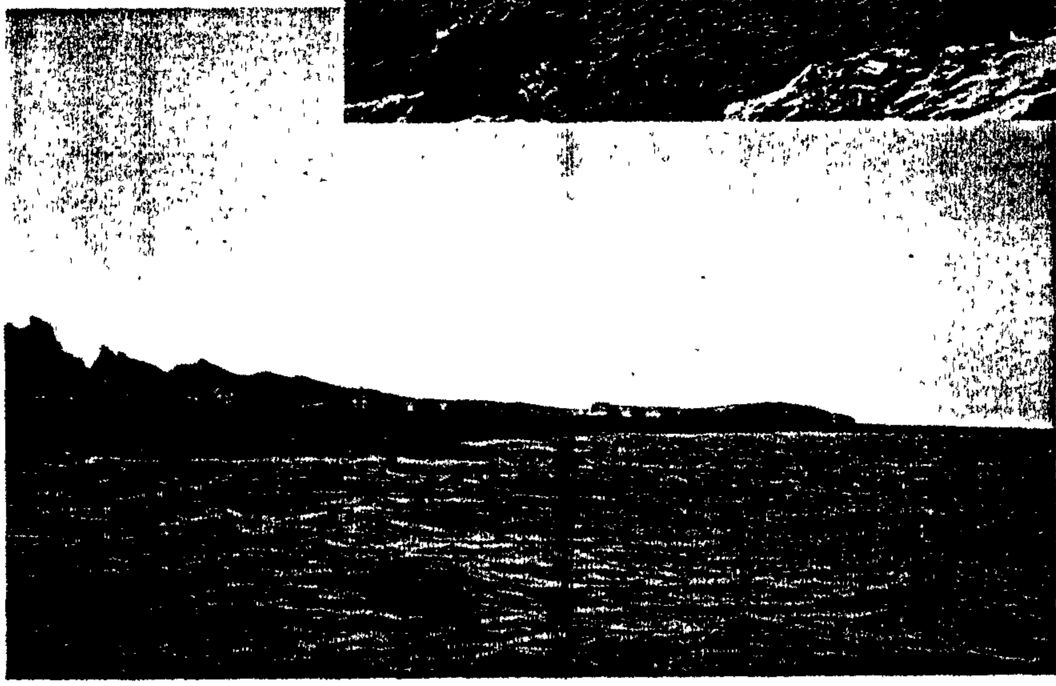
On rocky substrata, on the high buffeted levels, the disappearance of the pheophycean Alga Cystoseira stricta is highly typical of environmental deterioration. One can also suggest an annelidian pollution index, based on the quotient resulting from the sum of abundances for species used as "pollution markers" ("Sentinelles de pollution" or S.pol: Platynereis dumerilii, Theostoma cerstedi, Cirratulus cirratus, Capitella capitata, Nereis caudata) divided by the sum of abundances for species used as "clean water markers" ("Sentinelles d'eaux pures" or S.pur. Syllis spp, Amphighera mediterranea).

This quotient:

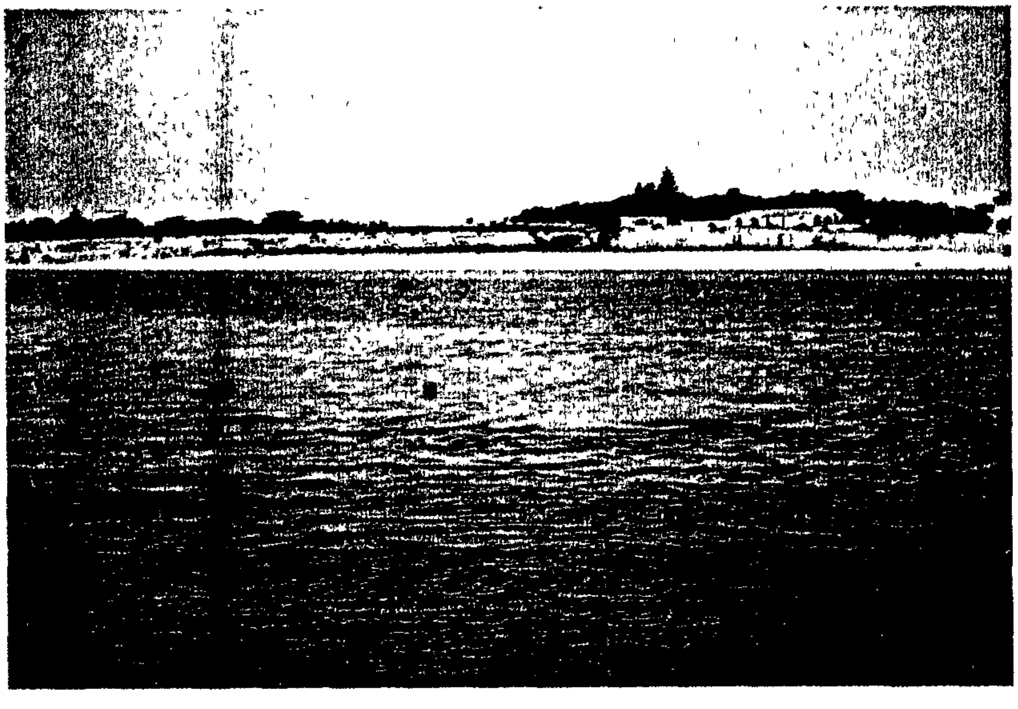
$$\frac{\Sigma \text{ Ab. S. pol}}{\Sigma \text{ Ab. S. pur}}$$

correlates well with the degree of pollution and increases along with it. It also appears to be lower than 1 in environments with no or little pollution. This index was proposed by Bellan under a more elaborate form, taking into consideration the sum of dominances of the two groups of species mentioned above, i.e. "pollution markers" and "clean water markers".





Stratified flow: sewage discharge on the sea surface. Note the narrowness of the eddy diffusivity strip between salt water and fresh water



Plume from a underwater shallow outfall. The sewage is dyed with Rhodamine. The tidal flow carries this sewage to the left of the photograph. The buoy shows the end of the underwater pipe

CHAPTER 3

BEHAVIOUR OF EFFLUENTS DISCHARGED INTO THE MARINE ENVIRONMENT

For the illustration of the computation methods described in this chapter, the reader is advised to refer to Appendix B where numerical examples of application are given.

3.1 DISCHARGE DISPERSION PHASES

Hydraulics as applied to Engineering usually describes just the general characteristics of a flow. On the other hand, water pollution studies require much more detailed information, since one must follow the evolution of specific masses of water within a much wider fluid area. Thus, one must take into account turbulence, a field of Fluid Mechanics which is extremely complex and where many questions still remain unanswered. Therefore engineers do not as yet have all the appropriate methods at their disposal and those that they do have are often complicated and require the use of sophisticated equipment such as computers.

The type of discharge discussed in this study is solely that of effluents with positive buoyancy falling into the general category of fresh water discharge into the sea.

For reasons of clarity in presenting the material, we distinguish three successive zones in the effluent discharged from an outfall system at a certain depth as it spreads in the ambient water, even if there are no strict demarcation lines among zones. The distribution is made on the basis of the mechanisms prevalent in the movement. Thus, if one follows the flow one can distinguish successively:

- a jet zone) Collectively called in Chapter 1, paragraph 1.3.1
- a plume zone) "phase one"
- a convection-diffusion zone, called in Chapter 1 "phase two".

As its name clearly indicates, the jet zone is primarily characterised by the velocity of the ejection into the sea of the effluent issuing from the outfall pipe. This first part of the flow extends between a few metres to several dozen metres.

In the plume zone which follows, the forces of gravity caused by the density difference between the effluent and the ambient sea water prevail over the initial inertia. We define as "plume" the ascending part of the flow up to the point where it starts to spread horizontally. If the plume reaches the surface of the sea, the gravitational forces continue playing a certain role in the horizontal spreading.

Beyond that, in the convection-diffusion zone, the contaminated water mass no longer has its own source of energy. It is only under the influence of both the prevailing currents and of the turbulence which continues causing a certain mixing of the effluent with the sea water, thus promoting reduction of pollutant concentrations.

In addition, the plume zone and the convection-diffusion zone are modified to a large degree by factors such as the type of the prevailing currents and by whether or not the receiving marine environment is homogeneous in density.

3.2 THE FUNDAMENTAL ROLE PLAYED BY DENSITY GRADIENTS

There are two essential factors affecting the density of sea water: temperature and salinity (see Appendices D and E). Therefore, the heating due to solar radiation, evaporation and fluvial input are all factors which make of the seas and oceans an environment which is heterogeneous in density. These density gradients explain a number of large scale oceanic circulations and it is only on the basis of systematic measurements of temperature and salinity (thus of density) that oceanographers were able to discover and explain these circulations.

Obviously, water masses of different density gradients have a tendency to stratify in horizontal layers in such a way that the density increases progressively from the surface to the sea bed. In practice this ideal balance is never achieved because the currents and the distribution of pressures introduce additional forces which prohibit such a static balance.

The separation between two layers of sea water of different density gradients is never a clear interface as is the case with two immiscible liquids. The transition zone is of considerable thickness which tends to increase under the influence of currents and turbulence. This fact complicates considerably the corresponding hydraulic computations.

In coastal waters, stratification of thermal origin is particularly frequent, especially in the Mediterranean. The corresponding interfaces are called "thermoclines". The formation mechanism of thermoclines is important and we think it useful to review it here. Solar radiation causes heating of the surface layers of the sea and part of the thermal energy is transmitted by the light rays. The latter penetrate into the water to different depths depending on the wavelength; the heating of the water, decreasing as one goes down in depth, takes place directly in the liquid mass (figure 5).

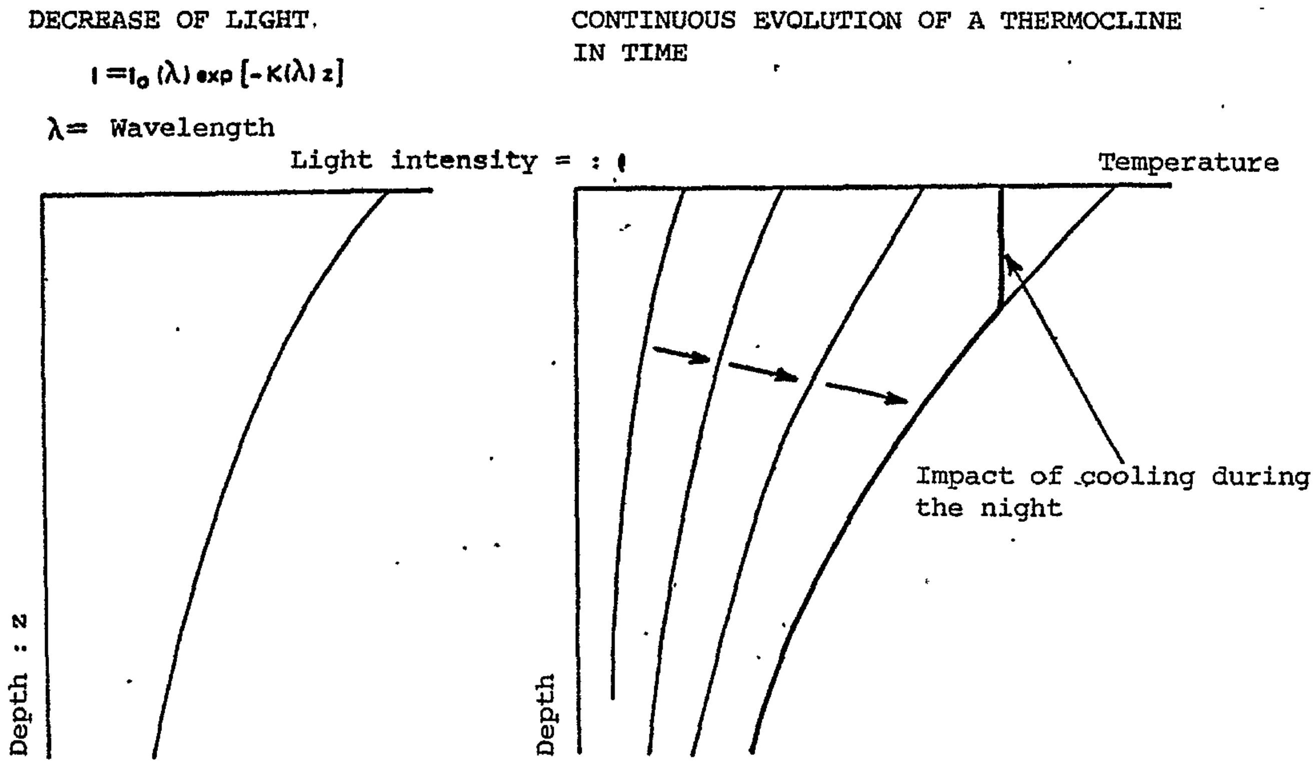


Figure 5: Formulation mechanism of a thermocline

The picture of heat exchanges between the sea and the ambient air is generally reversed during the night as compared with what it is during the day; but this phenomenon is primarily linked with calorific radiation, called black body radiation, which is exclusively surface radiation. However, it cools off a liquid layer whose density increases and which, becoming unstable, moves down to the depth where it can achieve a balance. The result is mixing and homogenization of the water masses down to a certain depth.

The wind accelerates to a greater or lesser degree the mixing of the superficial waters and helps to push down the zone of the heat gradient called thermocline. The various meteorological conditions further complicate this phenomenon and it is not unusual to observe several thermoclines at various depths. In the Mediterranean latitudes, the most important thermocline is the one called "seasonal" which forms in the spring and at the onset of summer, progressively disappearing in the fall. It forms roughly between -10 and -40m and the temperature difference can reach 10 to 20°C in a height of a few metres. Frequently, one can observe "diurnal" thermoclines in the first 10 metres of water, in which the corresponding heat difference is between 1° and 2°C. The real distribution of temperatures in terms of depth has a truly complicated configuration as is seen in figure 6.

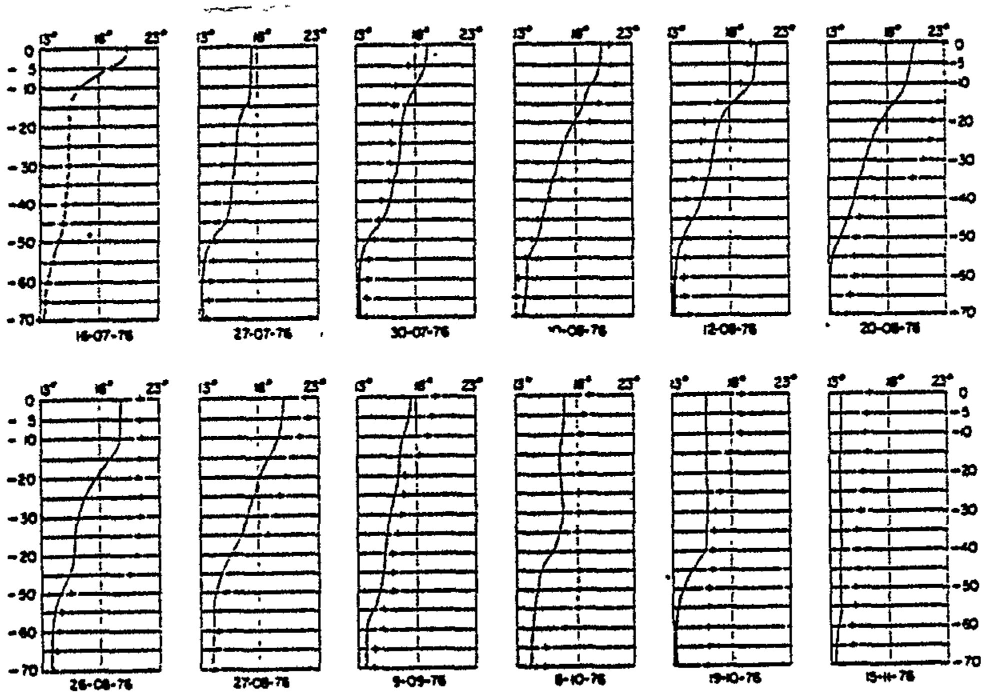


Figure 6: Thermoclines for the Courtiou bay measured and calculated in 1976

(Crosses correspond to values measured)

If a wind blows at a certain angle to the coast, it may give rise to a temporary tilting of the thermocline, simply in order to compensate for the friction effect of the wind on the surface of the sea. If the wind blows landwards, it tilts the thermocline by pushing it down toward the land; if it blows toward the sea, it tilts the thermocline up with respect to the land causing the rise of cold water, a phenomenon called upwelling.

If ΔT is the temperature difference and $\Delta\rho$ the density difference between two layers of water separated by a thermocline, we establish easily (figure 7) that the incline α of the surface caused by the wind brings about the tilting of the thermocline in the opposite direction along an incline β represented as:

$$\beta = \alpha \cdot \frac{\rho}{\Delta \rho}$$

$\frac{\rho}{\Delta\rho}$ being of the order of $\frac{4000}{\Delta T}$; β is much greater than α.

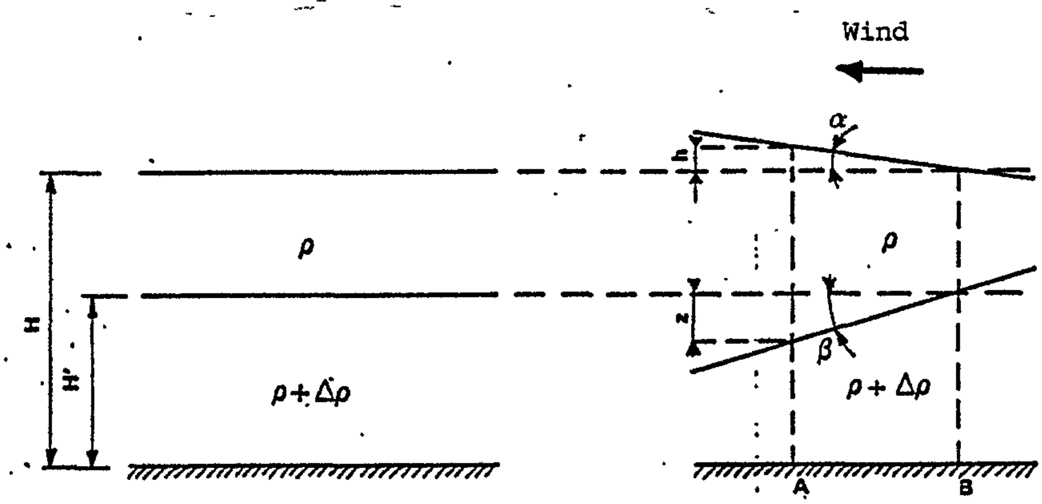


Figure 7: Principle of wind-caused tilting of a densimetric interface
Since pressures at A and B are equal, it follows that: $h\rho - z\Delta\rho = 0$, soit $z = h\rho / \Delta\rho$

If the velocity of the land wind increases, the thermocline tilts gradually until it touches the surface on the side of the land and by moving further and further away from it, it creates behind it a destratified zone of homogeneous temperature in which effluents can no longer be trapped at any depth. Thus, effluents come up to the surface on the side of the land since they follow the gradual tilting of the thermocline. Effluents accumulated for a long time at a certain depth can thus suddenly bring heavy pollution to the coast; this is a phenomenon which has actually been observed at certain coastal points.

3.3 JETS AND PLUMES

3.3.1 Possible maximum dilution, recirculation risks

A simplified computation easily gives the maximum dilution that can be achieved near a diffuser. One needs only to compare the flow of the outfall system with the liquid flow which is likely to go through the cross section of the sea defined by the diffuser length. Thus:

$$D_{max} = HLV/q$$

where:

D_{max} = maximum dilution theoretically possible
H = immersion depth of diffuser
L = diffuser length
V = average velocity of sea water
q = discharge flow

If the calculation of a jet according to the methods described below gave values higher than the maximum, it would mean that we would have, in the jet, a recirculation of water masses already contaminated and insufficiently removed from the diffuser by the existing currents. This recirculation would bring the dilution to, at the most, the previous maximum.

Along the same lines and most particularly in the Mediterranean, one shall verify that the surface currents can indeed remove all the polluted waters caused to rise to the surface by the jet(s) issuing from the diffuser. Thus, we have an approximate evaluation of the thickness H' of the layer of sea water affected by the effluent:

$$H' = Dq/(V\emptyset)$$

where:

H' = thickness of polluted layer
D = average dilution in the jet or plume
q = discharge flow in the jet
$\emptyset$ = diameter of the plume when it reaches the surface of the sea
V = average velocity of the natural flow of marine waters in the thickness H'

If H' is considerable as compared to total depth Y, there will be large scale recirculation of contaminated waters in the jet. The real dilution will only be roughly that reached in the vertical plume at the depth $Y-H'$.

3.3.2 A plume in a homogeneous environment

The analysis of the problem is relatively simple if the receiving medium is on the one hand homogeneous in density and on the other hand immobile or moved by a low general velocity of the flow.

The effluent discharged into the sea comes under three principal forces: its initial momentum (which in Hydraulics is defined as the product of the mass multiplied by velocity), its buoyancy (or density difference between the effluent and the receiving medium) and the friction on the surrounding waters. In a jet, momentum is preponderant over buoyancy; the opposite is true in a plume. There is no strict demarcation line between a jet and a plume.

A discharge from an outfall system starts out as a jet and rapidly develops into a plume.

Both jets and plumes are characterised by strong turbulence. Through friction they carry along the surrounding sea water and bring about a rather speedy dilution of the effluent. Instabilities appear soon, and give the plume a structure made up of successive puffs rather like those observed routinely in the case of smoke issuing from a chimney. Thus, the trajectory and the particular features of velocity or concentration in a plume can only be defined statistically.

The very numerous experiments carried out in hydraulics laboratories throughout the world have led to the formulation of the laws of averages describing simultaneously the succession jet-plume; these laws are of high precision and universally recognised today.

In order to make their application more practical, these laws have been expressed in the form of graphs to cover several standard cases given in Appendix F of this document. All elements needed for the computation of the general case of a plume emitted by a horizontal jet are given in Appendix D. While we refer to that part of the study for the precise computation of each particular case, we will give here certain general indications to illustrate the order of magnitude to expect in the results of such computations.

A discharge issuing from an outfall system is defined by the initial velocity of the jet U_0, the diameter of the pipe opening D and the depth from the surface at which the pipe is installed.

On the computation graph given in Appendix D, the asymptotic branches, to the right of the representative curves, correspond to the most frequent cases observed in sanitation projects. For that region of the graph (for $\eta \geq 10$) and by assimilating the curves to a straight line, we can give the following approximate expression of the dilution T_m:

$$T_m = 0{,}15\, Y^{3/2} . U_0^{-1/2} . D^{-5/4} \quad \text{(Units: m,s)} \qquad (3.1)$$

a formula covering all routine cases; it shows that dilution increases by the power of 3/2 of the height of ascension Y.

If Q is the flow issuing from the pipe, we can rewrite the expression as:

$$T_m = 0{,}13\, Y^{3/2} . U_0^{1/8} . Q^{-5/8} \qquad (3.2)$$

Dilution increases when the flow decreases. This shows that in order to increase dilution, one must install a multi-port diffuser at the end of the pipe so as to split up the discharge.

For instance, assuming that the ejection velocity is constant, one would increase dilution by:

- a factor of 4 with a 10-port diffuser
- a factor of 5 with a 13-port diffuser.

The following practical considerations both guide and limit us in the selection of the particular features of a diffuser.

- for the self-cleansing condition to be met, the velocity of the flow in the pipes should reach (with sufficient frequency) 0,75 to 1m/s;
- the constraint of load losses makes for a maximum velocity of 2m/s;

- in order that the diffuser ports not be obstructed, their diameter should be as a minimum 0,15 to 0,20m;

- moreover, for reasons of hydraulics, the sum of the port sections must not exceed the section of the outfall pipe.

The above formulae also show that dilution varies little with the initial velocity which (as we have just seen) can itself only vary within a rather narrow range.

Since the spacing of the diffuser ports must as a minimum be of the order of the diameter of the plume when it reaches the surface, one can calculate this diameter by using the formulae given in the part of the document referred to above; they give the following practical results, Y being the height of ascension:

- 90% of the discharged liquid is contained in a circle, the diameter of which is 0,4Y;

- 98% of the discharged liquid is contained in a circle, the diameter of which is 0,5Y.

3.3.3 A plume in a stratified environment

When the sea is stratified, density increases with depth (cf. paragraph 3.2). On the contrary, density in a rising plume increases with the height of upward movement as a result of gradual mixing with sea water. What may happen then is for the two densities to become equal at a depth below the surface. Because buoyancy is reduced to zero, the effluent becomes "trapped" between two layers of water and spreads horizontally at that level. This phenomenon is quite common and can be observed in the summer with effluents discharged from deep outfall systems.

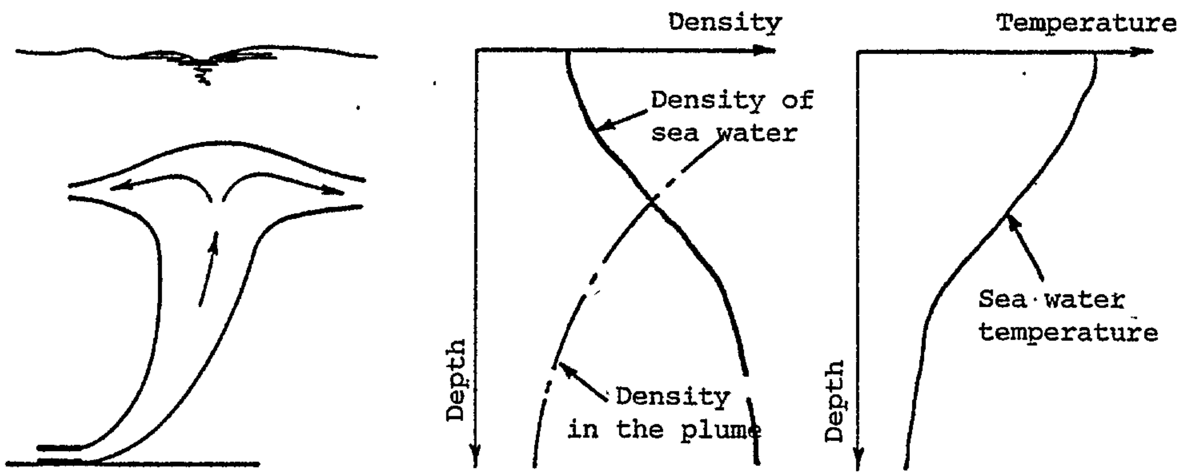


Figure 8 : Principle of trapping of a plume in a density stratified marine environment as a result of temperature varying with depth.

The calculation of such a plume is based on the same principles as those holding for a density homogeneous environment. However, the computation is more complex and for the sake of precision should be run on a computer, taking into account the law of the real distribution of density in the marine environment under consideration. Nevertheless, one can get a rough idea of the trapping risk by using the graph in Appendix D which gives the dilution of various depths. Once the dilution is known, one can calculate the temperature and the salinity in the plume. Appendix E gives formulae for the computation of density. By comparing the densities obtained for the jet with the density of sea water at the corresponding depth, one can establish whether or not there will be effluent trapping and if the answer is yes, at what level it is likely to occur.

When a decision must be taken on whether or not to install an outfall system in an area where there is a risk of seasonal effluent trapping at a certain depth below the surface (a situation which in practice occurs only' in the Mediterranean), one faces the hardest choices and the trickiest alternatives. The various cases may be summarised as follows:-

(a) The options are reduced, if the sub-littoral bathymetry and the condition that the discharge point be at a minimum distance from the shore prohibit any solution removing the risk of effluent trapping. In this case, one will decide to install the outfall system at the point which makes for the shortest seasonal duration of trapping conditions.

(b) A second case is that for which there is a solution to the installation problem, a solution which does away permanently with the risk of effluent trapping and which does not have any other major disadvantages, such as cost, higher pollution risks, problems of installation or maintenance of the system. In that case, it is highly advisable to opt for this solution.

(c) The third case is the most difficult, i.e. where there is a solution doing away with the trapping risk but which presents one or several of the disadvantages mentioned in (b) above. Thus, one must chose between the disadvantages and the seasonal effluent trapping. A strict rule for making the choice cannot be given; we can only shed some light on the subject by analysing the consequences of effluent trapping.

Firstly, we should state that a trapped effluent has the advantage of remaining invisible and not polluting the surface of the sea frequented by the users. This is an argument which often sways those in charge of tourist activities, especially the local political authorities. But this advantage is countered by serious disadvantages: when the trapping occurs in relatively deep waters, the water cushion above it, whose effect as a screen on the exchanges is considerably reinforced by the effect of the thermocline, prohibits renewal at a certain depth. Because the organic and mineral biodegradable matter cannot find the elements necessary for degradation, since the currents, often weaker below the surface, promote effluent stagnation, the result is the risk of a dystrophic process in the local flora. A large scale bloom of plant matter characteristic of eutrophication conditions can then begin in an explosive way and this has serious disadvantages.*

---

* A severe algal bloom, reported by fishermen, in the bay of Cannes in July of 1975 on sea beds at a depth of between 20 and 30m, which was the level of trapping of the effluents issuing from the new outfall system, spread on approximately 10 kilometres and suspended activities in the fishing grounds).

Leaving aside this risk, effluent trapping at a certain depth in the Mediterranean cannot be interrupted except by a strong land wind which in certain coastal areas is very rare in the summer season. Thus, effluent trapping that goes on uninterrupted for a long time can lead to a heavy accumulation of badly degraded pollutants, if the currents are weak or rotate around a point. If the thermocline tilts under the impact of a gust of wind, it will cause the rising to the surface and to the coast of this fermentable and sickening mushroom of pollution which will have the most disastrous effect on the sea users. This kind of accident, even if not very frequent, has nevertheless occurred in many sites where outfall systems are operating.

The opposite is true for the surface of the sea: thanks to the renewal of oxygen and to planctonic activity, since light and ultra-violet rays promote photosynthesis, the effluent which is not stopped while rising up will find on the surface the conditions most favourable to the self-cleansing of its degradable components and in addition will profit from the best conditions of dilution-dispersion.

For all those reasons, it is safe to conclude that the disadvantages of effluent trapping easily outweigh the visual advantages (at times only temporary) of its confinement under the thermal screen.

Therefore, in the third case defined above, where the solution which guarantees no effluent trapping requires certain financial or technical sacrifices, it is advisable to approve them because the dividends are the avoidance of unpleasant surprises of pollution welling-up and of algal bloom, both totally undesirable.

Finally, we should note that, as regards the effluent pollution risk, the increase of the velocity of effluent emission and of the flow per port, thus the decrease in the number of ports and perhaps even a sole jet, are all factors which contribute to a trapping-free situation.

However, one must honestly note that the picture drawn above in favour of non-trapping can be reversed, if the trapping risk occurs at a site where there are strong, permanent currents at all depths which favour rapid removal of pollution toward the open sea. Unfortunately, such current conditions are rare in certain sections of the Mediterranean coast where the risk of thermoclines forming is ever present in the summer.

From the above discussion one must primarily keep in mind the general philosophy of the multiple, complex and often contradictory aspects of the problem of eliminating a polluted effluent when its dilution and removal are prohibited either vertically or horizontally by the conditions of the sea.

We must also remember that in this case a thorough knowledge of currents in all meteorological situations is especially needed and this requires an extensive field measurement campaign.

3.3.4 A plume in an enrironment moved by a horizontal translation movement

If the marine environment is moved by a horizontal velocity of flow, the axis of the plume deviates, its trajectory is lengthened and dilution increases. In an immobile environment, this trajectory has a parabolic form of a vertical axis if the jet issues horizontally; under the effect of the current it quickly takes the form of a horizontal axis.

3.3.4.1 Homogeneous environment

There are no analytical solutions or graphs, except for the case of a plume issuing vertically in an environment homogeneous in density. For the computation of the trajectory and of the average dilution one can use the following formulae by Chu and Goldberg (1974); their application is very easy:

$$R = V/U$$
$$F^2 = V^2 / \left[g\left(\frac{\rho - \rho_o}{\rho_o}\right) D \right]$$
$$X = x/(RD) \qquad (3.3)$$
$$A = X \quad R^2X^2/(2F^2)$$
$$z = 1{,}44\ RD\ A^{1/3}$$
$$T = R\ A^{2/3} = 0{,}48\ z^2/(RD^2)$$
$$r = z/2$$

where:

U = velocity of flow in the marine environment,

V = velocity of jet emission,

x and z = plume axis coordinates, initial point being the point of emission and z being the vertical ordinate,

F = densimetric Froude number of the jet,

T = mean typical dilution,

D = diameter of opening of jet emission,

ρ = sea water density,

ρ_o = initial effluent density,

r = plume radius,

R, A and X = intermediate variables of computation for the simplification of formulae.

These computations can be done with pen and paper or on a pocket calculator.

On the contrary, it is difficult to establish the exact moment when the effect of dilution, due either to the initial velocity of the jet or to effluent buoyancy, becomes negligible when compared to the general turbulence of the flow of the marine environment. Certain scholars suggest the point where the axis of the plume resects the surface of the sea.

3.3.4.2 Stratified environment

There is no general method for the computation of a plume emitted into a density stratified environment which is moved by an overall velocity of flow.

3.3.5 Field measurements of control or simulation

We have already mentioned in paragraph 3.3.2 that the movements inside a plume are not predictable and we have also stressed that the characteristics that can be computed correspond to mean statistical values universally recognised.

If one is excessively conscientious and thinks of carrying out control measurements in the field, one is advised to refrain from such measurements. In effect, the means one needs for such a verification are not available at a reasonable cost today: means such as to ensure precision of location in space, immobility of the operator's boat at sea, lengthy samplings to ensure time averages, simultaneous measurement of numerous auxiliary parameters, etc. The results of such field measurements are illusory, whereas the computation methods given above are reliable.

3.4 EFFECTS OF RESIDUAL DENSITY DIFFERENCES

3.4.1 Horizontal spreading on the surface

In the preceding paragraphs we studied the behaviour of the plume between the effluent emission point and the level (either surface or intermediate) at which the residual buoyancy of the diluted effluent stabilises its upward movement; we have also indicated the method for computing the dilution, the trajectory of the axis and the diameter of the plume at any level.

But in the case where the stratification is not such as to trap the plume at an intermediate level, the latter rises to the surface and (except for the ideal, theoretical case) it still has some positive buoyancy. In theory, this buoyancy makes the diluted effluent float on the natural medium, which is of higher density and, because of the continuous flow, spread like an oil slick on water. In practice, such density spreading with no appreciable mixing with the underlying medium does not occur, unless the following two conditions are both present:

- very slight agitation of the surface (e.g. wind $<$ 3m/s);
- density difference of the two liquids higher than a certain minimum; expressed differently, dilution in the plume lower than a certain maximum (roughly 125).

In the absence of currents, the spreading plume is axially symmetrical in all directions. Simple hydraulics calculations give the following formulae, by which one can obtain the thickness of the polluted layer and the radial velocity of the flow in terms of the distance from the centre of the plume and of the flow respectively (friction is ignored):

$$H = 0{,}071 . Q^{1/2} . \left(r \frac{\Delta \rho}{\rho}\right)^{-1/4} \qquad (3.4)$$

$$V = \frac{Q}{2\pi r H} \qquad (3.5)$$

The distance reached with time is given by:

$$r = 2{,}18 \, [T^4 q^2 D \Delta\rho/\rho)^{1/7} \qquad (3.6)$$

where:

r = distance from the axis of the plume,

q = flow from the outfall system,

Q = total flow of the plume (flow from the outfall multiplied by average dilution),

D = average dilution at the point where plume begins,

H = thickness of surface layer of flow,

V = velocity of surface layer of flow,

$\Delta\rho$ = residual density difference at the peak of the plume,

$\Delta\rho_o$ = residual density difference at the point of discharge,

ρ = density of sea water,

ρ_o = density of effluent,

T = time

units : meter and second

To take an example, a discharge of 50 l/s at a depth of 20m gives the following values:

- dilution: 75
- total flow of plume: 3,8 m^3/s
- residual density difference: 0,00035

Distance from the axis of the plume (m)	Height of contaminated layer (m)	Velocity of flow (cm/s)	Theoretical distance reached after 12 h. (m)
10	0,56	11	
20	0,47	6	
40	0,40	3,7	105
60	0,36	2,8	
100	0,32	1,9	

The distance reached after 12 hours should be correlated with the phenomenon of destratification during the night mentioned in paragraph 3.4.2.

We insist upon the phenomenon of effluent spreading on the surface (even if it is rather an exceptional case) because for the problem at hand the most interesting case is always the most unfavourable one whose pollution impact must be computed.

Effluent spreading on the surface brings together the conditions for the weakest dilution; it may therefore correspond to the most unfavourable case.

Moreover, it is when the sea is very calm in the summer, which is the tourist season and the most sensitive in terms of pollution, that the occurrence probability of undiluted effluent spreading is the highest.

If the effluent is affected by unfavourable currents, it can bring to sensitive areas (beaches, shellfish growing areas) a surface layer of polluted water, which has undergone almost no dilution from the point where the plume originated. This shows clearly the double interest of good dilution in the plume's ascending phase. In effect, on the one hand we have seen that spreading requires a considerable density difference between the two liquids and on the other that, if spreading occurs, it transports almost undiluted pollution; thus it is preferable to have the maximum dilution possible at the point of origin.

In conclusion, one can state that adding an effective diffuser to an outfall system installed in shallow waters will help avoid the risk of pollution spreading on the surface.

However, there is also a natural correction which takes advantage of the nocturnal destratification and limits pollution spreading on the surface.

3.4.2 Nocturnal destratification

We have seen that a plume of fresh water risen to the surface can still be of different density than the sea water. Now the day-night alternation of the heat exchange conditions between air and water may modify this residual stratification under the following conditions:

At night, the sea cools off by radiation and possibly by evaporation depending on the wind and the amount of water vapour in the atmosphere (see paragraph 3.2). Because of these two phenomena, cooling is limited to the sea surface alone resulting in an increase of density. This surface layer, which is of higher density now, becomes unstable and sinks, bringing about a certain mixing and an equalisation of density to a certain depth.

Depending on conditions, the increase of density caused by the cooling may balance off the residual density deficiency of the effluent due to the lower salinity of the latter. In that case, the stratification disappears and the contaminated layer becomes thicker because of vertical diffusion.

In order to verify the conditions of such destratification, one can calculate the variation in temperature ΔT, required to balance off the residual density difference $\Delta \rho$, either by using the formulae given in Appendix E or the approximate formula:

$$\Delta \rho = -\Delta T/4000 \qquad (3.7)$$

The quantity of calories corresponding to this thermal difference per surface unit of the contaminated layer of thickness H is:

$$Q = \Delta T . H$$

In order for destratification actually to occur, it is necessary that the quantity Q not exceed Q' or the quantity of calories that the marine surface can, through radiation or evaporation during the night, transfer to the atmosphere taking into account meteorological conditions.

This is the theory behind the phenomenon of destratification, due to the nocturnal cooling of the surface. It concerns us here because it prohibits the undiluted effluent from rising to the surface when the sea is very calm. Verification of such situations is not routinely carried out in the context of the study with a view to installing a marine outfall system. The rather complicated method for computing Q' is however given in Appendix C, in case recourse should be made to it.

3.5 CONVECTION BY NATURAL CURRENTS

At the boundary of the zone of density spreading corresponding to a negligible spreading velocity, the energy contained in the buoyancy forces is exhausted. Beyond this boundary, the contaminated water masses move only under the action of the general currents prevailing at sea at the site under consideration. These currents are of diverse origin: tides, general oceanic circulations or currents characteristic of the mouth of a river. Currents are strongly influenced by the topography of the coast and of the sea bed. Near the coast, currents are roughly parallel to the direction of isobaths. The only aspect that should be considered in terms of pollution is the velocity of the flow in the layer contaminated by the effluent. Thus, the main problem is to find out the vertical distribution of horizontal velocities, i.e. to establish the velocity profile. This distribution has to do with: depth of water, friction on the sea bed, density stratifications of the marine environment and force of wind.

The various forces involved in the marine flows are often weak and this means that the Coriolis effect due to the earth's rotation can no longer be ignored. The result is rotation of the velocity vector as a function of depth, so that the direction of currents varies considerably between the surface and the sea bed. The Coriolis effect has little impact on tidal flows reaching 50 to 60 cm/s, but a considerable one on flows due to the wind.

3.5.1 Large oceanic circulations

In oceans and seas there are large circulations of water masses closely linked with the atmospheric and climatic mechanisms and with the perpetual heat exchanges between the sea and the atmosphere. In most cases they are closely connected with density currents and have been particularly well illustrated through the sole measurements of the distribution of temperature and salinity in the world's oceans. While the currents beyond the continental shelf are very evident, this is not the case for what interests us here, that is the coastal zone which is 1 to 2 km wide. In this zone, the oceanic circulations are slowed down considerably by friction, concealed by other kinds of currents or modified by topography (figure 9). They may also have a very pronounced seasonal character.

Their importance is not to be denied of course; however, one should exercise great caution when studying them and in order to confirm their existence and define their characteristics, one should carry out long-term measurements.

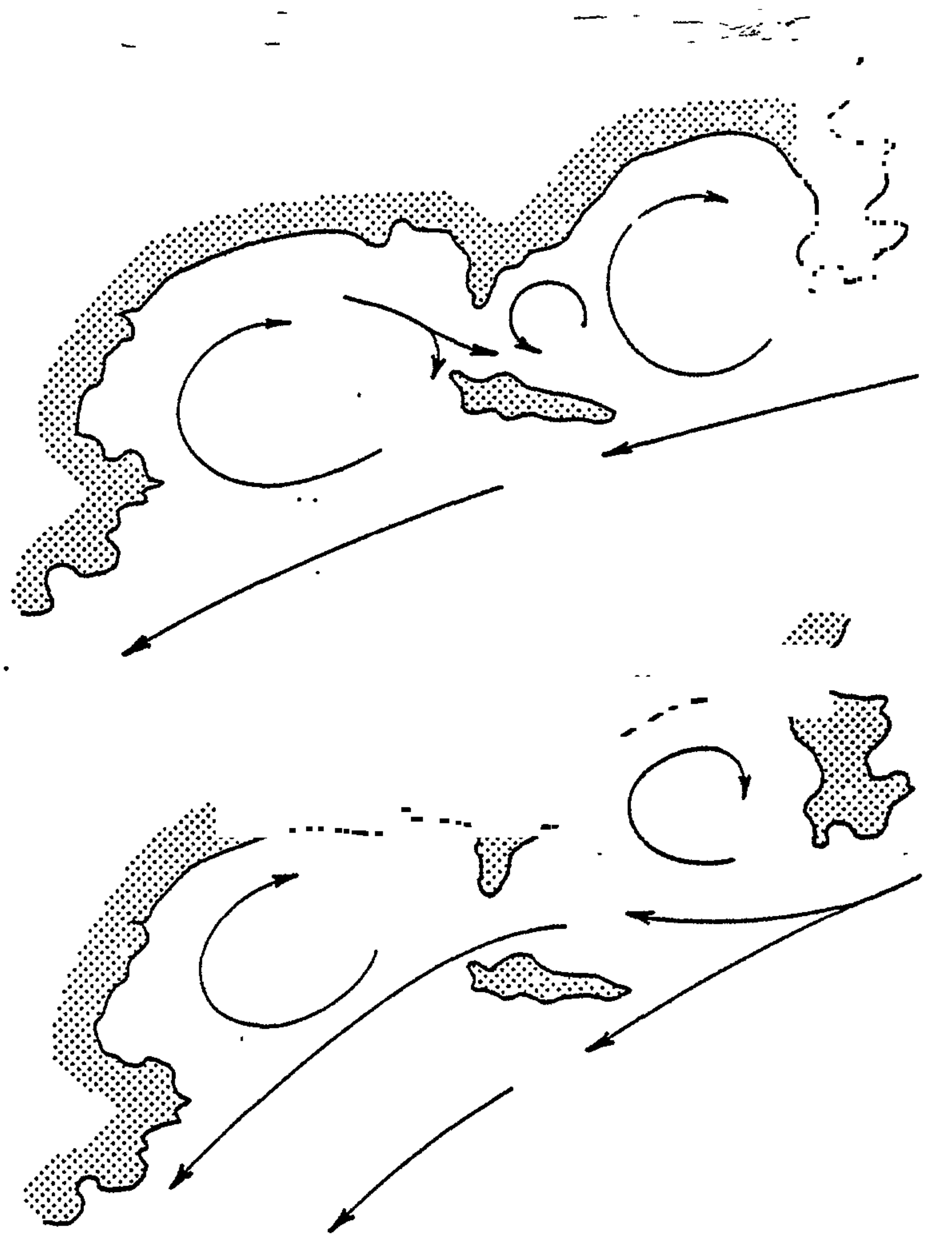


Figure 9: Probable circulation patterns induced in a bay

3.5.2 Tides

Tide is a phenomenon caused by the variations in time and space of the attraction field of the stars closest to the earth: the moon and the sun. Tide is weak in the middle of oceans, but its range becomes considerably greater on the continental shelf, where the topography of both the coasts and the sea bed plays an important role. The effects of level variations are well known; what is not so well known is that such variations are accompanied by the onset of velocities which may reach several metres per second (in large estuaries, in the Channel at the Cap de la Hague etc). In the Mediterranean, tides are generally very weak, but cause rather strong currents in the access channels to lagoons (channel of Caronte, channels in the Languedoc area of France).

Tidal flow is affected by friction on the sea bed and the velocity profile generally has a logarithmic form quite similar to that observed in channels and rivers. Thus, on a vertical, velocity fluctuates quickly near the sea bed and very little near the surface.

Usually, tidal currents are plotted at a given point at sea, the result being a current rose, which is a simple velocity odograph for a tidal cycle (figure 10). Near the coasts the current rose assumes an elongated form and the longest sides are roughly parallel to the isobath lines.

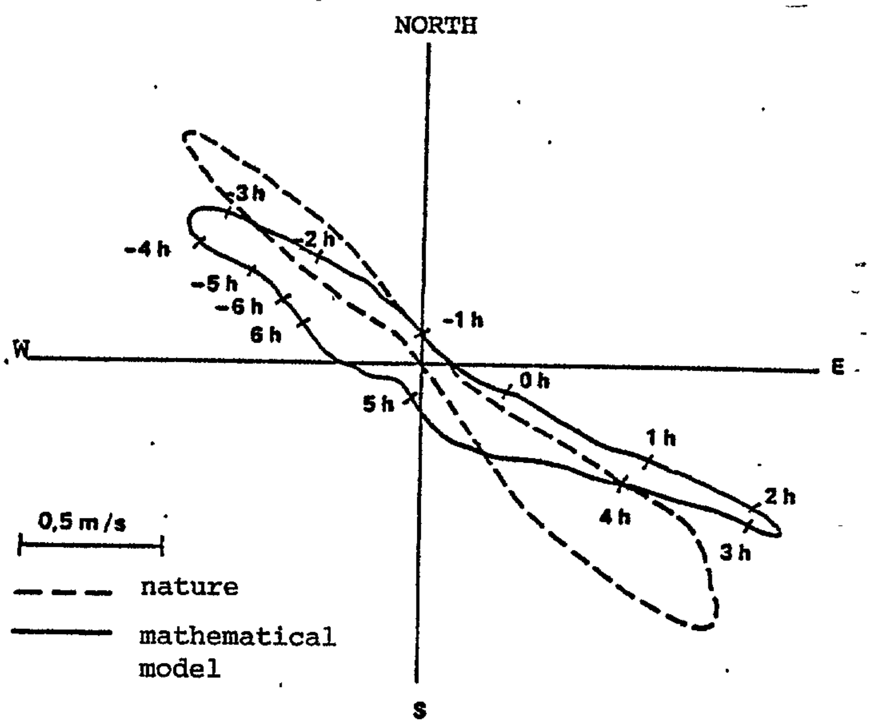


Figure 10: Example of a tidal current pattern (Odograph of the velocity vector measured at a fixed point for a tidal cycle)

If one follows a specific water particle in its course during a tide, one realises that it never returns exactly to the point where it started. There are always secondary currents, which generally promote progressive renewal of the waters.

Unfortunately, it is very difficult to determine these currents because they are secondary to tidal movement. It is only by carrying out appropriate and detailed field measurements (floats) that one can accomplish this task and even then only approximately.

The field of velocities in a given marine area can be obtained either by an adequate number of field measurements, or by a physical or mathematical model. Since the funds to be allocated to the study of the receiving environment are (because of financial considerations) proportional to the seriousness of the pollution risks of the planned discharge, one cannot in all cases undertake the most sophisticated study which in any case is not really imperative for small projects with low pollution risks. A limited campaign of field measurements which follows a well thought-out protocol should be sufficient. For larger projects the use of models is recommended. But whatever their type, the models do not fully cover the need for a certain number of field measurements which are required to fine-tune the models and establish boundary conditions.

The fine-tuning consists in selecting for all the nodes of the model grid the parameters of friction adapted to local conditions. The input of boundary conditions consists in reproducing the real water exchanges through the theoretical boundary separating the area covered by the model from the open sea. Thus, field measurements are needed for both fine-tuning and boundary conditions.

Taking into account the complexity and the number of field measurements to be carried out, if the problem is to be solved completely by this means alone, one can state that, assuming equal quality of results, the mathematical models are the least expensive solution today. However, they should be run on large computers which are available only in very few study centres. Moreover, selecting a mathematical model for the solution of the problem is not an easy task. The majority of models available world-wide for the computation of tides are designed primarily to give the levels of the water and not a field of velocities which is of such precision as to be used in studies of pollutant dispersion. The lack of precision results from the fact that certain factors have not been introduced in the equations.

All mathematical models give the variations in time of the water levels and of velocities at each node of the mesh of a grid established in advance to cover the area under study. For pollution dispersion studies one must deduce the trajectories of water masses.

The results furnished by a mathematical model are particularly affected by boundary conditions; the latter are often imperfectly known, if a sufficient number of field measurements has not been carried out. A solution to this problem might be to design two overlapping models. The first, with a large mesh to cover a large area and furnish the boundary conditions and the second with a smaller mesh to cover only the area under study.

3.5.3 Wind-generated currents

Seamen say that "it is the wind that makes the current". The statement holds for both the large oceanic circulations and in coastal waters. Even the weak summer winds considerably affect currents and constitute an effective moving force for the transport and dispersion of contaminants.

The main characteristics of wind-generated currents are three: the very characteristic configuration of the vertical velocity profile, the influence of the Coriolis effect and the effects of inertia which delay considerably the onset of flow.

Wind brings about a certain amount of friction on the surface of the water and by entrainment sets in motion the surface liquid molecules. This movement is transmitted in the water column according to a complex mechanism in which water viscosity and turbulence both play a role. Viscosity prevails in the boundary layers under the surface and near the sea bed; there the vertical gradients of horizontal velocity are maximal. In the liquid mass between these two extremes, it is turbulence (about which more in paragraph 3.6) that effectively promotes the flow caused by the wind; this is accomplished by the vertical transport of small water masses and of the momentum they possess.

If we use computer programmes designed to simulate this mechanism of turbulence and ignore for the moment the Coriolis effect, we get the two universal velocity profiles illustrated in figures 22 and 23. These profiles cover the following two extreme cases: the first is that of a wind, perpendicular to the coast producing parallel to itself displacement of water, the average flow of which is of necessity zero; the second is that of a wind parallel to the coast. In the two diagrams, the Y-axes represent "standardised" depths, that is to say depths divided by the total depth H and the X-axes represent standardised velocity, or velocity divided by the maximum surface velocity V_S. The approximate results of the computations, if W be the wind velocity measured at the standardised height of 10m above sea surface, are:

Wind perpendicular to the coast $\quad V_S = 0{,}04W \quad (3.8)$

Wind parallel to the coast $\quad V_S = 0{,}07W \quad (3.9)$

However, these velocity profiles are established only after the wind has been in operation for a sufficient amount of time, 2 to 12 hours approximately, so that inertia can be overcome and the process begin. On the diagrams one should note the very considerable variations of velocity in the immediate vicinity of the surface, a phenomenon which is simply confirmed by field measurements. At a depth of H/10 velocity is divided by 5 if the wind is perpendicular to the coast and by 2 if the wind is parallel to it.

This underscores the illusory character of the formulae which attempt to express the velocity of a current as a percentage of the velocity of the wind, without determining to what depth the velocity suggested applies; it also points out the error committed when the so-called "surface" velocities are measured by means of current meters submerged, to avoid possible risks, to a depth of approximately -2m. In fact, truly surface velocities can only be measured by means of flat floats that do not catch the wind at all.

We can see then that a layer of water contaminated by pollution will be subjected to differential convection depending on depth, a phenomenon intensified by vertical diffusion.

If we take into consideration the Coriolis effect, the velocity vector will change direction depending on depth. The diagrams in figure 24 give an idea of these variations depending on the relative direction of the wind with regard to the coast. The data in these diagrams are established for a total depth of water of 10m and a latitude of 43° North. Moreover one has:

$$V_s = 0{,}027\ W\ (1{,}52 + |\sin \beta|) \qquad (3.10)$$

On these diagrams one notes the clear difference between the direction of surface currents and that of the wind. This phenomenon had already been observed at the beginning of the century by the polar explorers who were surprised at seeing the icebergs drift at a 45^{o} angle to the direction of the wind; this was theoretically confirmed by Ekman in 1905. On the contrary, the average flow of water is always parallel to the coast. Thus, there will always be a very considerable difference between the direction of the wind and the direction in which the contaminated waters are transported. This difference is also affected by topography and to a lesser degree by the latitude of the site.

3.5.4 Influence of a stratified environment on currents

In the preceding paragraph, we briefly summarised the role played by turbulence in the vertical transport of momentum and the transmission to deeper layers of the surface action of the wind. One can intuitively explain that density stratification of sea water strongly inhibits turbulence. In effect, when there is a density gradient, any vertical displacement of a small water mass by an eddy propels this mass to an environment which is either higher or lower in density, and this brings immediately to the fore gravity or buoyancy forces giving rise to a torque higher than that caused by turbulence. Thus, vertical transfer of any momentum is inhibited, particularly the transfer toward the sea bed of the movement induced by the wind in a density stratified ambient.

A stability criterion for a stratified ambient is given by Richardson's adimensional number, or ratio of the density forces (relative density gradient $\partial\rho/\rho\partial z$) to the square of the vertical gradient of velocity ($\partial u/\partial z$) which generates the energy dissipated in the turbulence:

$$R_i = g\frac{\partial \rho}{\rho \partial z} \Big/ \left(\frac{\partial u}{\partial z}\right)^2 \qquad (3.11)$$

where:

- g = acceleration of gravity,
- z = vertical co-ordinate,
- u = horizontal velocity,
- ρ = density of sea water

In the coastal waters which interest us here, the Richardson number varies in practice between 0 and 1.

To give an example, figure 13 on page 76 compares the velocity profiles obtained in a stratified and a non-stratified ambient. They have been established for a wind of 4m/s and stratification which corresponds to a heat difference of 2^{o}C between -4 and -7m. The resulting density difference is $500 g/m^3$. We should note that velocity is roughly divided by 3 between the highest and the lowest points of the stratified ambient.

3.6 TRANSPORT AND DISPERSION BY CURRENTS

There is not as yet a precise definition of turbulence. What one observes in the majority of natural flows is considerable irregularities and disordered exchanges of small water masses in various directions bearing no relationship to the general direction of the flow. The fluctuations are both random and unpredictable.

Water can not be compressed. Thus, according to the principle of mass conservation, any random displacement of a small mass of water within a fluid, must be compensated by a displacement roughly opposite. This explains the vortical character of turbulence.

One immediate consequence of these eddies is the rapid propagation in all directions of all the properties attached to liquid particles: temperature, dissolved chemical substance, momentum, etc.

Turbulence is the result of internal instability between the forces of viscosity and those of inertia. It always dissipates kinetic energy and disappears quickly if there is no continuous supply of energy. It is not a property of the fluid, but depends on the flow under consideration and on boundary conditions: shape of solid walls, friction, etc.

The vorticity of turbulence should confer on it an isotropic character. In reality, the forces of gravity, those of friction, the shallowness of the water (taking into consideration the horizontal dimensions of the flows in the sea) considerably diminish this isotropic aspect of turbulence.

3.6.1 Equation of diffusion

Despite the importance of turbulence in various technical fields and the studies concerning it that have been carried out, the problem of expressing it in equation form has not been solved as yet. The problem continues to be one of closure, i.e. the unknown quantities are more numerous than the equations.*

We cannot give here all the theories on which equations of turbulence have been based; however, the simplest solution is based on the Navier-Stokes general hydrodynamic equations, into which the general effect of turbulence is introduced in the form of three parameters linked to the principal axes, in relation to which one studies the flow as follows:

$$\frac{\partial F}{\partial t} + u\frac{\partial F}{\partial x} = \frac{\partial}{\partial x}(K_x\frac{\partial F}{\partial x}) + \frac{\partial}{\partial y}(K_y\frac{\partial F}{\partial y}) + \frac{\partial}{\partial z}(K_z\frac{\partial F}{\partial z}) \qquad (3.12)$$

Where:

x, y, z = space coordinates; O_x is oriented in the direction of the velocity vector and O_z is vertical,

t = time,

u = velocity of horizontal flow (it is assumed that there is no vertical component and the selection of axes cancels a possible horizontal component in the direction of O_y),

K_x, K_y, K_z = parameters of turbulent diffusion,

F = a scalar quantity such as: a component of velocity, temperature, concentration of a pollutant, etc.

---

* However, there are more complete expressions of turbulence in equation form as well as simulation models of this phenomenon, both matters reserved for specialists.

We should especially stress the fact that the quantities K_x, K_y and K_z may vary in space and time depending on the characteristics of the flow. None of the three is a physical constant.

3.6.2 A topical and instantaneous source of pollution

Taking into account certain limited assumptions, such as permanent flow or small variations in velocity or depth, we can assume that these parameters of turbulent diffusion are constant at a given point and for a given moment. In this case, in a system of Lagrangian co-ordinates (moving origin for a speed u) and for initial conditions whereby a topical mass M of contaminant is injected at time t=O and for x=y=z=O, we have the following baseline analytical solution for the differential equation of diffusion:

$$c\,(x, y, z, t) = \frac{2M}{(4\pi t)^{3/2}\,(K_x.K_y.K_z)^{1/2}} \exp\left[-\frac{1}{4t}\left(\frac{x^2}{K_x} + \frac{y^2}{K_y} + \frac{z^2}{K_z}\right)\right] \qquad (3.13)$$

where c is the field of concentrations.

This solution can be rewritten as a product of the three Gaussian laws, each one relative to an axis of co-ordinates, e.g.:

$$\frac{1}{(4\pi K_y t)^{1/2}} \exp\left[-\frac{y^2}{4K_y t}\right] \qquad (3.14)$$

In a field of uniform velocity and for the precise initial conditions given above, the field of concentration has an ellipsoidal form. By analogy with the properties of the Gaussian law (figure 11), a characteristic dimension of this ellipsoid, say in the y direction can be expressed as follows:

$$y^2 \doteq 2K_y t \qquad (3.15)$$

which is an extremely simple relation giving immediately an order of magnitude for the phenomenon in the direction under consideration; (this is also a classic expression of the standard deviation).

Thus, the dimension of the diffusion coefficient is L^2T^{-1}, which can be expressed in either m^2/s or cm^2/s.

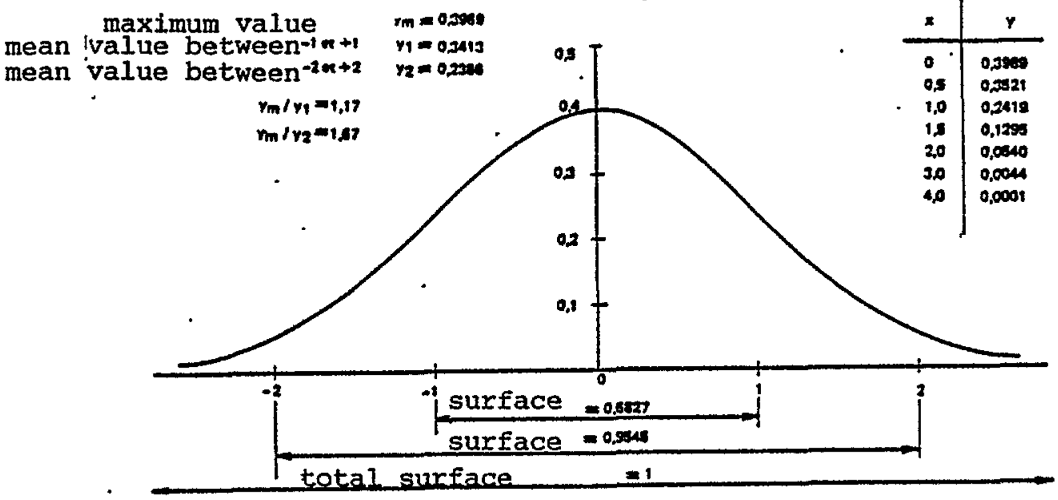


Figure 11: Normal law or LAPLACE-GAUSS law $y = \frac{1}{\sqrt{2\pi}} e^{-x^2/2}$

(The standard deviation of the reduced normal law is equal to 1. The x-axis is therefore graduated in standard deviations).

3.6.3 A topical and continuous source of pollution

A continuous discharge of effluent can be assimilated to a series of injections which are instantaneous but graduated in time. Thus, by integrating equation 3.13 we obtain the following general solution:

$$Q(x,y,z) = \frac{2Q}{4\pi r\sqrt{K_x K_y K_z}} \exp\left[\frac{u}{2K_x}(x - r\sqrt{K_x})\right]$$

(3.16)

$$r^2 = \frac{x^2}{K_x} + \frac{y^2}{K_y} + \frac{z^2}{K_z}$$

Where Q is the volume of contaminant assumed to be discharged to the surface of the sea at the point where the co-ordinates x=y=z=0 (the number 2 of the numerator disappears if the injection is made into an infinite marine mass).

This equation can be simplified, at least if one is interested only in the residual concentrations quite far from the source and near the flow axis. In this case x is greater than y and z.

We can thus:

- On the one hand ignore y and z in the expression of r^2 (second equation 3.16). Therefore: $r\sqrt{K_x} = x$ and the fraction of the right hand side of the first relation (3.16) becomes:

$$2Q/(4\pi x\sqrt{K_y K_z})$$

- On the other hand from the expression of r^2 we get:

$$r\sqrt{K_x}/x = \left[1 + \frac{K_x}{x^2}\left(\frac{y^2}{K_y} + \frac{z^2}{K_z}\right)\right]^{1/2}$$

By substituting for the right hand side of this equation the first two terms of its series expansion - of the form $(1 + x) \simeq 1 + nx$ - we have:

$$r\sqrt{K_x} \simeq x + \frac{1}{2}\frac{K_x}{x}\left(\frac{y^2}{K_y} + \frac{z^2}{K_z}\right)$$

And since x = ut, the exponential of (3.16) can be rewritten as:

$$\exp\left[-\left(\frac{y^2}{4K_y t} + \frac{z^2}{4K_z t}\right)\right]$$

Thus (3.16) becomes:

$$C(x,y,z) = \frac{2Q}{4\pi x\sqrt{K_y K_z}} \exp\left(\frac{-y^2}{4K_y t}\right) \exp\left(\frac{-z^2}{4K_z t}\right) \qquad (3.17)$$

Rewritten thus the relation (3.16) shows that:

- the longitudinal diffusion K_x no longer plays any role;

- the distribution of concentrations in directions perpendicular to the flow conserves a Gaussian character, the typical dimensions remaining of the order of:

$$y^2 = 2K_y t \qquad z^2 = 2K_z t \qquad (3.18)$$

- the concentration on the x axis is now a simple hyperbolic function of x:

$$C(x, y=0, z=0) = \left[\frac{2Q}{4\pi\sqrt{K_y K_z}}\right]\frac{1}{x} \qquad (3.19)$$

- the concentration at the point of injection is infinite, which conforms to the assumption of a topical injection, thus of zero volume.

- the ratio of concentrations between any two given points of the axis is simply given by:

$$C(x_1, y=0, z=0) \,/\, C(x_2, y=0, z=0) = x_2/x_1 \qquad (3.20)$$

If one wishes to get the standard deviation in either y or z and by the very definition of this standard deviation one obtains through double integration of (3.17):

$$\sigma_y^2 = \int_{-\infty}^{\infty} y^2 \int_{0}^{\infty} C(x, y, z)\, d_z\, d_y$$

$$\sigma_y^2 = \frac{Q}{u}\,(2K_y t) \qquad (3.21)$$

$$\sigma_z^2 = \frac{Q}{u}\,(2K_z t) \qquad (3.22)$$

These integrations present no special problems, once the two classic integrals are known:

$$\int_{0}^{\infty} \exp(-ax^2)\, dx = (1/2)\sqrt{\pi/a}$$

$$\int_{0}^{\infty} x^2 \exp(-ax^2)\, dx = (1/4a)\sqrt{\pi/a}\ .$$

3.6.4 Simplified manual calculations using the method of the probable source

In practice, the routine case is that of a polluting source risen to the surface of the sea, the result of one or several ascending plumes, the dimensions of which do not allow either the assimilation to a topical source or the direct application of the abovementioned results.

However, an approximate solution exists, if one uses a property of the equation of diffusion, according to which the field of concentration created by several topical sources moves, when one moves away from them, toward the field resulting from a probable unique and topical source situated upstream in the general flow.

This solution requires the admissibility of the essential simplifying assumption made, i.e. that the velocity of the flow of sea water is constant in intensity and direction at all points reached by pollution.

The computations concerning a simple rising plume help establish a concentration on the axis of the plume at the surface of the sea and a characteristic radius of this plume selected as representing the standard deviation of the distribution of concentrations.

By identifying these two values (at the concentration and at the standard deviation) of a probable permanent topical source by using equations (3.19) and (3.21), one can calculate directly the distance X_o and the volume issuing from this probable source which would give for the distance X_o downstream a cloud of width and concentration equivalent to those of the plume which is the real source. For this computation to be carried out, one obviously needs to know the average velocity u of the marine environment and the order of magnitude of the corresponding turbulent diffusion K_y.

Let C_p be the concentration on the plume axis and r the plume radius; we have a system of two equations in X and Q which can be solved by elimination:

$$r^2 = 2Q\, x\, K_y/u^2$$

$$C_p = 2Q/(4\pi x\sqrt{K_y K_z}) \qquad (3.23)$$

whence the characteristics of the probable source:

$$Q_o^2 = \pi C_p\, r^2 u^2 \sqrt{K_z/K_y}$$

$$x_o = r^2 u^2/(2K_y Q_o) \qquad (3.24)$$

$$t_o = x_o/u$$

This is only an approximate solution and it is not really likely that the initial thickness of the cloud of the diluted plume, as given by the formula (3.4), will really correspond to the characteristic vertical dimension given by (3.22).

An even more simplified solution can be based on the relations (3.18) by identifying the characteristic dimensions y and z of the polluted layer with respect to the radius r of the ascending plume and to the initial cloud thickness H deduced from (3.4). By multiplying the two relations (3.18) we can write:

$$t_o = rH/(2\sqrt{K_y K_z})$$

$$x_o = u t_o \qquad (3.25)$$

Thus, we have several possible solutions for the evaluation of dilution during the phase of convection-diffusion by the marine currents. It is clear that one can apply the formulae (3.19) and (3.20). But one should note that at distance x the dilution caused by the probable source will be at the flow axis:

$$\bar{T} = (x + x_o)/x_o \qquad (3.26)$$

Since x = ut this relation is equivalent to:

$$\bar{T} = (t + t_o)/t_o$$

Outside the axis the concentration can be given by formulae (3.17) or (3.16).

3.7 CALCULATIONS RUN ON COMPUTER

The calculation methods given in the previous section are but a rough approach to the calculation of the dilution resulting from diffusion in the phase of pollutant transport to the surface. Since, as we have stated, dilution in this phase is always small, such computation methods can often be adequate for this first stage of the study.

However, one should not lose sight of the fact that these methods are very approximate and that every time that it proves necessary, one should carry out computations based on mathematical models run on computer. However, designing specific programs for such computations is a lengthy and costly operation. Users are advised to call upon specialists who have all adequate means at their disposal. Even so, the task of the users is not easy because, out of the existing programs, they must select those that would give a correct solution to the problem at hand.

The computation models on jets and plumes are the least complex to design and the most reliable for the non-specialist user. They integrate the system of differential equations describing the jet (or plume) by small increments to cover its curvilinear axis. One uses the Runge-Kutta numerical integration method given in several specialised works. These models can easily be adapted to run on small computers available in study centres.

On the other hand, the computation of the effects of the horizontal convection-diffusion of effluents, risen to the surface of the sea, or trapped at the level of their density balance, is an extremely complicated problem and can only be tackled by a few well-equipped laboratories or scientific study centres. This complexity requires rather drastic simplifications to be brought down to the equations representing physical phenomena. In this way, one cuts down on program complexity and computation costs but reduces accordingly the scope of validity of the resulting model. Thus, it is important for the potential user to obtain all relevant clarifications on the computation programs available.

The most comprehensive mathematical models compute the velocity and the direction of currents at every point of the field represented by the equations on dynamics. This is the only solution, especially in tidal seas, or if the topography of the coast is paticularly complex. The great majority of such models require that the marine flows be almost horizontal and that they be expressed adequately by velocity averaged on each vertical. This enables the designer to create models for the solution of a plane, i.e. a "bidimensional" problem, since the equations to be solved no longer depend on three space co-ordinates but only on two. This assumption is often justified, because of the small depth of the water as compared to the horizontal dimensions of the field under consideration.

The assumption that sea water masses are homogeneous in density is often valid, since the diffusion of the pollutants under consideration very slowly crosses the horizontal barrier represented by the stratifications (case of the thermoclines in the Mediterranean).

One can design much simpler but a lot less precise models, if one uses a semi-empirical law to cover approximately the field of currents. Thus, one can represent a tidal current as a simple sinusoidal function of time, or wind-generated currents as a simple relation of proportionality with respect to wind velocity. The error, either as regards the intensity of the velocity or its direction, can reach 20 to 40% which is considerable. However, if one takes some precautions to limit the scope of such errors, one obtains models which are a lot less costly; such is the case of the models used to establish the Schemes for the Improvement of Coastal Waters (SAEL). A probabilistic approach or calculations of sensibility can compensate for the lack of accurate data on the field of currents.

A mathematical model exactly like a scale hydraulic model, reproduces only a limited marine area and introduces an imaginary boundary with the open sea. The model must reproduce the exchanges of water crossing this boundary. This is what is called the "boundary conditions" of the model. The boundary conditions must be established ahead of time, either by an adequate number of field measurements, or by a system of overlapping mathematical models. By moving the boundary of the model, where these boundary conditions must be established, far enough from the useful field we reduce quite considerably the consequences of the approximations made in evaluating them.

Depending on the programme and the degree of general application sought by the designers, the diffusion due to turbulence will be taken into account either by one, or by several numerical parameters (anisotropism and differences between horizontal and vertical diffusion may or may not be taken into consideration). These parameters may either be constant, or vary with the local conditions of the flow. The user must know that the numerical computation of diffusion presents problems of precision and that programmes ignoring this problem may introduce errors greater than the phenomenon computed.

3.8 DIFFERENTIAL CONVECTIONS

Flows in the coastal waters are most often characterised by small heights of water as compared to the horizontal distances travelled. Such flows are, on the one hand, almost horizontal and on the other, they are dominated by the effects of friction on the sea bed or of the friction induced by the wind. The result is considerable vertical gradients of velocity (see paragraph 3.5.3). What we are confronted with is "shear" flows, because the flow of horizontal layers at different velocities introduce internal shearing stresses.

If we mark, for example with a dye at a given instant t, a vertical prism of water (see figure 12), each element of this prism will occupy at an instant t+dt a horizontal position considerably staggered with respect to its initial position. This is a lot more effective than turbulence in "dispersing" the contaminant.

Since in practice one works most often with mean velocity, without taking into consideration the real profile of velocities (because it is too complicated to carry out a truly tridimensional computation), one often lumps together the effects of differential convection and those of turbulent diffusion. Hydraulics specialists talk then of "dispersion". Obviously, tridimensional computation models take into consideration differential convection by introducing a field of velocities which is sufficiently detailed and they can then deal only with turbulent diffusion. We should note that this is a problem encountered while carrying out field measurements. A spot of dye combines the two phenomena and it is up to the scientist carrying out the experiments to take additional measures in order to distinguish between the two. In this respect, the interpretation of aerial photographs of a spot of rhodamine is especially difficult.

---

* (See Appendix G)

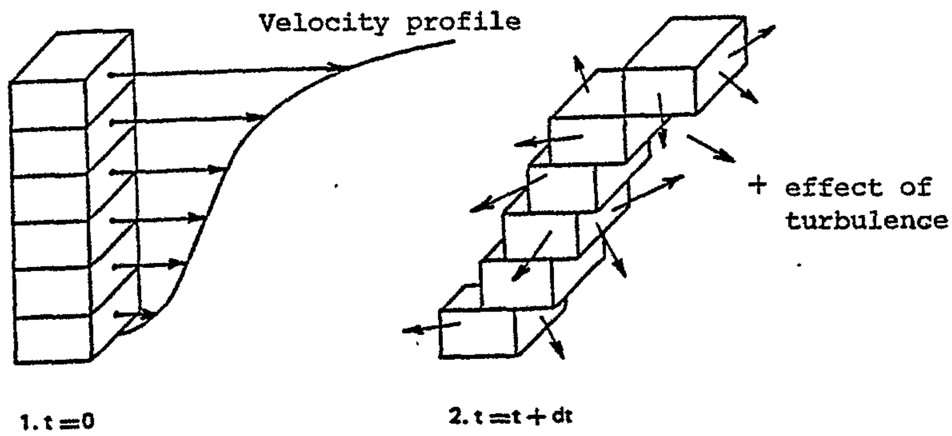


Figure 12: Differential convections in a shear flow. Relative positions of liquid prisms at two successive points in time.

3.9 COMPUTATION OF THE PARAMETERS OF TURBULENT DIFFUSION OR DISPERSION

It is G.I. Taylor who, in 1954, proposed a solution of this problem with regard to a flow in a pipe. He showed that the longitudinal parameter of dispersion which comprises the effects of both the diffusion and the differential convection can be expressed by:

$$K_x = aHu^* \qquad u^* = (\tau / \rho)^{1/2} \tag{3.27}$$

where:

- H = height of water (radius of the pipe in Taylor's experiments)
- τ = force of friction on the wall
- ρ = fluid density
- u^* = friction velocity
- a = numerical coefficient in the order of 10,1 in Taylor's pipe experiments

In 1959, Elder repeated Taylor's analysis and extended it to free surface flows in open channels. For this particular case, Elder proposed the following orders of magnitude:

$$K_x = 5{,}93\ Hu^* \tag{3.28}$$

$$K_y = 0{,}23\ Hu^* \tag{3.29}$$

However, the numerical coefficients which must be used vary considerably with the geometry of the flow and the real velocity profiles. Thus, measurements are in the majority of cases necessary in order to establish these values. These laws underscore the fact that the friction of the water on the solid walls is responsible for the turbulence which in turn generates diffusion.

The problem is even more complex in the vertical direction, since the parameter K_z depends on the configuration of the velocity profile and varies with depth. In the special case of a laboratory canal, in which the velocity profile follows a rather typical logarithmic law, Elder found an average value of:

$$K_z = 0{,}067\ Hu^* \qquad (3.30)$$

When the wind is the primary factor of shear, one can still use a similar formula but must use in this case the force of friction induced by the wind on the free surface τ_S, as has been shown in the specialised studies commissioned by the Ministère de l'Environnement (21):

$$K = a\ H\ u'^*$$

$$u'^* = (\tau_s/\rho)^{1/2} \qquad (3.31)$$

The Taylor-Elder formulae can be rewritten and translated into graphs; one should rewrite the velocity of friction on the basis of the slope of the energy line and of a classic law (e.g. Strickler's) of head loss. We can then write:

$$u^* = (g\ H\ j)^{1/2}$$

$$\bar{V} = K\ H^{2/3}\ j^{1/2}$$

and by simple transformations:

$$Hu^* = \sqrt{g}\ \bar{V}\ H^{5/6} / K \qquad (3.32)$$

where:

- g = acceleration of gravity
- H = height of water of the flow
- j = slope of the energy line
- $\bar{V}$ = mean velocity of flow
- K = Strickler's rugosity coefficient

A graph at the end of this document will give the practical determination of average K_y and K_z.

3.9.1 Influence of density stratifications

We have already indicated (see paragraph 3.5.4) that density stratifications inhibit turbulence. Thus, turbulent diffusion of dissolved matter will be extremely reduced at the thermocline level (figure 13). More specifically, when an effluent is trapped below the thermocline, a very small quantity of pollution will cross the thermocline and rise toward the surface, and a contrario, there will not be a sufficient quantity of dissolved oxygen crossing the thermocline toward the sea bed to ensure the biodegradation of organic matter. It is difficult to give precise values for the parameter of diffusion (or dispersion) to cover this case. The values cited are in the order of some cm^2/s.

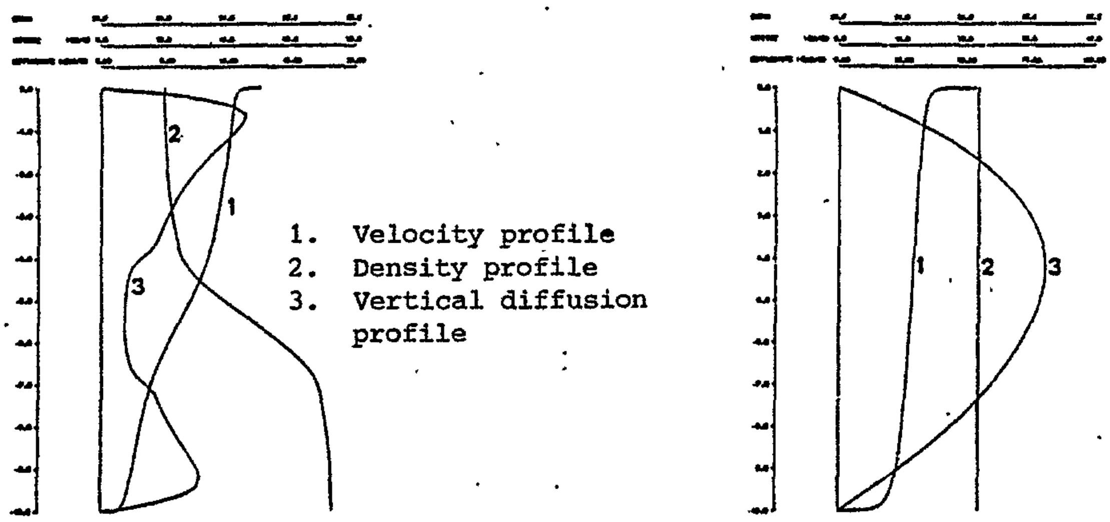


Figure 13: Vertical distribution of velocity in a density stratified and a non-density stratified ambient (wind of 4m/s)

3.10 COMPUTATION OF PROCESSES INVOLVING NON-CONSERVATIVE POLLUTANTS

The sea is a living environment, biologically and chemically active. Pollutants discharged by an effluent undergo biological or chemical changes depending on their nature. The two most common examples, very different in nature but linked to similar processes of mathematical formulation, are on the one hand the progressive disappearance of bacteria of human origin and on the other the biodegradation of oxidisable organic matter.

These two processes are predominant in the problem of the non-conservative pollutants contained in urban sewage. In both cases, it is believed that the rate of pollutants transformed at each moment is proportional to the residual concentration and that this is expressed by an exponential multiplying factor in the expression of the concentration as a function of time, concentration given by the equation of diffusion. This mathematical property makes possible the separate calculations of the effect of the convection-diffusion and of the effect of the biodegradation of the non-conservative pollutants following such an exponential law. The superposition of these two effects can then be obtained by the multiplication of the two factors of the decrease in concentration.

We will now deal in turn with the case of bacteria and that of organic pollution.

3.10.1 Bacterial decay

Concerning the discharge into the sea of urban wastewaters (the largest category of effluents), experience shows that microbial contamination controlled by the test germs of faecal contamination, is in almost all cases the critical or "limiting" factor. If it conforms to the standards established for the species, then the water will also conform to the health quality standards established for either bathing waters or shellfish growing waters.

One must understand thoroughly and appreciate the concepts on which the relevant legislation is based. The microbial parameters of the standards are mainly represented by the test germs, which in themselves are very rarely pathogenic, but which are a "tracer" or indicator of pollution of faecal origin. Their presence is linked with the assumption of contamination by dangerous microbial organisms or viruses, the numbers of which (generally not measured directly) can be considered as linked with the numbers of the test germs (which are measured). This indirect approach is dictated by practical considerations. The test germs, i.e. total coliforms, faecal coliforms and faecal streptococci are especially abundant and normally a lot more numerous than the pathogenic germs in urban effluents. Moreover, the laboratory techniques used to identify them are both sufficiently reliable and easy to use. On the contrary, counting them by the usual routine methods offers very little precision.

In reality then, the standards established on the basis of the test germs rely on a very indirect and thus chancy appreciation of the public health risk.

The standards are based primarily on the assumption that the relative proportions of the various germs in the polluted water do not deviate from the normal ratios, which excludes (especially for human origin pollutants) the case of an epidemic affecting a considerable proportion of the population. As soon as an epidemic outbreak becomes known, the control of the contamination of the water must be based on the collection of data on the microbial organisms specific to the illness.

Thus the calculation and design of a sea outfall system for the discharge of urban effluents into the marine environment must totally conform with the established mandatory standards covering the concentration of microbial test germs for the different uses of the sea. In those countries where appropriate regulations do not exist as yet, establishing such standards is thus the first measure to be taken; it is only then that one can approach the problem of establishing the best conditions for effluent discharge.

As an example, we give here the standards established for bathing waters in the EEC countries as mandated by the European directive of 8 December 1975:

BATHING WATERS	GUIDE Limits Number of germs in 100 millilitres	IMPERATIVE Limits Number of germs in:		
		100ml	1 litre	10 litres
Total coliforms	500	10 000		
Faecal coliforms	100	2 000		
Faecal Streptococci	100	-		
Salmonella	-		0	
E.coli	-			0

Similarly, for shellfish-growing areas, the following standards are mandatory in France:

SHELL-FISH GROWING WATERS	Number of faecal coliforms in 100 ml of shellfish flesh. Frequency of monitoring: 26 staggered over 12 months	Tolerance
"Healthy" area	≤ 300	3 measurements ≤ 1,000 2 measurements ≤ 3,000
"Non-healthy" area	(a) > 300 and ≤ 10,000	With the proviso of effluent treatment and the authorisation of Affaires Maritimes and ISTPM
	(b) > 10,000 in 25% of the samples	Authorisation by DDASS

Furthermore, in order to guide planners in their calculations, there is a regulation which establishes the indicative number 30 as the maximum factor of concentration in the flesh of shellfish for germs contained in sea water.

3.10.2 Decay law governing the test bacteria in sea water *

In the sea, the concentration of test germs in the contaminated waters decreases faster than can be accounted for by hydraulic dilution. The "decay" characteristic of the bacterial families which is added to dilution has been noted by all the specialists who have studied the problem.

The mechanisms involved in this decay are not well understood. This can be explained no doubt by the fact that there is a great variety of such mechanisms, the impact of which can be considered as a kind of self-cleansing property of sea water: factors such as salinity, ultra-violet radiation, antagonisms among living organisms, temperature and light possibly play a certain direct or indirect role. Also, a new theory today is that there is adsorption of bacteria on suspended solids either carried to the sea by the effluent or already existing there. In that case, the bacteria would follow the movement of the suspended solids supporting them and would settle, float, enter in the food chain, etc. Recent experiments have clarified these adsorption mechanisms. Therefore, bacterial "decay" is a phenomenon which may comprise a certain amount of true physical mortality, as well as several other elimination causes outside the pelagic environment where bacterial concentration is monitored.

---

* See bibliographical reference (18)

In the context of what interests us here, it suffices to keep in mind that, on the basis of actual counting of the bacteria in an effluent moving away from an outfall system, there is a continuous decrease in the concentration of such bacteria (dilution is deduced); what is more (a striking finding), regardless of the area in the world where the experiments are carried out, the decay law varies relatively little. It is this last feature that makes all the more interesting the mathematical formulation given here.

According to the theories on the kinetics of living groups, the number of births or deaths in the group per unit of time is proportional to the number of living individuals present in the group at that particular moment. These theories can be expressed by an exponential law representing the group population as follows:

$$N = N_0 \exp(-2{,}3\, t/T_{90}) \qquad (3.33)$$

where, for a bacterial population:

N_0 = initial number of germs per unit of water volume
N = residual number of germs per unit of water volume
t = time of stay in the sea
T_{90} = time needed in order that the number of germs be divided by 10, or a 90% reduction.

One might think that the T_{90} coefficient is a constant. However, even on the basis of the strictest protocol of measurements carried out in the open sea and in different parts of the world, the uncorrected values obtained fall within a rather large range. Be that as it may, one notes in homogeneous series of measurements that the values of T_{90} taken as a whole are roughly equivalent to a log-normal distribution law (Gaussian distribution of the logarithm of T_{90}). This law can be expressed as follows:

$$P\left[\operatorname{Log}(T_{90})\right] = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\operatorname{Log}(T_{90}) - m}{\sigma}\right)^2\right] \qquad (3.34)$$

where m and σ are the average and the standard deviation of this law respectively and P the probable density. We also have:

$$m = \overline{\operatorname{Log} T_{90}} = \operatorname{Log} \overline{T_{90}} \qquad (3.35)$$

$\overline{T_{90}}$ being the geometrical mean.

In order to take into account this probability law in the expression of N, one can use a mathematical weighted average (generalised average):

$$N = N_0 \int_0^\infty \exp(-2{,}3\, t/T_{90})\, P\left[\operatorname{Log}(T_{90})\right] d\left[\operatorname{Log}(T_{90})\right]$$

and by simple transformations we get the following formula:

$$N = (N_0/\sqrt{2\pi}) \int_0^\infty \exp\left[-(2{,}3\, t/T_{90}) \exp(-\sigma x) - x^2/2\right] dx \qquad (3.36)$$

The diagram in figure 26, at the end of the document, gives a graphic representation of this relation. The use in the x-axis and the y-axis of standardised variables confers upon it a universal character. One has only to introduce the selected values of T_{90} and of the standard deviation in order to read directly as a function of time the ratio N/N_o, i.e. the ratio of remaining germs and those initially counted.

The important feature of this diagram is the correction brought to the pure exponential law by the introduction of dispersion represented by the standard deviation σ. It follows that, in each subsequent period of time equal to T_{90}, the abatement factor (which is equal to 90% for the first time period) will progressively decrease; the greater the standard deviation, the greater the decrease.

Since direct measurement of T_{90} at the site of an outfall is not recommended because of unreliable results, the thing to do is to select the values to be introduced in the diagram. The following table gives an idea of the values measured in the course of serious experiments. As a rule, for the Mediterranean coastal waters, one can adopt values for T_{90} of 2,5 to 3 hours and for σ of 0,4 to 0,5.

Measurement Site	Authors	Date	Temperature of sea water	Total Coliforms		Faecal Coliforms		Faecal Streptococci	
				T90 hrs	σ hrs	T90 hrs	σ hrs	T90 hrs	σ hrs
Marseille Courtiou	SOGREAH	Jul.1977	16,9	2,63	0,35	2,61	0,43	2,86	0,56
Gulf of Giens	SOGREAH	Jun.1977	19,5	2,00	0,81	2,02	0,32	2,03	0,93
La Rochelle	SOGREAH	Jun.1978	15,8	1,00	0,50	1,00	0,50	1,60	0,60
Royan (Terre Nègre)	SOGREAH	Sep.1978	18,1	1,70	0,45	1,70	0,40	1,83	0,57
U.K. (Plymouth)	Gameson & Gould	1969-1973	17,0	2,43	0,38				
Brazil (Sao Paulo)	Occhipinti	-	18to28	1,25	0,66				
USA (California)	Foxworthy&Kneeling	-		2,00	0,72				
Abidjan(Ivory Coast)	SOGREAH - CRO	1977	20,0	2,16	0,47				

However, in using this law some caution should be exercised for the very shallow areas which are totally uncovered at low tide. When the tide rises, the breaking of waves puts back in suspension the settled matter and the adsorbed bacteria. Thus, in a bay in the North of France higher contamination levels of test germs have been observed than those that would be accounted for by the actual quantities of discharged effluents.

3.10.3 <u>Organic pollution of urban sewage</u>

Pollution by oxidisable organic matter is not generally a problem for sea water as is the case with rivers and lakes. There are many reasons for this: the large area available for sea-air contact, the importance of oceanic circulations and of the volume of water for the dilution of the effluents discharged and the very low content of sea water in organic matter. However, the picture may be different in certain closed bays or harbour basins, where there is very little renewal of the waters. Dystrophy or eutrophication may in that case appear.

Long-term *in vitro* measurements (BIOLAIGUE experiment*) have shown that in a confined enclosed area a flow of standard urban sewage corresponding to 1g of DCO/day/m^3 of water can be discharged without any real harm to the environment. In the case of urban sewage containing approximately 100g of DCO/day/person, the available marine area per person should be $100m^3$ in order that the environment not suffer any harm. This ratio can be decreased proportionally if the discharge area is not entirely confined.

The algal bloom, which occurred in 1975 in the bay of Cannes under the thermocline which trapped the ascending effluent plume, shows however that the receiving capacity of the marine environment in terms of organic pollution is not unlimited.

Special care should be exercised when oxygen renewal diminishes (trapping under a thermocline).

---

* See bibliographical reference (22)

CHAPTER 4

CERTAIN ASPECTS OF OUTFALL SYSTEM CONSTRUCTION

There is a high number of marine outfall systems and oil pipelines throughout the world. However, the proportion of such works broken near the coast is also impressive and this should make us cautious. After solving the problems of selecting the ground plan, charting the sea bed and possibly also levelling the ground for the laying of the pipe, one must carefully study and find solutions to the following four types of specific and interdependent problems:

- Resistance to corrosion;
- Mechanical resistance to swells and breaking of waves;
- The pipe-laying technique;
- Impact of the outfall system on the stability of the coast.

The cost of a marine outfall system, the cost more generally of all works at sea and the cost of subsequent repairs on a broken pipe call for caution in the preliminary studies. As a follow-up, constant monitoring of all parts of the system is required. More than anything else however, one should stress that adequate financial means must always be available in order to ensure without delay either the repair of any damage or the construction of reinforcing works that may prove necessary.

As a general rule, the most exposed part of an outfall is that lying in the surf zone; as a rule of thumb it would be that part of the pipe laying on the sea bed at depths less than 10 or 15m. In order that the outfall resist well to the wave-breaking stress one can do either of the following: one can construct heavy and massive works, i.e. one-piece pipes in reinforced or prestressed concrete, protected if need be by a shell of blocks of adequate size; or one can follow closely the natural profile of the sea bed which means pipes buried deeply into the ground. Certain outfalls are laid within true concrete jetties. Such works are only possible if the shore is stable with hardly any littoral drift; otherwise the jetty would cause heavy erosion of the beach on the one side and beach accretion on the other.

A most critical period in the life of an outfall system is that of laying, i.e. for as long as all the anchoring and protective devices have not been completed.

The key to success and to substantial savings at the same time is (a) to study in detail all the stages of construction and (b) to select for the construction and the laying of the system a period which is as favourable as possible, in terms of meteorological conditions and the state of the sea. Once the operation has begun, speed ensures its success. Small details, such as filling the pipe already laid, may have serious consequences.

4.1 CORROSION PROBLEMS

Corrosion is nowadays a problem handled rather well. Corrosion may be caused either by the sea water or by the effluent itself. Thus, selecting the material(s) for the construction of the pipe is essential; the choice is also important for the problems of mechanical stress.

Cast iron, whose corrosion resistance is good, is no longer used today for the construction of sea outfalls because of the fragility of joints.

Plastics may seem very attractive. Their greatest disadvantage is lack of weight and because of this, plastic pipes must be deeply buried or ballasted with concrete. They are also susceptible to perforation. Some plastics, polyvinyl chloride for instance, are attacked by marine organisms. This was the case of a sea outfall in Rio de Janeiro which, in less than a year, became inoperative.

A good material is steel with welded joints and the classic coatings of either fibreglass or asphalt products; it is used extensively by the oil companies in the construction of sea lines. Because of its flexibility and its mechanical strength, it adapts well to the curvatures of the sloping sea bed, it can be self-supporting if the bed erodes locally and it resists the exceptional stresses during pipe laying. On the other hand, the anti-corrosion coating is susceptible to the internal abrasion of the pipe or the external abrasion due to slight movement on the sea bed.

Lately, there seems to be a preference in connection with urban sanitation projects, for reinforced or prestressed concrete pipes and especially for steel cylinder concrete pipes. It is now possible to make concrete which is very compact, hardly affected by sea water. Pipes made of such material are extremely strong because of their mass and because they are in one piece and have no joints at all. Laying is made easier because they can be pulled on the sea bed.

Cathodic protection supplements the protection of steel pipes and that of the steel reinforcements and linings of concrete pipes.

4.2 MECHANICAL STRENGTH OF OUTFALLS

4.2.1 Longitudinal profile

Most of the outfalls are simply laid on the sea bed, at least from a certain depth down. Therefore, the pipe must conform to the contour of this longitudinal profile without undue stresses.

The problem in most cases is to establish a route for the outfall which ensures a profile as regular as possible with as little grading earthwork as possible. The ideal solution would be to reach very quickly a depth of between -10 to -15m, in order to avoid the wave-breaking action and then continue at a gentler gradient.

One should avoid most especially:

- the high points which have a negative impact on the hydraulic function of the pipe (air pockets);

- the rock outcroppings which might cause a rupture by buckling on the support, in case of near-by sediment erosion;

- laying the pipe without adequate anchoring devices on a steeply sloping sea bed; this might cause a longitudinal sliding of the pipe.

Pulling the pipe on the sea bed is easier if carried out in a consistent gradient line situated on the vertical plane of the laying. Transversal slanting will make the pipe deviate laterally and after the pulling is completed, will cause excessive traction stress and pipe twisting (figure 14).

Either because the longitudinal profile of the sea bed comprises certain undulations or because, under the action of currents there is a subsequent erosion, it may be that a certain length of the pipe does not rest on the ground. It must then be able to resist like a girder or else backfilling must be carried out.

4.2.2 Accidents caused by navigation

Quite a high number of outfalls and sea lines have been severely damaged by either fishing trawlers or by the anchors of boats. It is difficult to estimate in advance the stresses resulting from such accidents. The first precaution to take is obviously to mark on navigation charts all existing outfalls and to pass regulations prohibiting trawling and mooring at the oufall sites. The other solution would be to bury the outfall pipe deeply into the ground. For information, let us state here that an anchor of 900 Newtons penetrates 1,50m into sand; a very large anchor of 27,000 Newtons penetrates 2m into sand and up to 6m into mud.

4.2.3 Stability of the sea bed

Many accidents are due to the instability of the sea bed. Uplift in interstitial water may trigger underwater sliding of material in the form of fluid lava. Exceptional marine currents or heavy swells may cause erosion or changes in the sea bed, such as to cover an outfall completely or else to make the pipe overhang the ground: vibration in the latter case is a very real risk (Abidjan sea line, North Sea pipeline etc.).

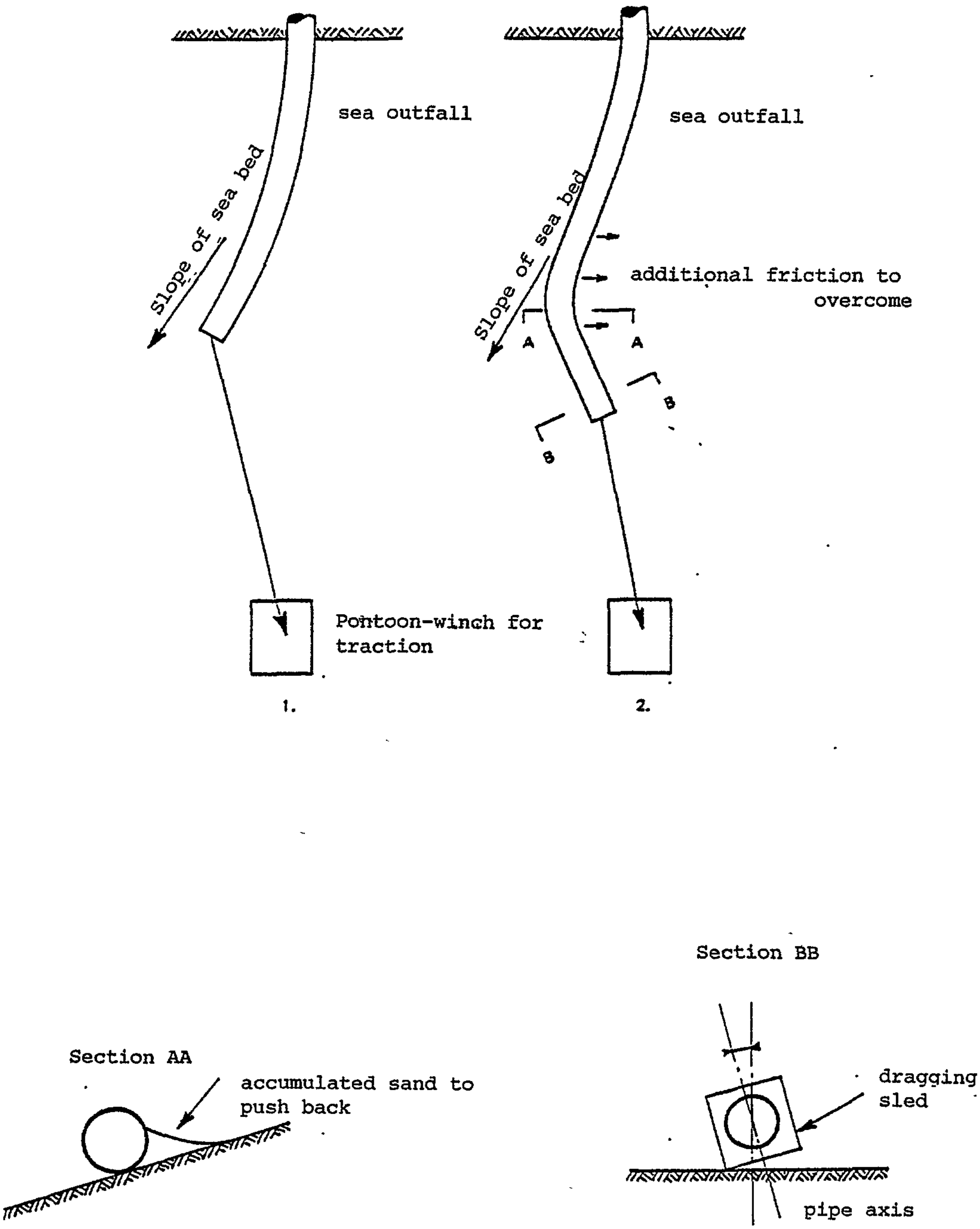


Figure 14: Impact of transversal gradient on pulling the pipe on the sea bed.

4.3 HYDRODYNAMIC STRESSES

The hydrodynamic stresses on submerged pipes are due either to general currents, to wave generated currents or to wave-breaking. Concerning the first two cases, many experiments on small scale models have been carried out and gradually led to the establishment of relatively simple computation formulae, such as Morison's formulae. Even if established for a pipe which has no contact with the sea bed, these formulae give satisfactory results and are unanimously accepted even for pipes resting on the sea bed.

On the other hand, there is no formula for the stresses caused by wave breaking and the safety standards required can only be met after carrying out small scale experiments in "canal à houle". Let us note in passing that even though the majority of outfall accidents has taken place in the surf zone, such accidents are often due to a lack of maintenance of the protective works.

4.3.1 Forces due to a permanent current

A permanent current induces on an immersed horizontal cylinder two forces: a horizontal drag and a vertical lift both of which tend to lift the cylinder. These forces are expressed as follows:

$$F_H = 0,5\, C_H\, \sigma D V^2 \qquad (6.1)$$

$$F_V = 0,5\, C_V\, \sigma D V^2$$

where:

F_H and F_V = drag and lift forces per unit of cylinder length

σ = density of the fluid in motion

D = cylinder diameter

V = fluid velocity as would be established if the cylinder were not submersed in the fluid (or velocity in an area not disturbed by the cylinder)

C_H and C_V = adimensional drag and lift coefficients

In theory, the coefficients C_H and C_V depend on the Reynolds number and the ratio d/D, d being the distance between the lower generating line of the cylinder and its horizontal wall constituting the bottom.

In practice, we assume C_H = 1 and for C_V the following values:

d/D	0	0,2	0,4	> 0,6
C_V	1	0,6	0,4	0,35

Concerning these formulae, one must obviously take into consideration the highest flow velocities likely to occur at the site under consideration.

4.3.2 Forces induced by waves

These are more difficult to determine because of the complexity of the wave itself. One must firstly define what is called a "design wave", considered the most critical on the basis of a statistical analysis of the available data. This wave is characterised by several parameters, its period T, its height H and its wave length L. Then by using Morison's formulae one can define the stresses exerted on a submerged pipe. However, the formulae contain numerical drag coefficients, the values of which vary, depending on several parameters, and they must be established only on the basis of small scale experiments.

In the literature one finds the results of numerous such experiments and they vary widely. Let us note that the drag of a submerged pipe depends on wall rugosity; the latter can vary considerably if the wall is gradually covered by algae or shellfish.

The hydrodynamic forces acting on a submerged cylinder comprise a horizontal force and a vertical lift. Each has two elements:

- A force linked to form resistance;
- An inertia force proportional to the derivation of velocity and to the volume of the cylinder.

The Morison formulae illustrate these forces:

$$F = F_T + F_1$$

$$P = F_T' + F_1'$$

$$F = 0,5\ C_D \rho D \left| V \right| V + C_H \rho W\ (dV/dt) \qquad (6.2)$$

$$P = 0,5\ C_P \rho D f(V2) + C_Z \rho W\ (dV/dt) \qquad (6.3)$$

where:

F	=	horizontal force per unit of pipe length
P	=	lift per unit of pipe length
D	=	pipe diameter
V	=	velocity generated by the wave
ρ	=	density of sea water
W	=	$\pi D^2/4$ (or volume of a pipe element)
$F(V^2)$	=	an experimental function of velocity

C_D, C_H, C_P, C_Z = coefficients variable with the Reynolds number, the distance of the pipe from the ground, the submersion depth of the pipe and the height of the wave.

If we assume that the wave is a sinusoidal function of time, thus also velocity V, the derivation of this velocity will be reduced by $\pi/2$, so that the forces of drag and inertia are not simultaneously maximal. In order to obtain the maximum stresses exerted on the pipe we can use the following practical formulae:

$$F^2_{max} = (F_x HD \sin \alpha)^2 + (F_D H^2 \sin^2 \alpha)^2 \qquad (6.4)$$

$$P_{max} = \left| F_Z HD \right| + \left| F_p H^2 \sin \alpha \right| \qquad (6.5)$$

where:

H = maximum height of the wave (maximum distance between crest and trough)

D = pipe diameter

= angle formed by the direction of the breaking wave and the pipe axis

F_X, F_D, F_Z, F_P = parameters obtained from the graphs in figures 15 to 18 (documents: Laboratoire National d'Hydraulique).

4.4 PIPE-LAYING TECHNIQUES

There are several different techniques for the laying of submerged pipes: the bottom pull method, the flotation method and construction and installation from a lay barge, floating or trestle-supported platform. The selection of the particular method will be based on the material the pipe is made of, the type of the joints, the weight of the pipe, local conditions for pipe-laying and the public works equipment available in the area.

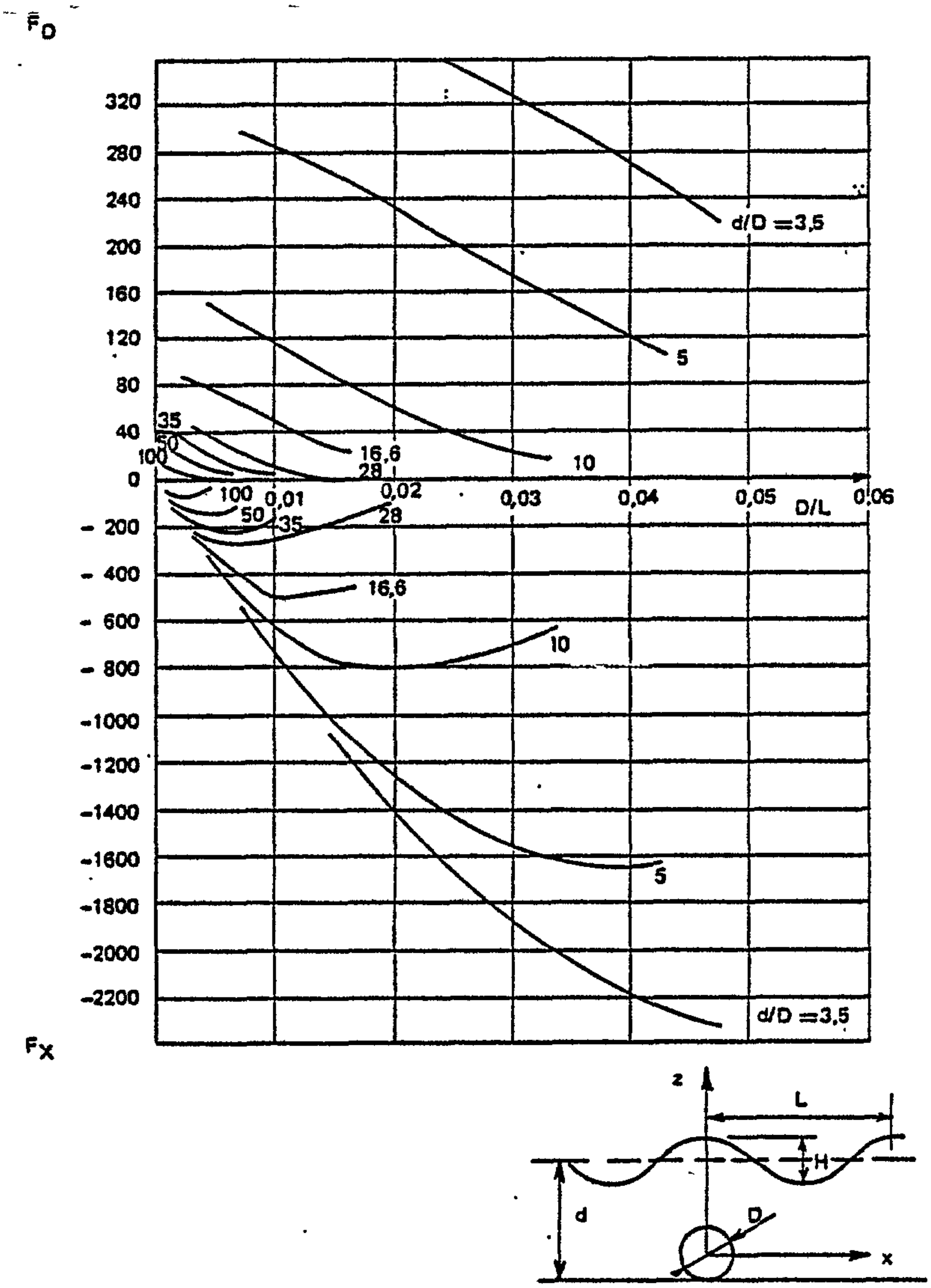


Figure 15: Value of the parameters F_X and F_D expressed in Newtons/m^2 (pipe resting on the ground). (from: Laboratoire National d'Hydraulique).

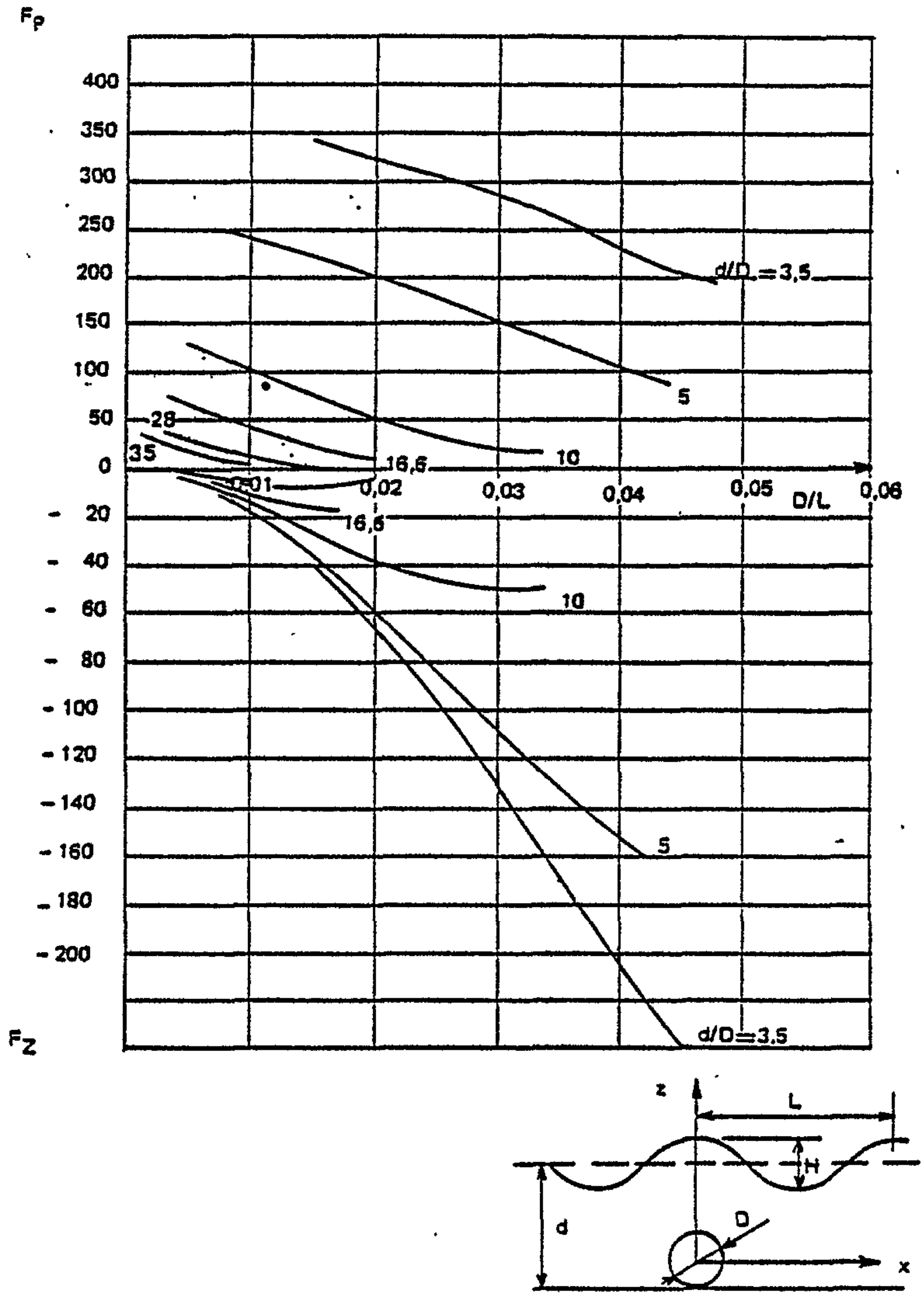


Figure 16: Value of the parameters F_Z and F_P expressed in Newtons/m^2 (pipe resting on the ground). (from: Laboratoire National d'Hydraulique).

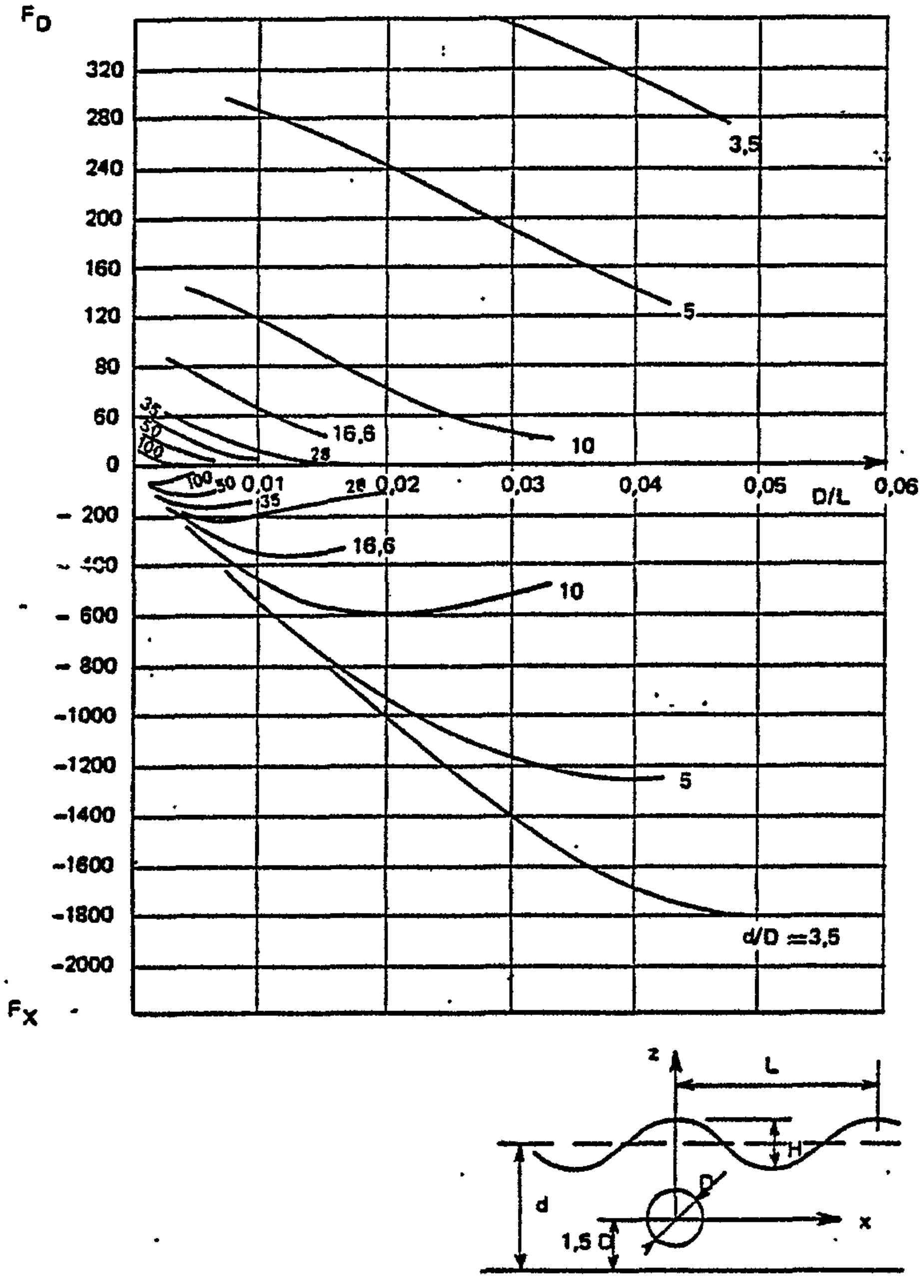


Figure 17: Value of the parameters F_X and F_D expressed in Newtons/m^2 (pipe not resting on the ground). (from: Laboratoire National d'Hydraulique).

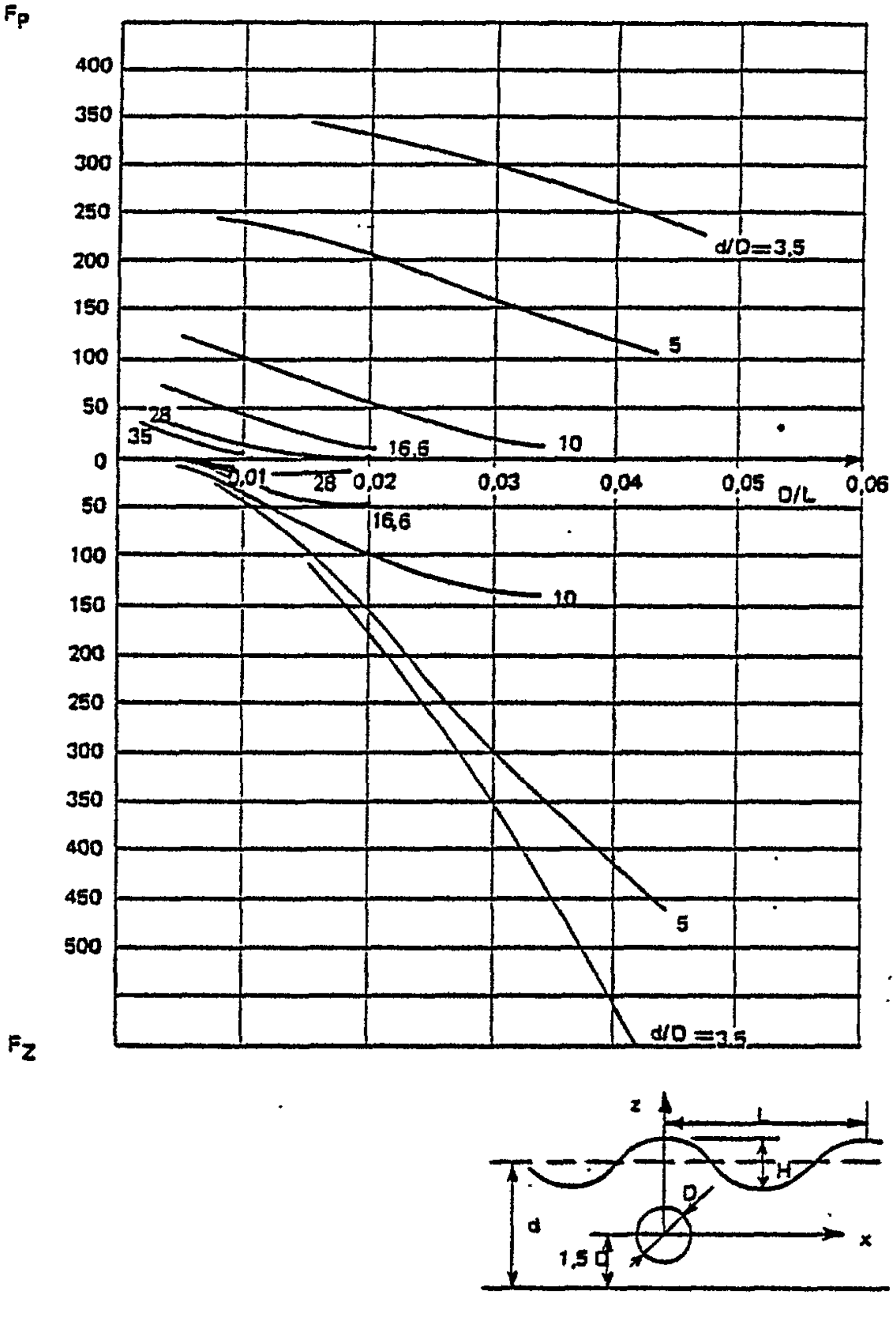


Figure 18: Value of the parameters F_Z and F_P expressed in Newtons/m^2 (pipe not resting on the ground). (from: Laboratoire National d'Hydraulique).

4.4.1 The bottom pull method of pipe-laying

This technique is becoming the classic one to use in the case of outfalls made of reinforced concrete with sheet metal liner whose welded joints resist well to traction stresses. It requires a rectilinear alignment for the outfall, a laying surface with no appreciable floor dynamics and adversities, slopes with gentle gradient which will impose upon the pipe a range of curving compatible with the constraints of flexion that the pipe can take. The only limit seems to be the strength of the available winches and pulleys and the resistance to traction of the pipe itself. Here are some examples:

- Cannes - 1972 - external diameter: 1740mm - reinforced concrete with sheet metal liner - length: 1100m, traction resistance: 400t.

- Menton - 1976 - external diameter: 800mm - reinforced concrete with sheet metal liner - length: 1200m, traction resistance: 60t.

However, in the literature, one finds the case of a pipe 5000m in length with a 1070mm diameter which was laid by the bottom pull method using a 13,000t winch.

Most often one reduces the apparent weight of the pipe in the water by pulling it empty of water, or even partially lightened by floats. In this way one decreases the friction on the sea bed and the traction stress.

The bottom pull method is a high risk operation if the sea becomes rough, because the pipe is not protected against the stresses caused by the breaking waves and because anchoring and maintaining at sea the pontoon-winches can become problematic. Thus speed is essential for this operation, which must be carried out at a time of the year when the chances that the sea will be calm are the highest. In most cases, pulling proceeds by about 100m per day and the speed of pulling is approximately 60cm/mn. The process can be accelerated, if there is room available on the shore for the preparation of rather long pipe sections, because this cuts down the number of joints that have to be made when installing the pipe in the sea. In the case of the Cannes outfall, the pipe sections were 60m long each, at Menton only 20m; but in the literature, mention is made of a case where the sections were each 450m long. Given the cost of maintaining immobile the pontoon-winches used and of all the equipment needed for this operation at sea, speed is also a cost-saving factor.

4.4.2 Floatation method of pipe-laying

This technique is used mostly for the laying of steel pipes whose diameter is less than 1m. It consists in assembling the pipe on land or along the shore. It is then towed out as a floating unit to its definitive installation and submerged.

Steel pipes of small diameter do not always float, even when empty and in that case they may be supported by floats. The latter are often let free at the moment of submersion by means of a firing device. Feeders, many kilometres long, have been installed in this way, especially those used for the supply of l'île d'Yeu with drinking water.

This method is sometimes hazardous even when the sea is calm. Thus it is used exclusively in relatively calm marine areas, or for sea lines that are of such length as to exclude the use of the bottom pull method.

A variant of this method, patented by Electricité de France, is the "S-curve" laying method. The pipe sections are assembled on a lay barge which moves toward the offshore waters by following the definitive route of the outfall pipe. The portion of the pipe already constructed hangs down under its own weight between the shore and the barge and lays itself gradually on the sea floor as the finished part becomes longer. The shape that the pipe takes between the sea bed and the barge gives the method its name.

4.4.3 Lay-barge tower method

Very large diameter pipes are often constructed directly on the site by assembling the sections on the sea bed.

In order to accomplish this, one uses special floating barges equipped with piles which can be lowered vertically to the sea bed when the barge is in working position. The barge is then lifted on these piles out of the reach of waves and immobilized there. The barge is equipped with lifting equipment for handling the pipe sections. This method can be used for work in depths up to 60m and was the one selected for the installation of two large outfalls: one in Los Angeles (Hyperion) (3,700m - diameter: 3,66m) and the other in Rio de Janeiro (4,300m - diameter: 2,44m).

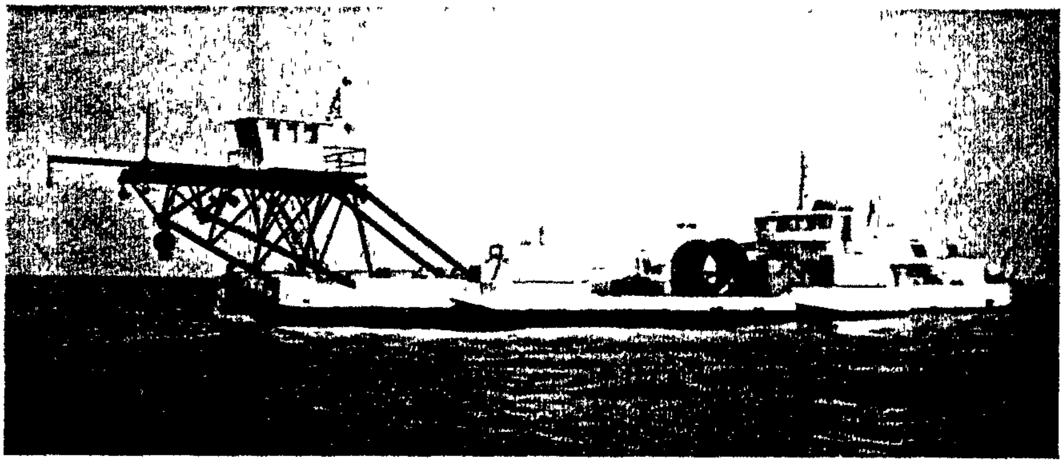
4.5 PROTECTIVE WORKS

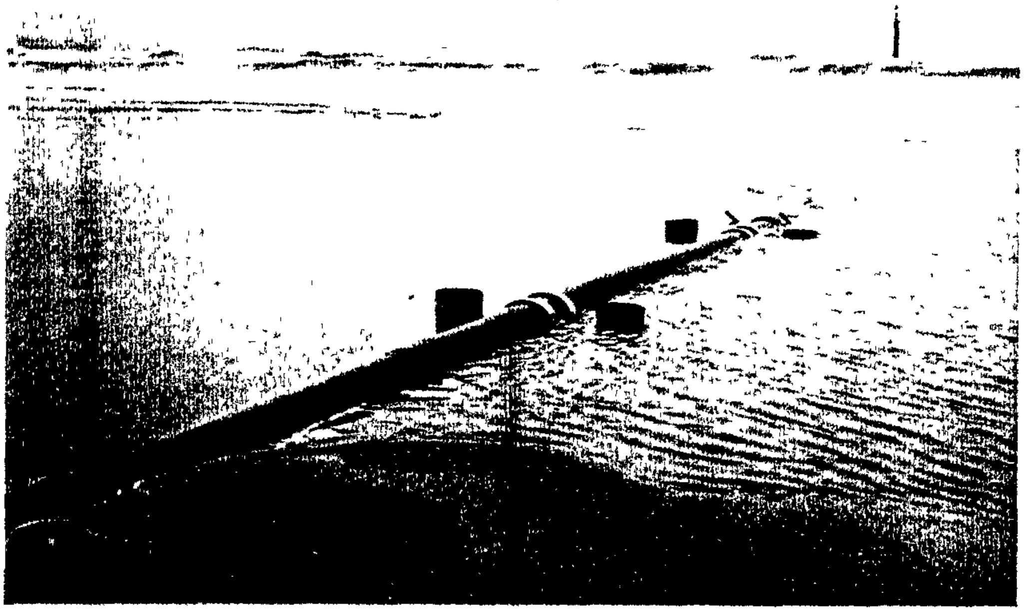
Outfalls are extremely vulnerable in the surf zone, or roughly to depths 10 to 15m. The majority of the outfalls damaged has suffered the damage in the inshore waters. Thus the way to protect the outfall must be the object of an in-depth study by specialists and also possibly of small-scale testing.

There are two ways to protect an outfall: either to bury the pipe at sufficient depth (the trench may or may not be protected by a rock cover), or to construct a jetty with natural or artificial blocks of stone; there is also the solution of a reinforced concrete jetty between two series of sheet piling (Cannes).

However, a protruding jetty constructed along a sandy coast can have serious consequences for the stability of the coast. Even if the waves do not have a predominant direction and even if the direction of the transport of solids is not strongly marked, there will always be beach accretion on the one side of the jetty and rapid erosion on the other. Moreover, this physical change of the beach brings about the laying bare of the jetty and rapid degradation may ensue. Figures 19, 20 and 21 illustrate various techniques used for the anchoring and protection of outfall pipes.

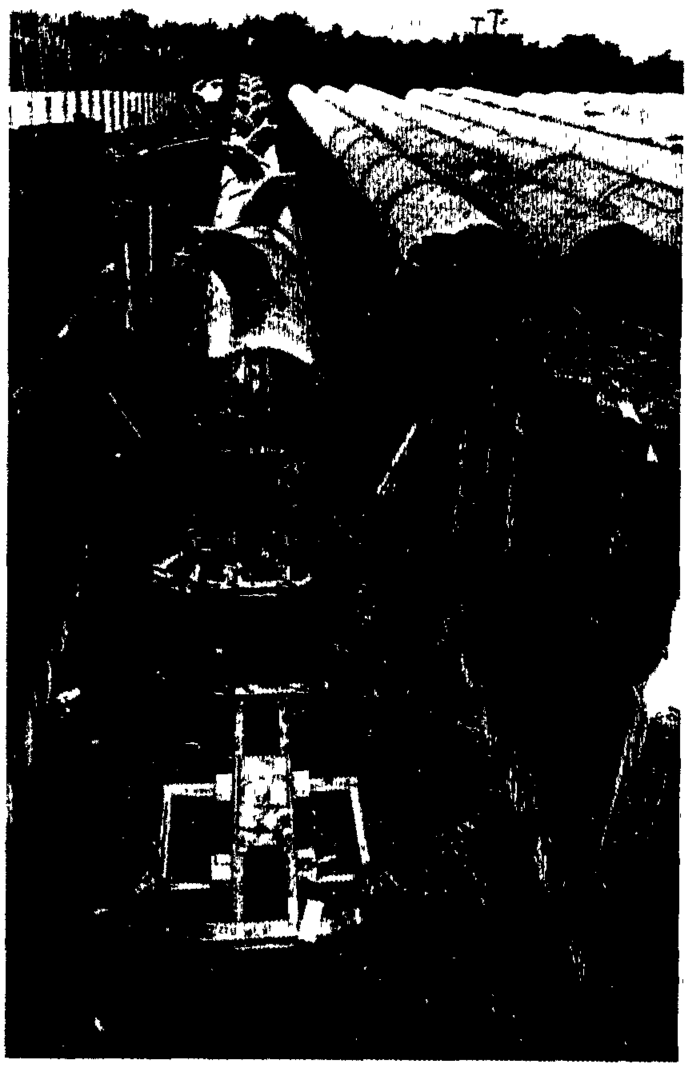
Underwater outfall at Menton (French Mediterranean coast) The winch ponton is pulling the pipe on the sea bed

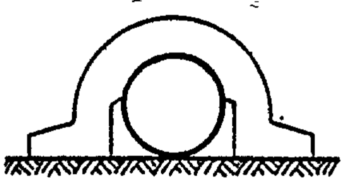




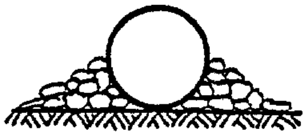
Underwater industrial outfall at Calais (French Channel coast)

Underwater outfall at Cannes (French Mediterranean coast) The diffusor is on the launching slipway. The pipe is assembled in sections 60 metres long (diameter 1500 millimetres)

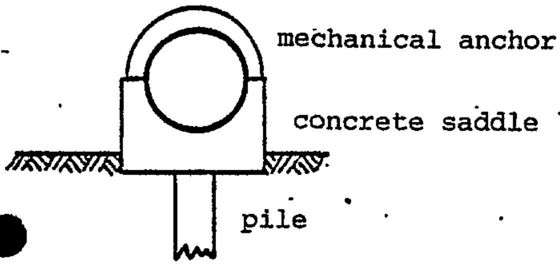




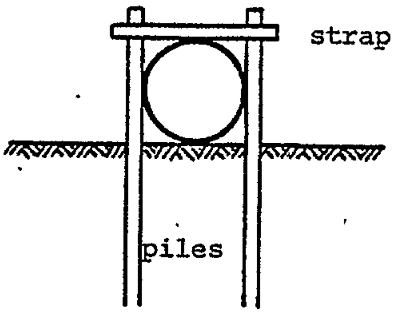
1. Laying on the sea bed with concrete cavaliers for ballasting



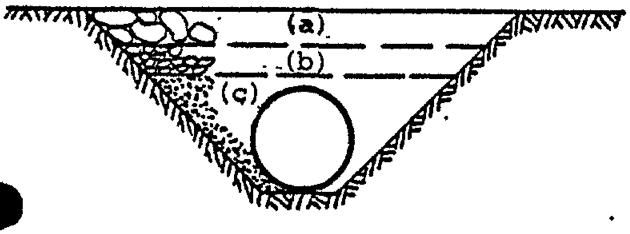
2. Rock ballasted pipe



3. Laying on piles and concrete saddle



4. Anchoring by means of piles and a strap



(a) natural or artificial blocs
(b) filter
(c) sand

5. Laying in trench with rock jacket

Figure 19: Examples of anchoring and protection methods for marine outfall systems.

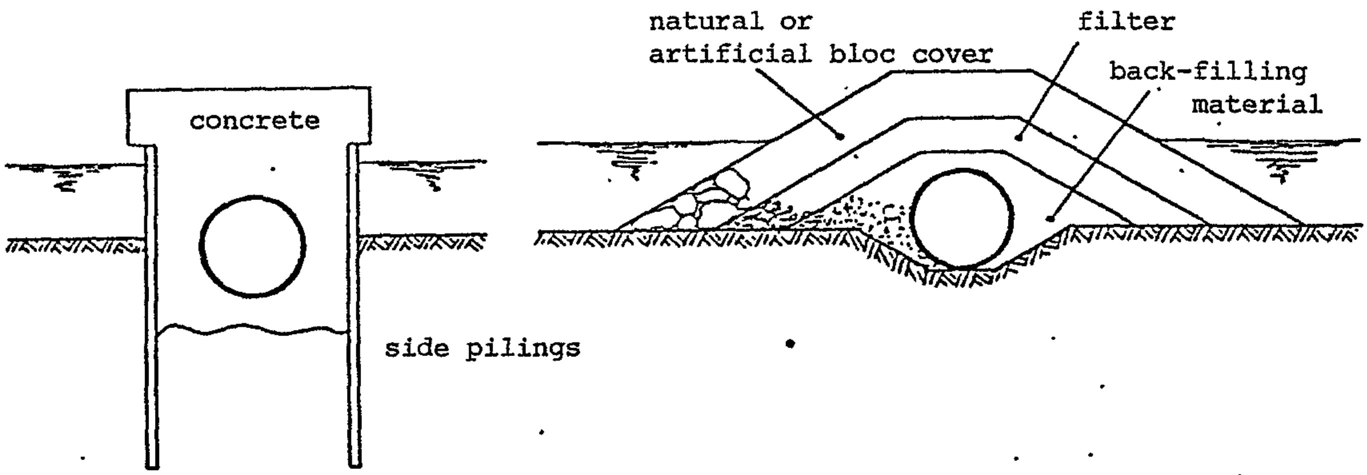


Figure 20: Examples of jetty construction to protect the outfall pipe.

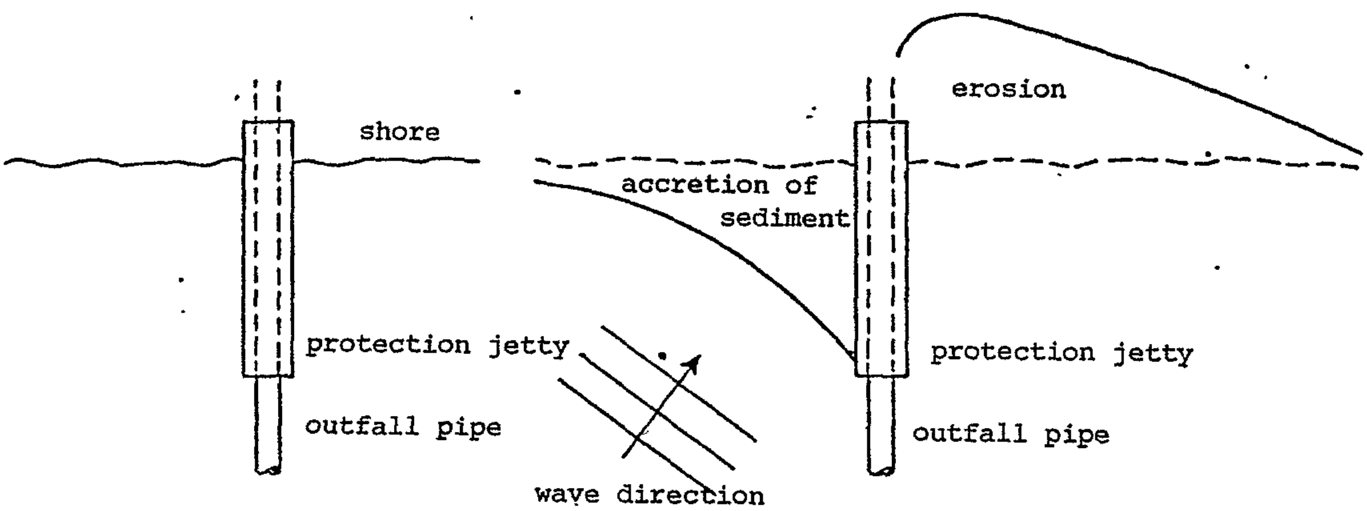


Figure 21: Erosion risks for sandy littoral

Let H = total depth
V = wind velocity measured 10 metres from the ground

Then: (units MTS) :

the real depth will be obtained by multiplying by H the ordinates read on the graphs.

the real velocity will be obtained by multiplying by 0,07V the abscissa read on the graphs.

the vertical turbulent diffusivity will be obtained by multiplying by 0,000082 HV the abscissa read on the graphs.

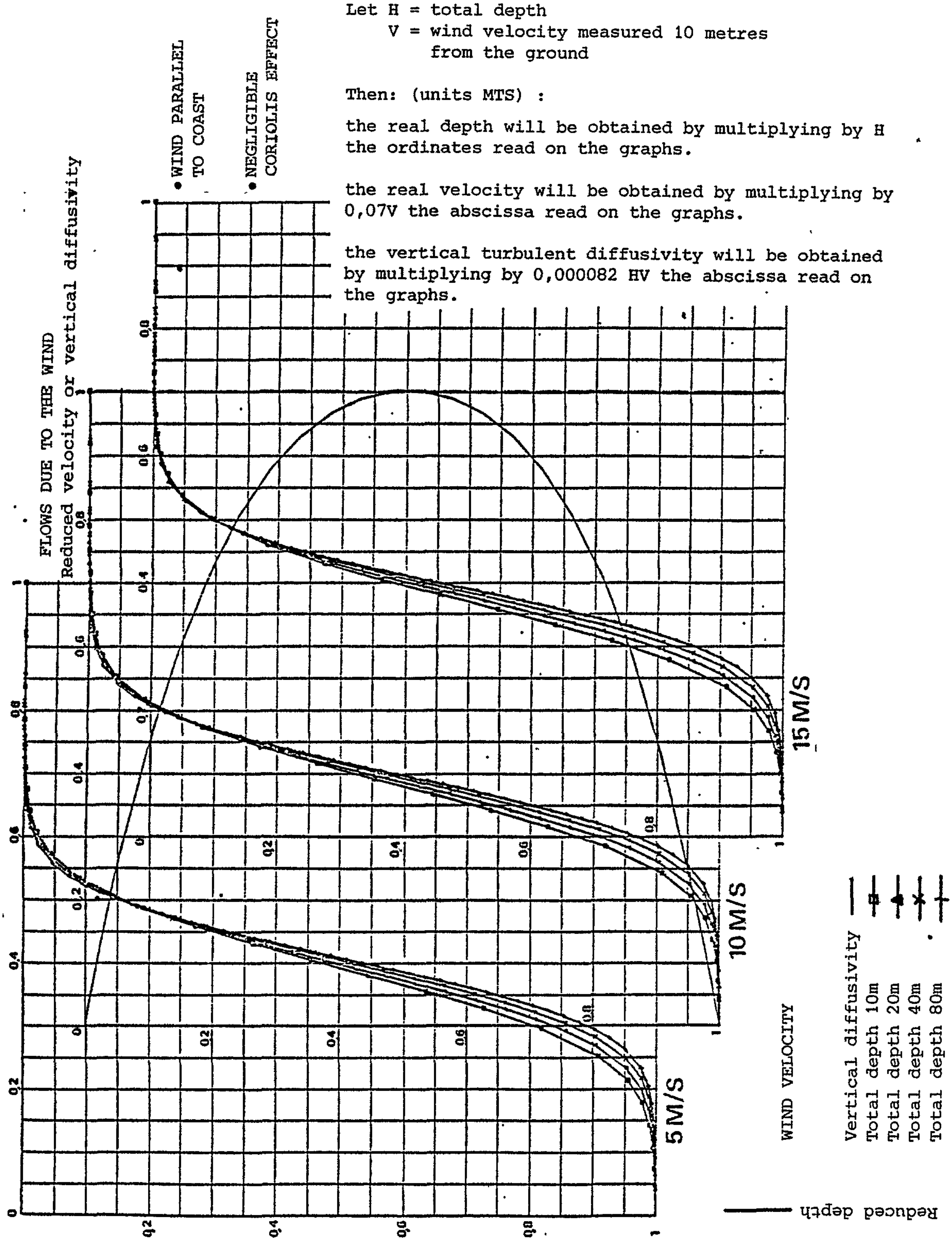


Figure 22. Diagram obtained with the EOLE Programme

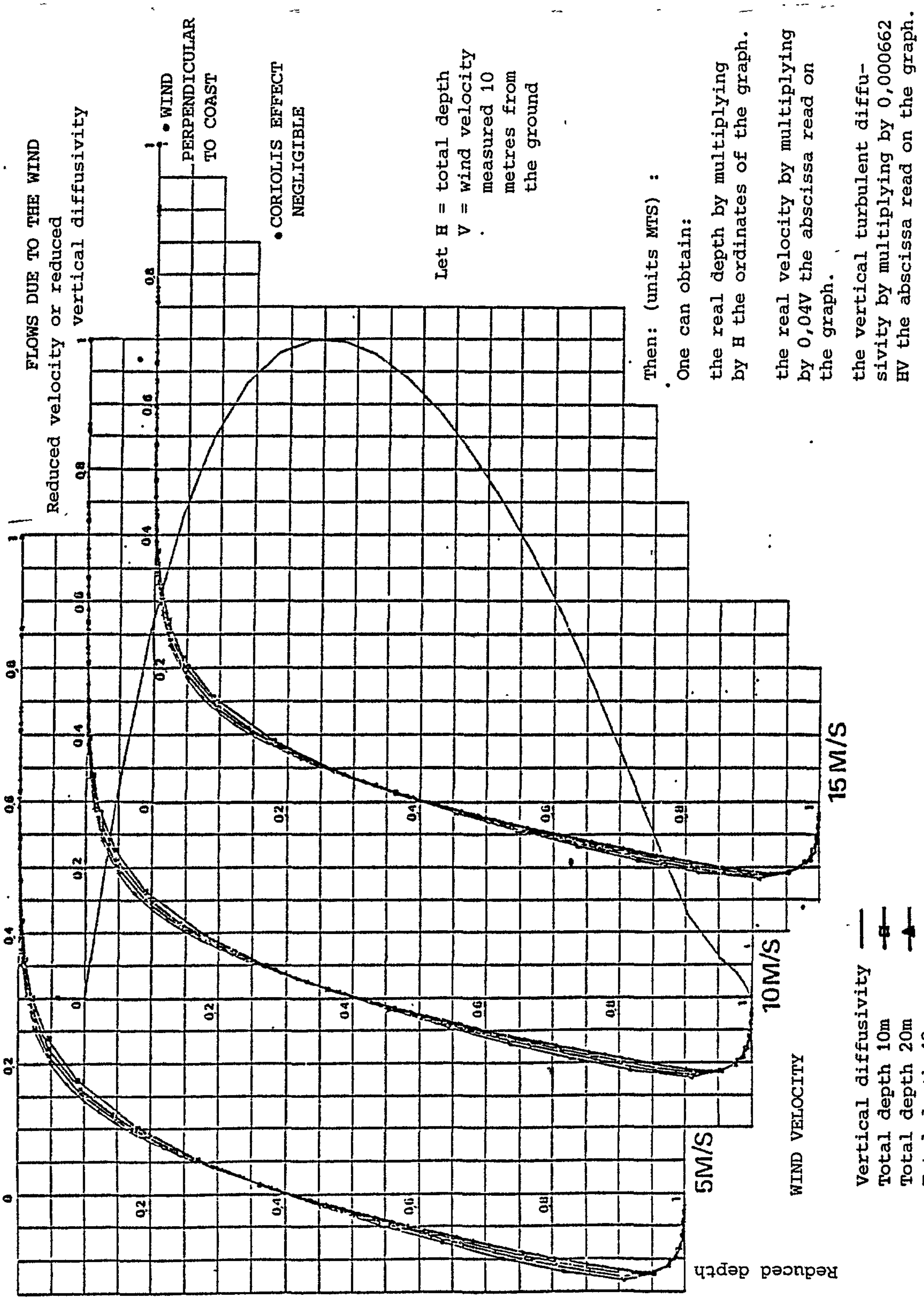


Figure 23. Diagram obtained with the EOLE Programme

FLOWS DUE TO THE WIND WITH THE IMPACT OF THE CORIOLIS EFFECT

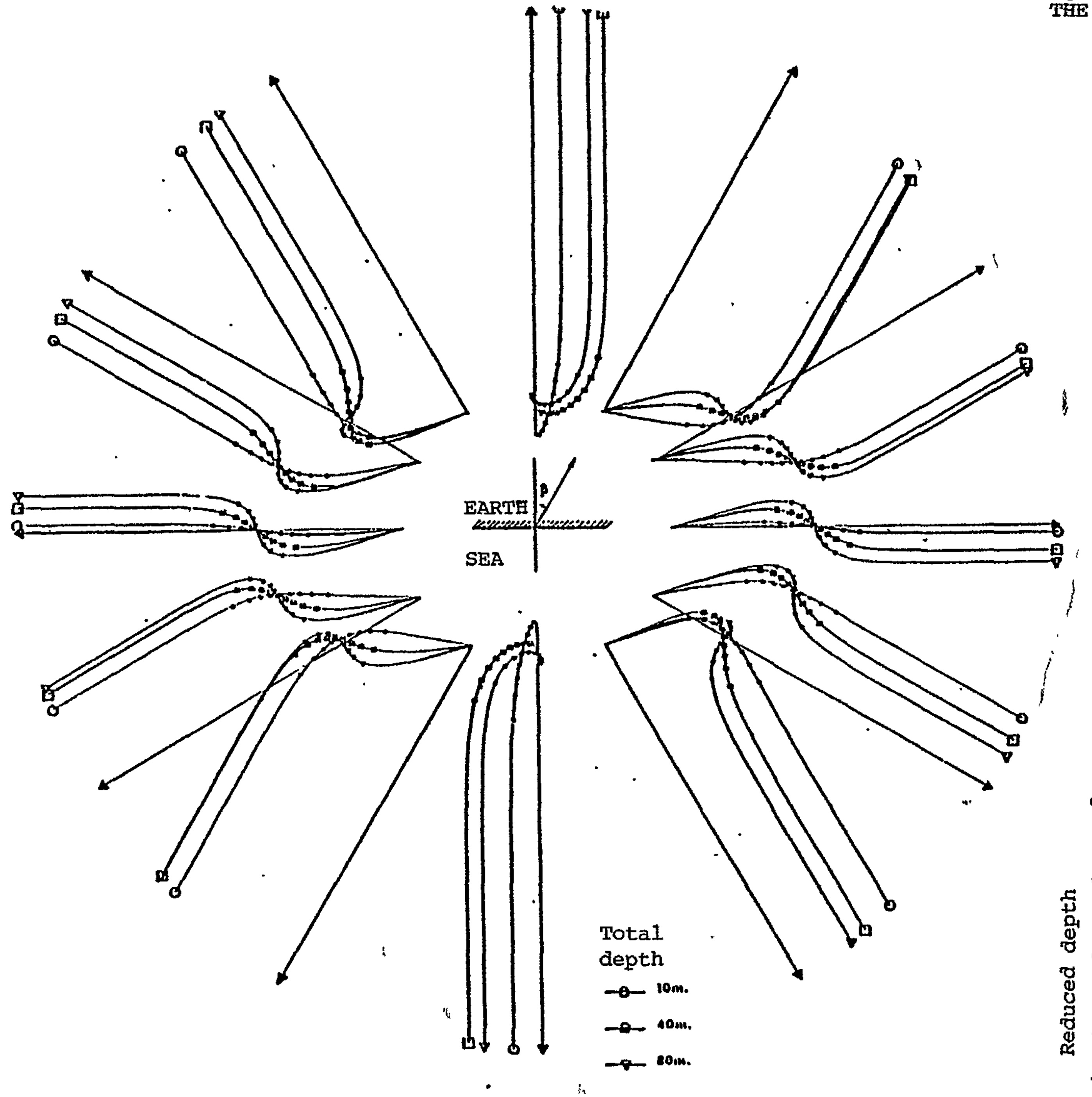


Figure 24.

PLANE PROJECTION OF THE CURVE DESCRIBED BY THE EXTREMITY OF THE VELOCITY VECTOR

LATITUDE 43°N

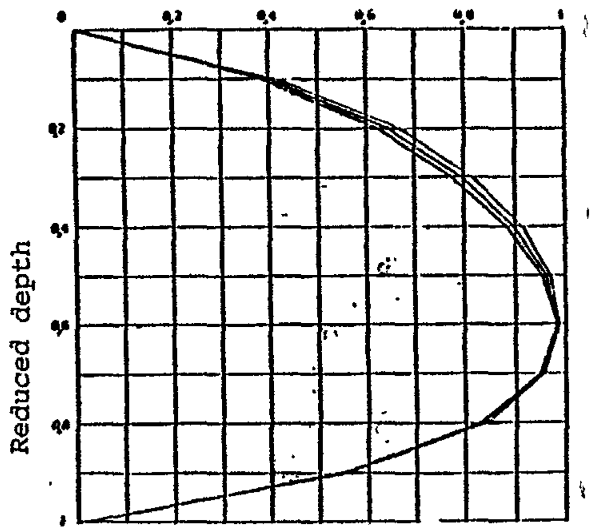
The axes define the wind direction in relation to the coast in the centre of the graph. The curves are graduated in 1/10th of the total depth.

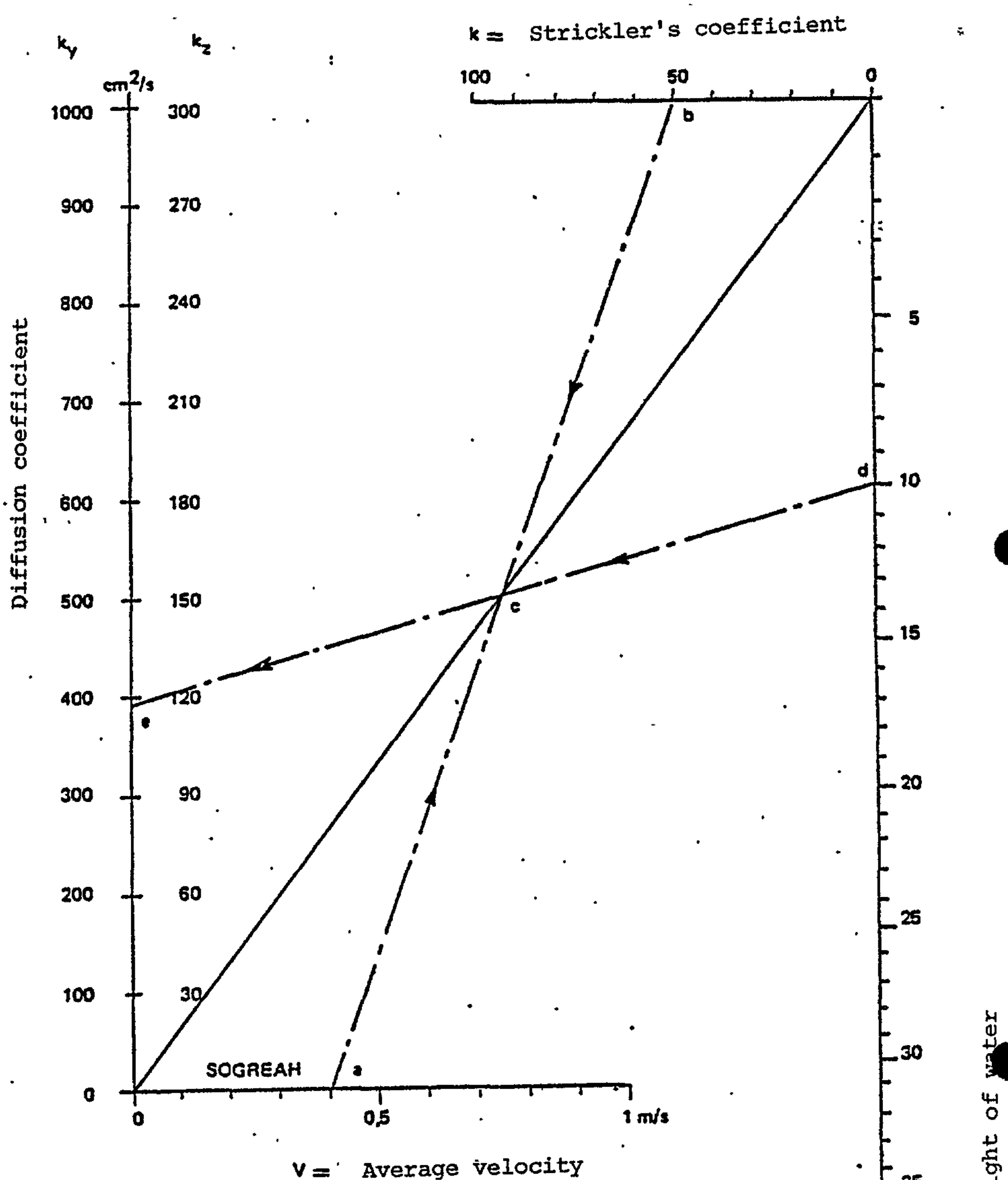
Let H = total depth
V = wind velocity measured 10m from the ground (V ⩽ 10 m/s)
β = angle of the wind in relation to the normal to the coast

We can obtain:

- real velocity by multiplying length measured and expressed in decimetres by: $1{,}61 \times 0{,}027\, V\, (1{,}52 + |\sin \beta|)$
- approximate vertical turbulent diffusion by multiplying the abscissa of the diagram by: $0{,}000018\, HV\, (2{,}80 + |\sin \beta|)$

Reduced diffusivity





$k_y = 0{,}23\,H\sqrt{gHj} = 0{,}72\,H^{5/6}\,V/K$

$k_z = 0{,}067\,H\sqrt{gHj} = 0{,}21\,H^{5/6}\,V/K \sim 0{,}3\,k_y$

join ab whence c
join cd whence e

Figure 25: Graphic representation of Elder's formula (Diffusion coefficients in a canal)

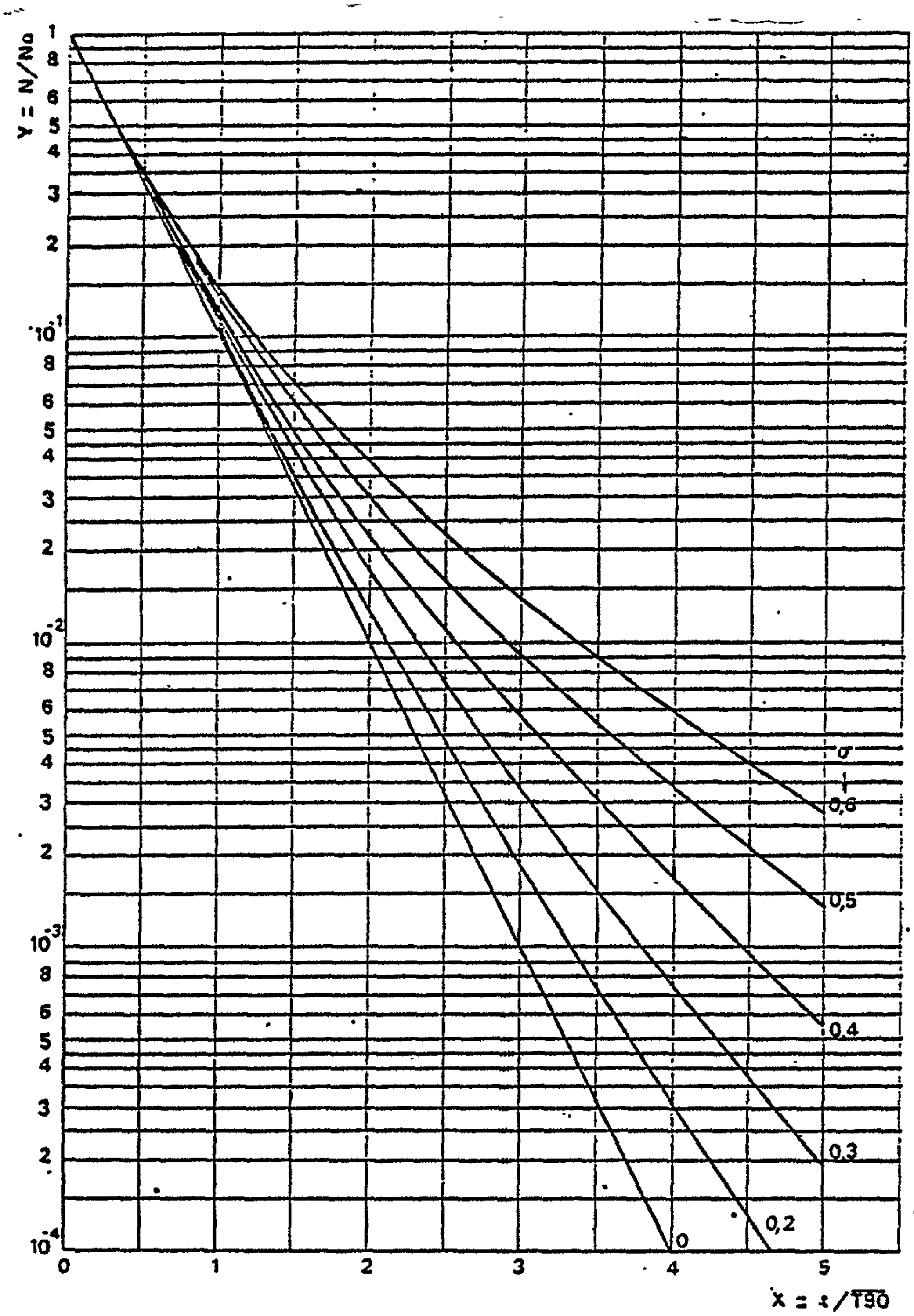


Figure 26: Effect of coliform decay in the sea

A P P E N D I C E S

A P P E N D I X   A

MODEL OF STANDARD SPECIFICATIONS FOR THE STUDY OF THE MARINE ENVIRONMENT WITH A VIEW TO INSTALLING A SEA OUTFALL SYSTEM

The present document is designed to serve as a guide to engineers charged with establishing the technical specifications for either the invitation to bid or award the contract to carry out the study on a sea outfall project.

All articles of this draft document can be adapted to suit the particular case.

A.1 OBJECTIVES

1.01 ....* is considering the discharge into the sea of urban sewage**. It undertakes the marine environment studies needed in order to determine the most favourable discharge site and guarantee that the quality of the water shall conform to existing regulations.

1.02 The study required shall comprise five parts:***

- Assembling the baseline data already available;
- A compaign of oceanographic measurements;
- A study of the features of the benthic living environment;
- A study on the dilution of effluents and of the contaminated area surrounding the discharge sites under consideration;
- A preliminary draft design project for a sea outfall.

A.2 DOCUMENTS AND BASELINE DATA

2.01 The plans and documents accompanying this Invitation to Bid (the list of which is given hereunder), define the objectives and establish the scope of the studies.

List: ....

....

....

....

---

* Name of Construction Manager.

** The present document is conceived for this category of effluents; however, it can be used mutatis mutandis for effluents of another type.

*** List to be adapted to the particular case.

2.02 The plans illustrating land use (master plans or urban development plans, etc.) establish the various urban development areas of the municipality as well as the various uses to which the coast and the coastal waters are put, namely: beaches, harbours, shellfish growing areas, aquaculture, specially protected areas, etc.

2.03 The plans of the sewerage system establish the existing sewers, the projected trends for the sewage network, the sewers under consideration and the probable installation of sewage treatment plants.

2.04 The flows of sewage that shall be taken into consideration in the study are the following:

- mean flow in the summer season:.......
- peak flow in the summer season:.......
- mean flow outside the summer season:.......
- flow of storm highest in a ten-year period:.......

2.05 The accompanying documents furnish the available analytical data concerning the composition of these effluents, especially the contents in: total and faecal coliforms, faecal streptococci, organic matter, suspended solids and possibly specific industrial residues.

2.06 The marine area to be covered by the study is defined on the map attached to the Invitation to Bid; the map moreover indicates the areas to be protected against pollution.

2.07 The Contractant can refer to sea chart No.....where the zero soundings correspond to the coast.

The contractant must look for and assemble all other available documents and sets of data needed for the study, mainly:

- meteorological data (force, frequency of winds)
- maps of currents
- map of benthic populations
- other

A.3 MEASUREMENT CAMPAIGN

3.01 The campaign of oceanographic measurements shall comprise continuous measurements by means of recording instruments and measurements localised in time which aim at establishing the trajectories followed by the water masses, the diffusion due to turbulence and possibly also the rate of bacterial decay.

3.1 Continuous measurements

3.1.1 The continuous measurements shall be carried out by.......current meters*. These instruments shall be designed in such a way as to record simultaneously: the velocity and the direction** of the current, temperature and conductivity*** of the water, pressure****.

3.1.2 These measurements shall last for 3 months as a minimum*****. It is mandatory for this period to include also the period of intensive use of the sea in the areas to be protected, i.e. the months from............ to.............****** inclusive.

3.1.3 The frequency of recording shall be based on the five parameters defined in 3.1.1 and shall be carried out every 10 minutes.

3.1.4 Analyses of the data recorded on the instruments shall provide: The variations in time of the 5 parameters recorded, their statistical values (mean, standard deviation, extreme, etc.). The classified values or the rose of currents, the part of currents which can be attributed to tides, possibly the components of currents parallel or perpendicular either to the direction of the coast or the direction of the planned outfall and any other element likely to make more profitable the subsequent use of the data collected through measurements.

3.1.5 (Case of waters with low depth, 5 to 20m maximum). The Construction Manager proposes to install..........current meters on.........different verticals, approximately marked on the map attached to the Invitation to Bid, which correspond roughly to the possible location sites of the pipe opening(s) of the projected outfall system. The Designer charged with carrying out the study may suggest better installation sites for the current meters, provided he duly justifies his choice. The submersion depths of the instruments shall be compatible with the low water mark of spring tides. The depth will be different for each instrument. At least one of them shall measure velocities as close to the free surface as possible, taking into account the practical constraints of keeping taut the line supporting the instrument.

---

* Three is a minimum. The number will be higher if the topography is complex, or the volume of the flow to be discharged justifies the installation of more instruments.

** The direction is generally given in relation to the magnetic North and requires a subsequent correction equal to the magnetic declination of the site.

*** Salinity is deduced directly from the conductibility of sea water.

**** Indispensable in tidal seas; this sensor eliminates any ambiguity as to the exact submersion depth of the instruments.

***** This number can be higher depending on local conditions.

******This period in most cases is June to September, or the tourist period, but for shellfish growing areas the periods of intensive harvesting should be included. This provision requires moreover that the timetable for the Invitation to Bid, the drafting of contracts and the procurement of instruments shall have been correctly estimated.

3.1.6 (Case of deep waters). The Construction Manager proposes to install current meters in sets, attached to a number of verticals approximately marked on the map attached to the Invitation to Bid. The Designer charged with carrying out the study may suggest better installation sites, provided he duly justifies his choice. The distribution of instruments along the various oceanographic lines is defined as follows*:

.... current meters on the vertical ...... at depths of ....
.... current meters on the vertical ...... at depths of ....

On the vertical supporting the greatest number of instruments, one of them shall be located as close to the free surface as possible, taking into account the practical constraints of keeping taut the line supporting the instruments.

3.1.7 (Case of possible thermal or saline stratification risk). One of the lines shall moreover be equipped with a special recording device called temperature and conductivity chain. The cable on which the sensors are attached shall be submerged between the depths of........and.......** in the layer of the density gradient.

3.2 Batch measurements

3.2.1 Trajectories of water masses

3.2.1.1 During the period when the current meters are installed,....... measurement cruises*** lasting one day each shall be devoted to marking the trajectories of water masses.

The trajectories shall be "marked" with about 20 drogues distributed over the whole marine area under study. The days for the drogue survey shall be chosen in such a way as to ensure that all possible meteorological conditions (winds and tides) have been covered in the best way possible.

3.2.1.2 For the two thirds of the floats in operation, the drogues shall be submerged between 0,5m and 1m under the free surface of the sea. For the remaining third, the drogues shall be submerged at a depth of ......m****.

3.2.1.3 These floats shall be monitored in space and time during 5 to 6 hours. One must ensure a sighting for each float every 20 to 40 minutes approximately. Spatial positioning can be carried out by means of topographical sightings from the shore).

3.2.1.4 The results shall be furnished in the form of trajectory charts. Mean velocities shall be calculated.

---

* If the minimum solution of 3 instruments is chosen, then two lines shall be used, one supporting two current meters and the other only one.

** As a rule between -20 and -40m.

*** As a rule three to four cruises shall be given over to this task, with a view to surveying all possible circulation patterns due to tide and wind conditions.

****This depth could be approximately 1/10 of the average total depth at the site, but in any case between -2m and -5m. The essential objective here is to show clearly the variations in velocity and direction of currents in relation to depth.

3.2.1.5 (Article from the Consultation File). Those bidding may propose to the Authority issuing the Invitation to Bid other technical solutions, such as: transmitter floats, radio localization systems, etc.

3.2.2 Evaluation of the horizontal turbulent diffusion

3.2.2.1 During the period when the current meters are installed, two* cruises for the measurement of diffusion due to the turbulence of natural flows shall be carried out. Each measurement shall consist of registering by aerial photography the relative displacements of 15 to 20 drogues in relation to the centre of gravity of all the floats. The meteorological conditions to be chosen for these measurements shall correspond to the most unfavourable conditions in terms of pollution for the areas one is aiming to protect, areas which would be most severely threatened by the discharge under consideration.

3.2.2.2 Each set of floats shall be cast in the sea in a configuration as restrained as possible taking into account the dimension of the floats and the difficulties of marine work. Then, 8 to 10 photographs of each set shall be taken graduated over 100 to 120 minutes. The exact time of each photograph must be known down to the second.

3.2.2.3 In order to put the negatives automatically in scale, one can let float near the drogues a pole of known length (for instance 10m).

3.2.2.4 The floats must not catch the wind at all. The drogues shall be submerged to between 0,5m and 1m under the free surface.

3.2.2.5 Taking into consideration the lack of certainty inherent in this type of measurement and in order to make the most of the equipment installed, ...** sets of floats shall be put in the water during the same cruise, at sufficient distance in order to survey the marine area under consideration and to avoid any interference. The aircraft from which the photographs are taken shall pass in turn over each set of floats. Appropriate measures shall be taken in order that there be no possible error in the identification of negatives.

3.2.2.6 From each photograph one shall calculate the centre of gravity of all the floats monitored. One shall look for the system of orthogonal axes which on one axis minimises and on the other maximises the standard deviation of the float distribution.

A.4 DATA PROCESSING FOR THE COMPUTATION OF THE DISPERSION OF EFFLUENTS

4.01 Processing of the various data obtained in the different stages of the study up to this point will make it possible for those carrying out the study to establish the possible location sites for the outfall system, the most unfavourable conditions etc.***

---

* Minimum 2

** Minimum 3

*** The problem is more complex than it may at first appear. In effect, when the currents are fast the diffusion of effluents is greater. In the case of tidal flows, or in bays, the most critical situation is that of effluent recirculation.

4.02 These working assumptions shall be presented in an interim report submitted to The Construction Manager for his approval. After a preliminary elimination computation, one can suggest the site(s) and the particular features of the outfall which seem most suitable to the discharge under consideration.

The interim report shall include suggestions either to continue processing data to be collected from measurements at the site which appears to be the most suitable, or possibly at two sites vying for this distinction, or even, if the sites where instruments were installed prove unsuitable, to start a new series of measurements at a more favourable site.

4.03 The report shall also define the meteorological and hydrological conditions considered as the most unfavourable in terms of pollution for the marine areas under protection.

After consultation with the Construction Manager and preliminary selection of one or several discharge points, one can proceed with carrying out more complex computations on effluent dispersion.

4.1 Rising plumes and diffuser

4.1.1 The person (or team) responsible for the study shall calculate for each of the working assumptions the dilution achieved in the buoyant effluent plume(s) as it (they) rise(s) toward the free surface. If need be, he shall redefine the characteristics of the diffuser in terms of diffuser diameter and spacing of the ports, in order to obtain the best results.

4.1.2 If the ambient marine waters are likely to be density stratified, one shall always strive to find a solution which shall ensure that the effluent plume reaches the free surface of the sea, since effluent trapping under a stratification must be considered an unfavourable occurrence. Where effluent trapping at intermediate layers can not be avoided, data shall be provided both on the depth of the submerged sewage field and the corresponding dilution.

4.1.3 The number and the diameter of the diffuser ports shall be such as to ensure that their total flow shall at most be equal to that of the outfall section.

4.1.4 The spacing of diffuser ports shall be higher than the maximum diameter of the primary buoyant plumes in order to maximise the benefits from the horizontal turbulent diffusion. One shall avoid great differences in dilution occurring in the various plumes issuing from the diffuser ports at its offshore end; in order to accomplish this, one may, if need be, vary the port diameters.

4.2 Convection - horizontal diffusion

4.2.1 One shall evaluate the dilution during the phase of effluent convection and diffusion to the free surface. These computations must take into consideration the thickness of the polluted layer and the probable velocities of sea water flow in this layer.

4.2.2 If the prevailing flows are wind generated, one shall in addition take into consideration the following:

- duration of the winds;
- their probable direction;
- differences in direction between winds and currents as a result of the Coriolis effect;
- the effects of lateral density spreading due to the residual buoyancy of effluents;
- turbulence and transversal and vertical diffusion. The diffusion coefficients to be used shall be those resulting from field measurements if such measurements were carried out. In this case, the necessary transpositions shall be made in order to account for the differences in velocity and height of water between the conditions prevailing during measurements and the assumptions on which the computations are based.

  If field measurements are not carried out, the diffusion coefficients can be estimated as a function of the characteristics of the local environment, by using formulae such as the Taylor-Elder formulae applicable to shear flows. One shall reject the 4/3 laws which do not apply to near shore conditions.

4.2.3 After consultation with the Construction Manager, the decision shall be taken on whether the computations shall be manual and approximate, or whether they shall be run on computer using the best available mathematical models.

4.3 Computation of the decay of the non-conservative pollutants

4.3.1 If the effluent contains such pollutants, one shall calculate the conditions of decay of the test germs of faecal pollution, using the available methods and graphs.

4.3.2 One shall make sure that the organic pollution and its oxidation do not present a particular problem at the site under consideration.

A.5 STUDY OF THE BENTHOS

5.01 The study of the benthos shall establish the general characteristics of the flora and the small fauna living on the sea bed of the marine area defined previously in paragraph A.2. This study will be based on:

- the data concerning the nature of the sea bed furnished by the sea chart;
- the map of benthic populations which can be obtained from:........

5.02 The Contractant shall carry out a series of sample takings of sea floor materials for a granulometric analysis and an analysis of those plant and animal species remaining on a sieve of 1 millimetre mesh. He shall assign to this task duly qualified personnel, or shall subcontract it to a laboratory specialising in marine biology.

5.1 Sampling network

5.1.1 Taking into account the topography and the nature of the sea bed at the site under consideration, the samplings shall follow the scheme roughly outlined below:*

5.1.2 Each point of actual samplings shall be the object of correct geographical positioning; the method to be used is left to the discretion of the successful bidder.

5.2 Realisation of samplings and processing of data

5.2.1 At each point decided upon, two or three samplings shall be carried out by means of a dredger which shall allow the collection of 20 to 50 dm^3 of sediment. If the bottom is rocky one shall grate a surface of approximately $400cm^2$.

5.2.2 The nature of sediments shall carefully be examined and a sufficient quantity of the sediment shall be saved for later granulometic analysis.

5.2.3 The remaining sediment shall be passed through a sieve of 1 millimetre mesh. The animal and plant material collected on the sieve shall be fixed with neutralised formol. It shall then be sorted, identified and counted.

5.2.4 Each sampling shall be used for the computation of a diversity index and for the establishment of a rarefaction curve.

5.2.5 A certain number of chemical analyses either of the sediments or of the industrial effluents shall be carried out in order to determine their content in organic matter (organic carbon, nitrogen, phosphorus, etc.).

5.2.6 Some samples can be used for further research into specific pollutants, such as hydrocarbons, detergents, pesticides, etc. if such research appears useful.

5.3 Synthesis of results

5.3.1 The results of the study shall be presented in map form and shall be used for the establishment of the various areas of benthic populations (biocenoses).

5.3.2 The report shall determine the general state of the marine environment, define the rich areas that should be especially protected, as well as the areas that lend themselves to the establishment of a marine outfall system because of limited impact on the marine environment.

---

* For instance, samplings every 200 to 500m on a series of radials to be further defined, or random sampling at ...... points per km^2.

A.6 <u>(Possibly) DRAFT PROJECT OF A MARINE OUTFALL</u>

6.01 The Contractant shall furnish a brief draft project of a marine outfall which shall include especially:

- study of the alignment profile of the outfall pipe and the sea floor grades compatible with the stress tolerance of the pipe;

- the meteorological conditions and the wave conditions, on the basis of which one shall establish the period of pipe-laying most favourable for work;

- the area available on land for the construction site;

- the hydraulic stresses caused by the wave and surf action and the means for effective protection of the outfall;

- the choice of material(s) most suitable to the particular case;

- the computations of hydraulic pressure drop in the diffuser and the outfall pipe and the computation of the additional backflow height needed for the injection of effluent into the sea.

APPENDIX B

NUMERICAL EXAMPLES

B.1 DILUTION IN BUOYANT JETS OR PLUMES

1.1 Density homogeneous receiving water

- Flow of outfall = 0,500 m^3/s
- Depth of discharge Y = 30 metres
- Outfall pipe diameter Ø = 0,80 m
- Density: of Effluent $\rho_o = 1$; of Sea water $\rho_m = 1{,}027$

Diffuser: 25 ports of diameter D = 0,15m, horizontal emission of jets, flow velocity of sea water considered as negligible.

- Verify that: $25\,D^2 \leqslant \text{Ø}^2$ (0,56 ⩽ 0,64)
- Flow of jet: $Q = 0{,}500/25 = 0{,}020\ m^3/s$
- Initial velocity of jet: $V = 4Q/(\pi D^2) = 1{,}13\ m/s$
- Density gradient: $\Delta\rho = (\rho_o - \rho_m)/\rho_o = 0{,}027$
- Froude number: $F = V/(g\Delta\rho D)^{0,5} = 5{,}68$
- Following table of symbols in Appendix D: $\eta = Y/(FD) = 35{,}2$
- Using graph in Appendix D: $\xi = 1{,}2$
- Final dilution on jet axis: $T_m = Y\xi/D = 240$
- Final density on jet axis: $\rho = \rho_m - \Delta\rho/T_m = 1{,}02689$
- Standard deviation of jet at the free surface: (radius of circle containing 68% of the effluent) $r = Y/(8\sqrt{2}) = 2{,}65\ m$
- Radius of circle containing 90% of the effluent: (minimum port spacing on diffuser) $R = 1{,}5\,r = 3{,}98\ m$

1.2 Density stratified receiving water

Same data as above, but heat stratification present with:

Sea temperature on the surface:..............T = 16° Centigrade
Sea temperature at a depth of 30m:...........T = 12° Centigrade

Solution No.1

One adopts the same diffuser as above with horizontal emission of jets. Flow velocity of sea water considered as negligible.

One follows the same procedure as the one given in the previous paragraph but for a series of intermediate values for Y.

Thus one can establish from which value for Y the density of the jet becomes greater than the density of the sea water at the same level. If such a case occurs, there will be trapping of effluents at the depth of the balance determined thusly.

Let T be the temperature of sea water in $^{\circ}C$ at level z; one has the approximate solution:

$$\rho_m(z) = 1{,}030 - T/4000$$

or a linear density gradient.

Let:

ρ be the density of the plume calculated on the assumption that sea water has a constant density corresponding to that at the depth of discharge (30m and T = 12° or ρ_m = 1,027),

Y be the height of water over the diffuser,

T_m be the dilution at level Y,

one obtains the following table:

Y	η	ξ	T_m	ρ	$\rho_m(z)$
15	17,6	0,84	84	1,02668	1,02650
13	15,3	0,80	69	1,02661	1,02657
12	14,1	0,75	60	1,02655	1,02660

There is trapping of effluents at approximately 12,5m over the diffuser, or a depth of -17,50m.

Solution No.2

One adopts the same diffuser but the jets are emitted vertically. Using the same procedure, we obtain the following table:

Y	η	ξ	T_m	ρ	$\rho_m(z)$
15	17,6	0,72	72	1,02663	1,02650
14	16,4	0,69	64	1,02658	1,02653
13	15,3	0,67	58	1,02653	1,02657

There is trapping of effluents at about 13,5m over the diffuser, or at a depth of -16,5m.

The exact computation by numerical integration gives the trapping depth of -15m (see reference (15) in the bibliography).

Solution No.3

We adopt only one vertical jet issuing from a port of diameter D = 500mm.

Using the same procedure we obtain the following table:

Y	η	ξ	T_m	ρ	$\rho_m(z)$
30	8,45	0,48	28,8	1,02606	1,02600
29	8,16	0,47	27,3	1,02601	1,02603

There is trapping of effluents at about 0,5m under the free surface.

The exact computation shows that the free surface is fully reached by the effluent.

However, the increase in rising height is obtained at the detriment of dilution.

1.3 Density homogeneous receiving water with sea water flow

- Flow of outfall: $= 0,500\ m^3/s$
- Depth of discharge: z = 10 m
- Outfall pipe diameter: Ø = 0,80 m
- Density: of Effluent $\rho_o = 1$
  of Sea water $\rho_m = 1,027$
- Velocity of sea water flow: U = 0,30 m/s
- Diffuser: 25 ports of diameter D = 0,15, vertical emission of jets.
- Verify that: $25\ D^2 \quad Ø^2$
- Initial jet velocity: V = 1,13 m/s
- Density gradient: $\Delta\rho = 0,027$
- Froude number: F = 5,68
- Velocity ratio: R = V/U = 3,77
- Calculate (formulae 3.5): $A = z/(1,44\ RD)^3 = 1852$
- Solve: $R^2 X^2/(2F^2) + X - A = 0$

  $0,22\ X^2 + X - 1852 = 0$

  $X = 92$
- Dilution on surface: $T = RA^{2/3} = 569$
- Horizontal distance travelled: $x = RDX = 52\ m$
- Plume radius on surface: $r = z/2 = 5\ m$

B.2 INITIAL THICKNESS OF POLLUTED LAYER

If we take the case of the example given in paragraph 1.1 and apply the classic elements of Gauss' law (figure No.11), we obtain in turn:

- Final dilution on the jet axis: $T_m = 240$
- Plume radius (1 standard deviation): $r = 2{,}65$ m
- Real mean dilution in circle r: (See figure No.11) $T = 1{,}17\, T_m = 280$
- Total discharge flow of elementary plume: $Q = 0{,}02 \times 280 = 5{,}6\ m^3/s$
- Residual mean density gradient: $\Delta\rho = 0{,}027/280 = 0{,}00010$
- Thickness of polluted layer (formula 3.4) in the circle of radius r = 2,65m $H = 1{,}34$ m
- Radial horizontal velocity: in the same circle (formula 3.5) $V = 0{,}25$ m/s

Similarly, as a function of the distance from the centre of the plume, by varying r in the formulae (3.4) one obtains:

r	H	V
10	0,95	0,09
50	0,64	0,028
100	0,64	0,016

The distance theoretically travelled in 12 hours (through the effect of density spreading) by a mass of water issuing from the jet is approximately (formula 3.6) 189m.

B.3 CONVECTION - HORIZONTAL DIFFUSION

Let us take again the example given in paragraph 3.11. One assumes a mean flow of sea water of 0,12 m/s and bottom friction equivalent to a Strickler coefficient of 50.

The graph of Elder's formula (figure 25) gives the following parameters of turbulent diffusion:

- Horizontal transversal diffusion: $K_y = 0{,}0285\ m^2/s$
- Mean vertical diffusion: $K_z = 0{,}0085\ m^2/s$

One looks for a topical continuous release point source on the surface, situated upstream of the flow which ensures that the dimension of its horizontal plume be of the order of magnitude of the final diameter of the buoyant plume. In order to accomplish this one must identify the standard deviations of the two plumes.

- Radius of buoyant plume (1 standard deviation): $r = 2,65m$
- Concentration on the jet axis: (if the concentration of the raw effluent is 1) $C_p = 1/T_m = 1/240 = 0,00417$
- Using formulae (3.24): $Q_0 = 0,0270$

  $x_0 = 68,2\ m$

  $t_0 = x_0/u = 568\ s$
- Vertical standard deviation, formula (3.22): (to compare with H = 1,34m) $\sigma_z = 1,46\ m$
- Table of dilutions:

x (m)	On the axis $\frac{x-x_0}{x_0}$	Exact Formula (3.16)		Formula (3.17)	
		y = 20 m, z = 0	y = 0, z = 5 m	y = 20 m, z = 0	y = 0, z = 5 m
100	2,5	30,8	3,0	33,0	4,2
500	8,3	18,3	8,8	18,0	9,8
1 000	15,7	23,7	16,1	23,6	17,0
2 000	30,3	37,5	30,7	37,4	31,7

Let us remember, when studying these numerical examples, the assumptions defined in the preceding chapters while establishing the formulae used above.

Formula (3.17) is a simplification of (3.16) on the assumption that one is interested in calculating the dilution quite far from the source (y and z negligible in relation to x) and quite near the horizontal flow axis (y low).

We can see from the numbers in the above table that the two formulae (which give quite divergent results for x = 100m) give very close results for x = 500m, tending to converge as one moves farther and farther away from the source.

Thus, it is absolutely legitimate to use the simplifying formula (3.17) for distances of 1000m or more, which is generally the case of the distance between the point of discharge from an outfall and the areas to be protected.

For such a distance, the dilutions, even at 20m from the axis, obtained by means of the simplifying formula, conform totally with those obtained by using formula (3.16).

Finally and as a practical matter, by using simple computations, one obtains quite adequate results in terms of precision, if one takes into account the constraints of the working assumptions. But it is useful, when one decides on which formula to use, to remember the simplifying assumptions on the basis of which the formulae were established.

On the other hand, the numerical examples given here confirm the orders of magnitude of the dilutions corresponding to the two effluent dispersion phases indicated in the table given in paragraph 1.3.1 in Chapter 1.

In effect, we have obtained:

- for the phase of vertical rising, a mean dilution on the surface of 280, if a diffuser is used and of 29 without a diffuser;

- for the phase of transport to the surface, a minimum dilution on the axis of about 8 at a distance of 500 metres from the source and of 16 at a distance of 1000m.

We have verified therefore that the contribution of the phase of horizontal transport to total dilution is quite small.

APPENDIX C

COMPUTATION FORMULAE FOR SEA-AIR HEAT EXCHANGES
(Nocturnal destratification)

A plume of fresh water risen to the surface of the sea may still present a considerable density difference in comparison with sea water (see paragraph 3.4). Now the alternation day-night as concerns the sea-air heat exchange conditions can modify this residual stratification.

During the night, the sea cools off by radiation and possibly by evaporation depending on the wind and the content of the atmosphere in water vapors. These two phenomena imply that the cooling off is limited to the free surface alone and that there is consecutive increase of density. This surface layer which is higher in density becomes unstable and sinks, bringing about mixing and equalization of density down to a certain depth. Depending on the prevailing conditions, this density increase due to the cooling may do away with the residual density gradient of the effluent caused by salinity. Stratification disappears and the contaminated layer becomes thicker.

In order to verify the conditions of such destratification one calculates the variation of temperature ΔT needed to do away with the residual density gradient $\Delta\rho$, either by using Appendix E, or the graph in Appendix D, or also by the approximation formula:

$$\Delta\rho = -\Delta T/4000$$

Then one compares the quantity of calories corresponding to the heat gradient for the polluted layer of a thickness H:

$$Q = \Delta T \cdot H$$

Let Q' be the quantity of calories that the marine surface can transmit to the atmosphere by radiation or evaporation, taking into consideration the meteorological conditions. If $Q' \geqslant Q$, then the nocturnal destratification will be complete. This quantity Q' can be obtained from the following series of formulae:

$$Q' = Q_R - Q_A + Q_E$$

$$Q_R = 0{,}97\sigma\,(T_S + 273)^4$$

$$Q_A = 0{,}937.10^{-5}\,\sigma\,(T_A + 273)^6\,(1 + 0{,}17\,C^2)$$

$$Q_E = \rho\, bW\,\left[(e_S - \psi e_A)(L + C_p T_S) + N(T_S - T_A)\right]$$

$$L = 596 - 0{,}54\,T_S$$

$$\alpha = 7{,}45\,T/(235 + T)$$

$$e(T) = 4{,}575.10^{\alpha}$$

where:

Q_R = energy radiated by the surface of the sea (black body),

Q_A = energy radiated by the atmosphere,

Q_E = energy lost through evaporation,

Q', Q_R, Q_A and Q_E are expressed in Kcal/m^2/day,

T_A = air temperature, 2m above the surface of the water,

T_S = water temperature on the surface of the sea,

T = one or the other of the values of T_A and T_S to evaluate the terms e_A and e_S,

T_A, T_S and T are expressed in degrees centigrade,

C = nebulosity of the air in octas (number of eighths of the celestial vault covered with clouds),

σ = $1{,}171.10^{-6}$ (Kcal/m^2/j/^{o}K) Stephan-Boltzman constant,

ρ = water density (kg/m^3),

e_S = $e(T_S)$ = tension of saturating vapour at temperature T_S(mm Hg),

e_A = $e(T_A)$ tension of saturating vapour at temperature T_A (mm Hg),

W = wind velocity, 2m above water surface (m/s),

ψ = relative humidity,

C_p = specific heat of water ($\simeq$ 1 cal/cm^2/^{o}C),

b = 0,00018,

N = 278,7,

L = latent heat of evaporation (Kcal/kg).

APPENDIX D

SIMPLIFIED COMPUTATIONS OF DILUTION BY GRAPHICAL METHODS

Quite frequently, urban or industrial effluents of coastal regions are discharged into the sea through submarine outfalls. In order to determine the size of the project and to evaluate the impact of effluent discharge on the marine environment, one must have such hydraulic data as: effluent dilution, dimensions of the polluted area, advection-dispersion by currents, possible non-conservative effects like verified decay of test germs of faecal pollution, etc.

For the determination of these characteristics by the most precise methods one must carry out computations which are quite complex and must as a rule be run on computer. However, on the basis of certain simplifying assumptions one can obtain simple formulae or graphs which can quickly give an approximate solution.

Appendix D gives these simplifying methods. They were essentially established in order to facilitate the work of Administration Engineers entrusted with evaluating applications for permission to discharge effluents or with assessing the studies carried out by Consultant Engineers. It is the Administration Engineers who must in each particular case make a judgment on the degree of validity of the simplifying assumptions used, as well as on whether the use of graphs is justified. These provisos are general; some of the graphs presented in this Appendix are more applicable to the Mediterranean, others to tidal seas.

In this document one shall find (in a simplified form for a quick review) graphs for the computation of:

- Jet or plume, horizontal or vertical, emitted in a still and density homogeneous receiving water,

- Jet or plume, horizontal or vertical, emitted in a still and linearly density stratified receiving water,

- Jet or plume, vertical, emitted in a density homogeneous receiving water and animated by a mean horizontal velocity,

- Dilution in the distant field through advection-dispersion under the effect of a rectilinear and uniform current,

- Bacterial decay at sea.

On principle, one uses the term "plume" if buoyancy is prevalent among the forces acting upon the flow and the term "jet" if, on the contrary, momentum is greater than buoyancy. One also uses the term plume to denote the cloud of contamination transported to the surface of the sea through advection-diffusion.

All symbols used are described at the end of the Appendix.

JET EMITTED HORIZONTALLY OR VERTICALLY, STILL AND DENSITY HOMOGENEOUS RECEIVING WATER

Assumptions

The receiving marine water is density homogeneous; the currents are negligible.

The opening through which the jet issues is circular, of a horizontal or vertical axis.

There is no jet interference with solid walls or other jets.

The jet (or plume) revolves symmetrically around its axis, the transversal distributions of velocities and concentrations are Gaussian.

Formulation (see description of symbols page 143 at end of Appendix).

Calculate: $F = u_o/\sqrt{gD(\Delta\rho/\rho o)}$ and $\eta = Y/(FD)$

The graphs on the following page give, depending on the direction of the emission of the jet:

$\zeta = T_m D/Y$	whence	$T_m = c_o/c_m$
$\xi = X/(FD)$	whence	X (for horizontal jet only)
$\lambda = s/Y$	whence	s and $\sigma = s/\sqrt{\mu k}$

Proportion of effluent found in a circle of radius r (section of the jet at depth Y).

$$M/M_o = 1 - \exp(-r^2/\sigma^2) = 1 - c/c_m$$

One finds 90% of the effluent in a circle such as $M/M_o = 0{,}9$ i.e. $r \neq 1{,}5\ \sigma$

Remarks

- In the first approximation μk 64. If $X \leq Y$, s tends toward Y whence roughly: $\sigma \neq Y/8$. Thus r = 1,5 Y/8 is the diameter of the circle containing 90% of the effluent and r = Y/8 the diameter of the circle containing 68% of the effluent. In these circles dilution is equal to 3,08 T_m and 1,65 T_m respectively.

- The velocity of the jet emission is necessarily superior or equal to the velocity in the outfall pipe. Since this velocity is limited, one can increase dilution by reducing the diameter D and creating a diffuser.

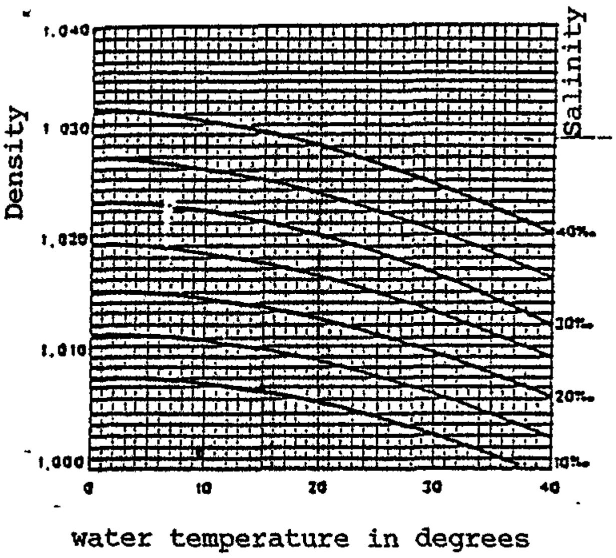
VALUE OF COEFFICIENTS μ and k

Angle of the jet axis in relation to the horizontal	NUMERICAL PARAMETERS			$\eta =$
	μ	k	μk	Y/FD
Degrees	(adimensional)			
0	0,800	77,0	61.6	0
10	0,789	79.5	62,7	0.06
20	0,780	81.8	63.8	0.18
30	0,773	83.5	64.5	0.33
40	0,766	86.1	66.2	0,60
50	0,761	86.8	66.1	0.96
60	0,756	88.3	66.7	1.50
70	0,750	89.5	67.1	2.66
80	0,744	90.9	67.6	5,20
90	0,740	92.2	68.2	∞

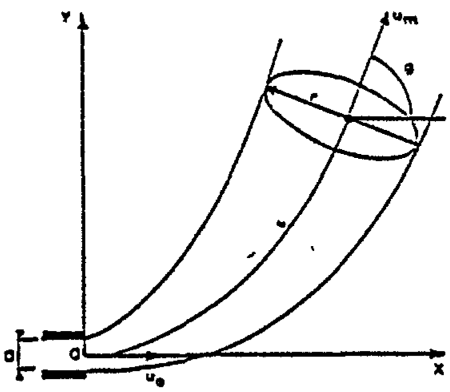
VALUES OF

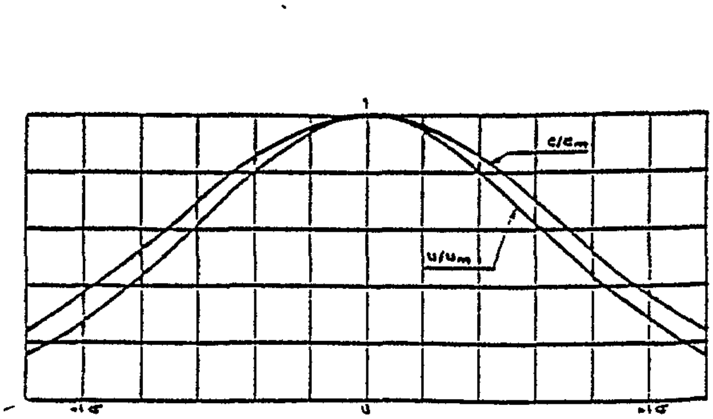
$M/M_o = 1 - \exp(-r^2/\sigma^2) = 1 - c/c_m$

r/σ	$M/M_o = 1-\exp(-r^2/\sigma^2)$	Relative dilution in the circle of radius r c/c_m
(adimensional)		
0,2	0,0392	0,9607
0,4	0,1479	0,8521
0,6	0,3023	0,6977
0,8	0,4727	0,5273
1,0	0,6321	0,3679
1,2	0,7631	0,2369
1,4	0,8591	0,1409
1,6	0,9227	0,0883
1,8	0,9608	0,0392
2,0	0,9817	0,0183
2,2	0,9921	0,0079
2,4	0,9968	0,0032
2,6	0,9988	0,0012
2,8	0,9996	0,0004
3,0	0,9999	0,0001

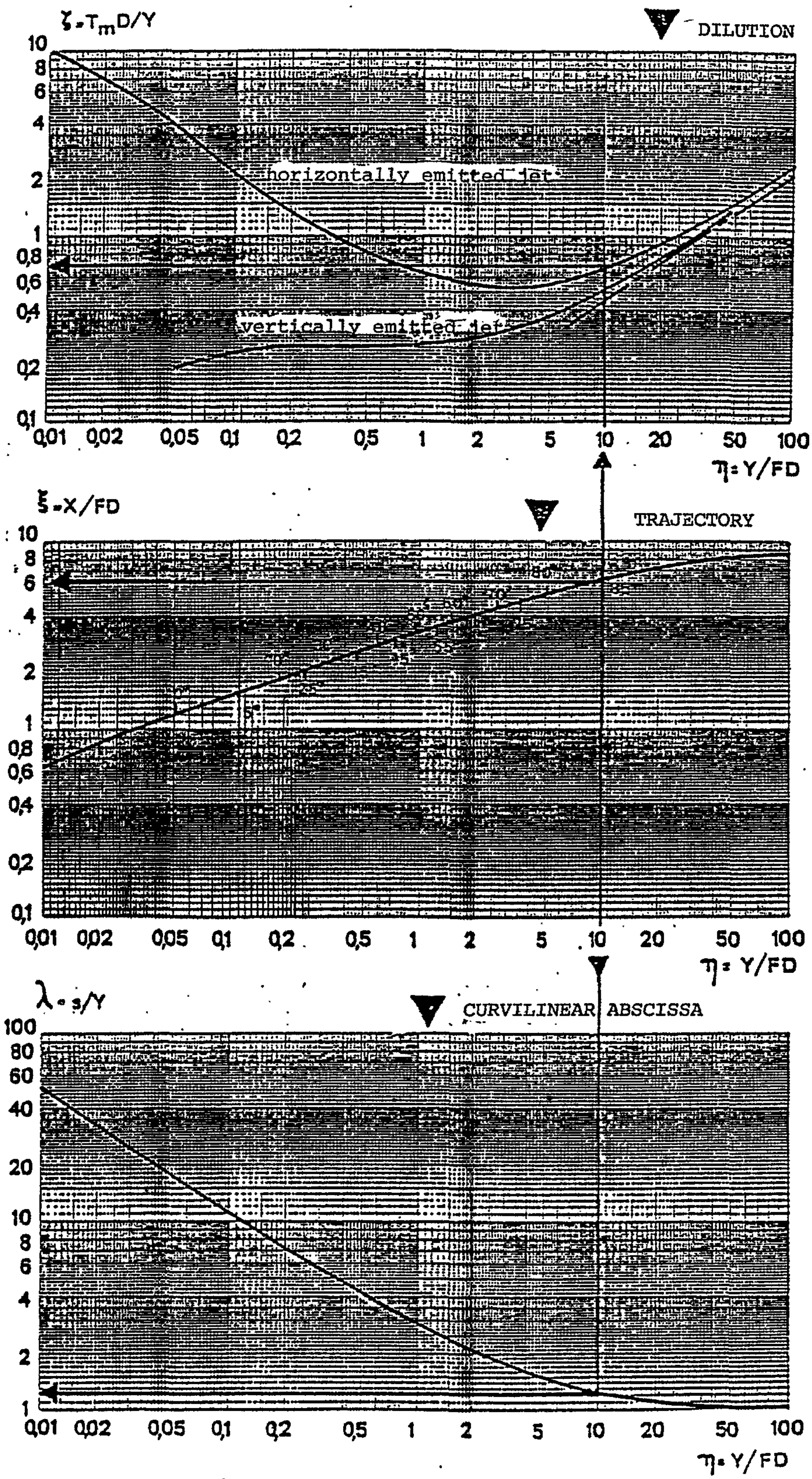


SEA WATER DENSITY





STANDARD DISTRIBUTION OF VELOCITIES AND CONCENTRATIONS


ζ = T_m D/Y
DILUTION
horizontally emitted jet
vertically emitted jet
η = Y/FD
ξ = X/FD
TRAJECTORY
η = Y/FD
λ = s/Y
CURVILINEAR ABSCISSA
η = Y/FD

NUMERICAL EXAMPLES

Working assumptions: A marine outfall discharging $2m^3/s$ through a diffuser laid at -20 metres with 15 ports of 300 millimetre diameter and horizontal axes. Sea water density is 1,027; effluent density 1,000.

1. COMPUTATION OF DILUTION

One calculates in turn:

- the elementary jet discharge $Q = 2\,(m3/s) / 15 = 0{,}133\,(m3/s)$
- the initial velocity $u_0 = 4Q/\pi D^2 = 4 \times 0{,}133\,(m3/s) / \pi \times \overline{0{,}3}^2\,(m2) = 1{,}39\,(m/s)$
- the variation of relative density $(\rho_1 - \rho_0)/\rho_0 = (1{,}027 - 1{,}000) / 1{,}000 = 0{,}027$
- the Froude number (formula 1) $F = u_0 / \sqrt{\frac{\rho_1 - \rho_0}{\rho_0} g D} = 1{,}89\,(m/s) / \sqrt{0{,}027 \times 9{,}81\,(m/s^2) \times 0{,}3\,(m)} = 6{,}69$
- the adimensional quantity (formula 2.1) $\eta = Y / FD = 20\,(m) / 6{,}69 \times 0{,}3\,(m) = 9{,}97 \doteq 10$
- the DILUTION graph gives for this value $\zeta = 0{,}67$
- thus the real dilution on the jet axis at the surface of the sea is: (formula 2.2) $T_m = \zeta Y / D = 0{,}67 \times 20\,(m) / 0{,}3\,(m) \doteq 44{,}7$
- the concentration on the jet axis (formula 2.4) $c_m = c_0 / 44{,}7$

2. COMPUTATION OF THE TRAJECTORY AND ITS ANGLE

- for the same value of η the TRAJECTORY graph gives $\xi = 6$
- the jet axis reaches the surface of the sea at the real abscissa (formula 2.3) $x = \xi FD = 6 \times 6{,}69 \times 0{,}3(m) \neq 12$ metres

The centre of the impact of the plume at the surface of the sea is 12 metres away from the vertical of the point of emission.

- This procedure can be used in order to establish the trajectory point by point.
- The angle between the horizontal and the tangent to the jet axis is shown on the TRAJECTORY graph, i.e. in this case 85*.

3. COMPUTATION OF THE DEPTH OF DISCHARGE

At what depth must the effluent be discharged in order to obtain at the surface dilution set at 500?

* One proceeds by trial and error on the basis of a series of values for Y.

The solution is: Y = 98 m; $\eta = 48{,}8$; $\zeta = 1{,}54$; $T_m = 503$

4. COMPUTATION OF THE PLUME DIAMETER

Because of turbulence, there is no precise boundary of the plume. One admits generally that it is a circle within which a certain proportion of the effluent is found. This proportion is selected in advance, e.g. 90% whence r = 1,5σ. Taking the example given in paragraph 1, one carries out the following computations:

- for η = 10 the CURVILINEAR ABSCISSA graph gives λ = 1,2 and by using the formula 2.5 we get s = λY = 1,2 x 20(m) = 24(m)
- for η = 10 table 3 gives μk = 68.
- calculate the standard deviation $\sigma = s/\sqrt{\mu k} = 24/\sqrt{68} = 2.9$
- establish the ratio M/M_o of the effluent and in table 2 read the corresponding value r/σ, whence r. Thus for M/M_o = 0,90, we obtain r ≠ = 1,5σ = 4,36 (m).

The diameter 2r of the jet defines the spacing between successive ports of a diffuser.

JET EMITTED HORIZONTALLY OR VERTICALLY, STILL AND DENSITY STRATIFIED RECEIVING WATER

Assumptions

The water density in the receiving marine ambient increases linearly with depth; the currents are negligible.

This density stratification is not affected by the jet itself.

The opening through which the jet issues is circular, of a horizontal or vertical axis.

There is no jet interference with the solid walls or with other jets.

The jet (or plume) revolves symmetrically around its axis, the transversal distributions of velocities and concentrations are Gaussian.

The vertical density gradient may be due to a variation in salinity (for instance, proximity to a river) or temperature or still to a combination of these two factors.

Formulation (see description of symbols page 143 at end of Appendix).

Calculate: $F = u_0/\sqrt{gD(\Delta\rho/\rho_0)}$ $\quad \epsilon = (\rho_2-\rho_1)/((z_2-z_1)\rho_1)$ and $N3 = DF^2\epsilon(\rho_0/\Delta\rho)$

The graphs on the following page give, depending on the direction of the emission of the jet:

$Y_3 = Y/(FD)$	whence	Y	Height of plume rising (level of spreading)
$T_3 = T_m/F$	whence	$T_m = c_0/c_m$	Final definition on the jet axis
$D_3 = 2r/Y$	whence	r	Radius of circle containing 90% of the effluent

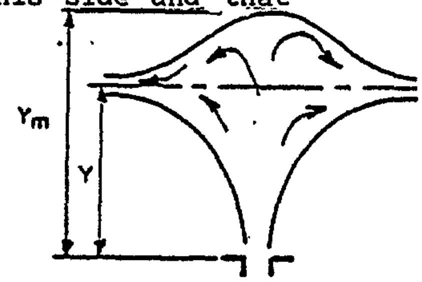
Remarks

- If the obtained height Y is less than the total depth of the sea at the point of emission, there is effluent trapping and the effluent will spread between two waters at the level where balance is achieved.

- The graphs have been established on the basis of systematic computations with the computer programme EMMA 2 (computations according to the DITMARS method - Schmidt number = 1,16. Entrainment coefficient = 0,0835). The points derived from the computations align perfectly on the curves T_3 and D_3. On the other hand, there is a certain dispersion this side and that of the curve Y_3 ($\pm$ 5 to 10%).

The "dome" effect.

The distribution of velocities in the plume is expressed by a very pronounced "dome" effect (see figure on the right).



For a jet or plume emitted vertically the total height Y_m can be calculated by using the formulae:

if $N_3 \gg 1$ $\qquad Y_m = 3{,}58\ FD/N_3^{1/4}$

if $N_3 \ll 1$ $\qquad Y_m = 3{,}58\ FD/N_3^{3/8}$

Numerical example

Jet discharge $Q = 0{,}020\ m^3/s$; port diameter $D = 0{,}15\ m$; depth of emission 30m; initial density gradient $\Delta\rho/\rho_0 = 0{,}027$; vertical sea water density gradient $\epsilon = 3{,}25 \cdot 10^{-5}\ m^{-1}$

$u_o = 1{,}13\ m/s \qquad F = 5{,}67 \qquad N_3 = 0{,}0058$

Horizontal jet emission:

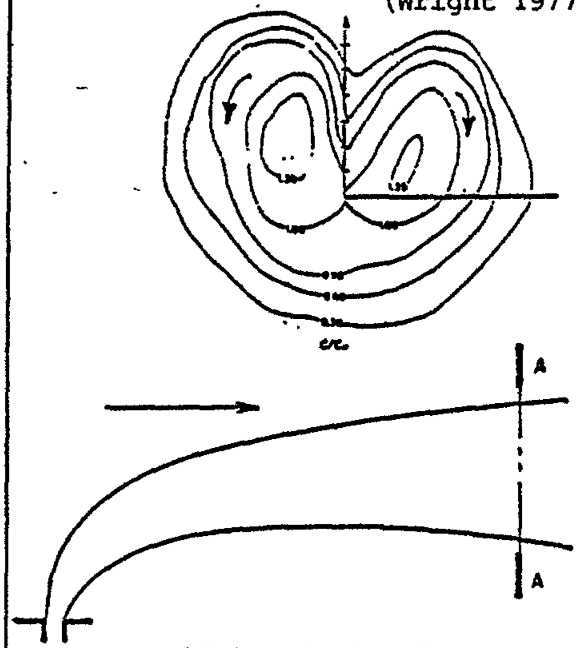
$Y_3 = 17$	whence	$Y = 14{,}5m$
$T_3 = 13$	whence	$T_m = 74$
$D_3 = 0{,}36$	whence	$r = 2{,}6m$

Vertical jet emission:

$Y_3 = 19$	whence	$Y = 16m$
$T_3 = 13$	whence	$T_m = 68$
$D_3 = 0{,}31$	whence	$r = 2{,}9m$

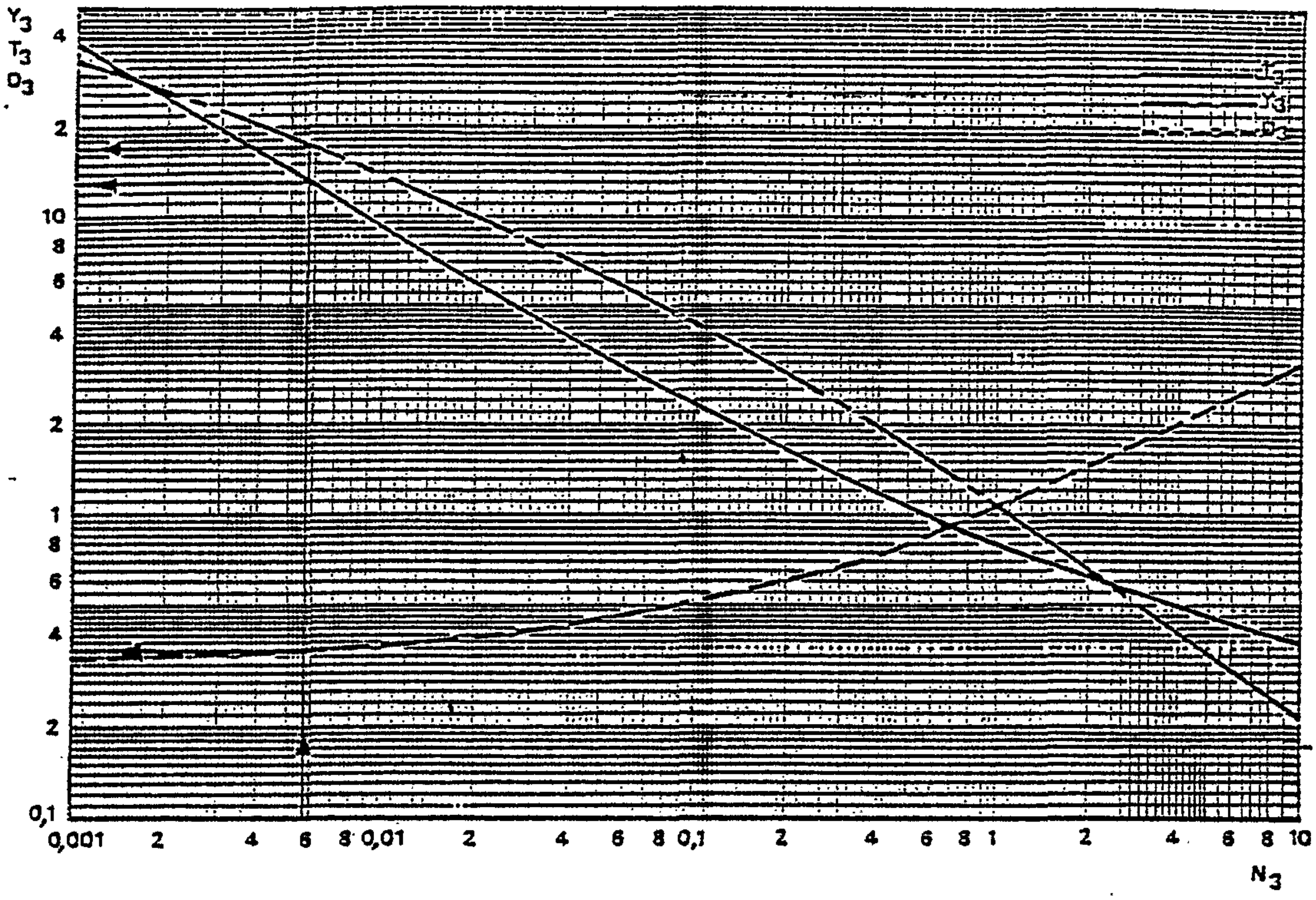
In this last case $Y_m = 21m$ (which can usefully be compared with $Y = 16m$).

Isoconcentration in section AA (Wright 1977)

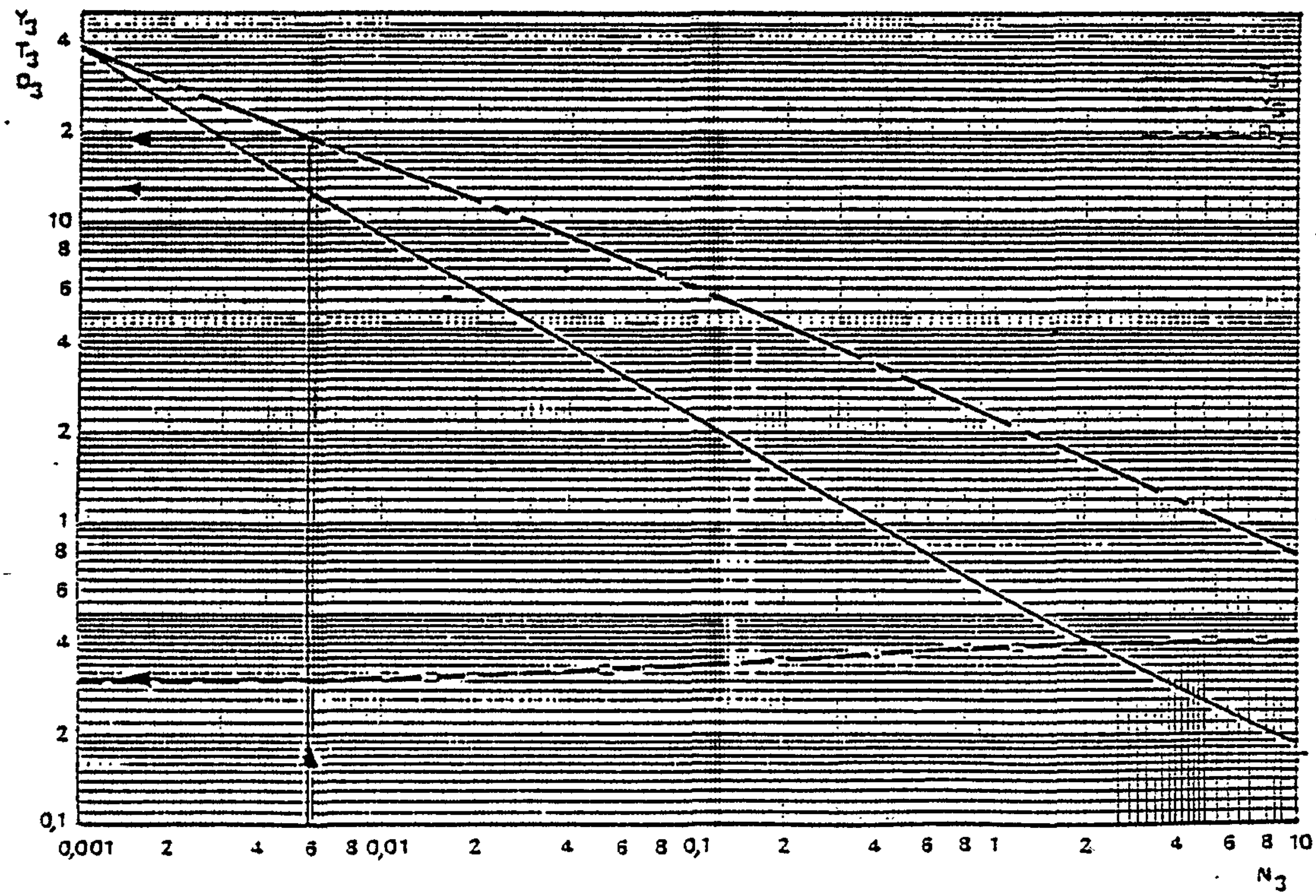


Jet in a high velocity flow

HORIZONTAL DISCHARGE



VERTICAL DISCHARGE



JET EMITTED VERTICALLY, DENSITY HOMOGENEOUS RECEIVING WATER WITH HORIZONTAL FLOW

Assumptions

The receiving marine environment is density homogeneous and animated by a rectilinear and uniform horizontal movement.

The velocity of flow is constant throughout the depth, thus the friction induced shear is not taken into consideration.

The emission port is circular with a vertical axis.

There is no jet interference either with the sea floor (which implies that $u_o/u_1 \gg 4$), or with the solid wall or other jets.

Formulation (see description of symbols page 143 at end of Appendix).

One seeks to determine in most cases at what distance X the axis of the jet (or plume) intersects the free surface of the sea (Y being in that case equal to the total depth) and the dilution obtained at that point. In addition, by using the same method of computation, one can also establish the distances X which correspond to any intermediate depth Y and thus establish the complete axis of the plume point by point.

A general solution this problem does not seem to exist; the graphs on the following page are valid in several respects.

Calculate:

$F = u_o/\sqrt{gD(\Delta\rho/\rho_o)}$ $\quad\quad U = u_1 F/u_o$

$Y_1 = Y/(FD)$ $\quad\quad Y_2 = Y_1 U^{1/3}$

$X_m = 1{,}61/U^4$ if $U < 0{,}94$

$X_m = 0{,}35/U^2$ if $U > 0{,}94$

Let us first use graph 1. On the basis of Y_1 and depending on the value of U, read X_1 on the useful curve. If $X_1 > X_m$ move to the next graph. If not, read:

$X_1 = u_oX/(u_1 DF^2)$ whence X

$T_1 = T_m/F$ whence $T_m = c_o/c_m$

If we use graph 2, on the basis of Y_2 and depending on the value of U, read X_1 on the useful curve. If $X_1 < X_m$ use the other graph. If not, read:

$X_1 = u_oX/(u_1 DF^2)$ whence x

$T_2 = T_m/(FU^{1/3})$ whence $T_m = c_o/c_m$

The diameter of the circle containing 90% of the effluent is approximately:

$2r \sim 0{,}4$ to $0{,}5Y$ if $U < 0{,}94$

$2r \sim 0{,}6$ to $0{,}8Y$ if $U > 0{,}94$

Remarks

- The discharge flow behaves like a jet if $u_1F/u_o > (\pi/4)^{1/4} = 0{,}94$ and like a plume in the opposite case.

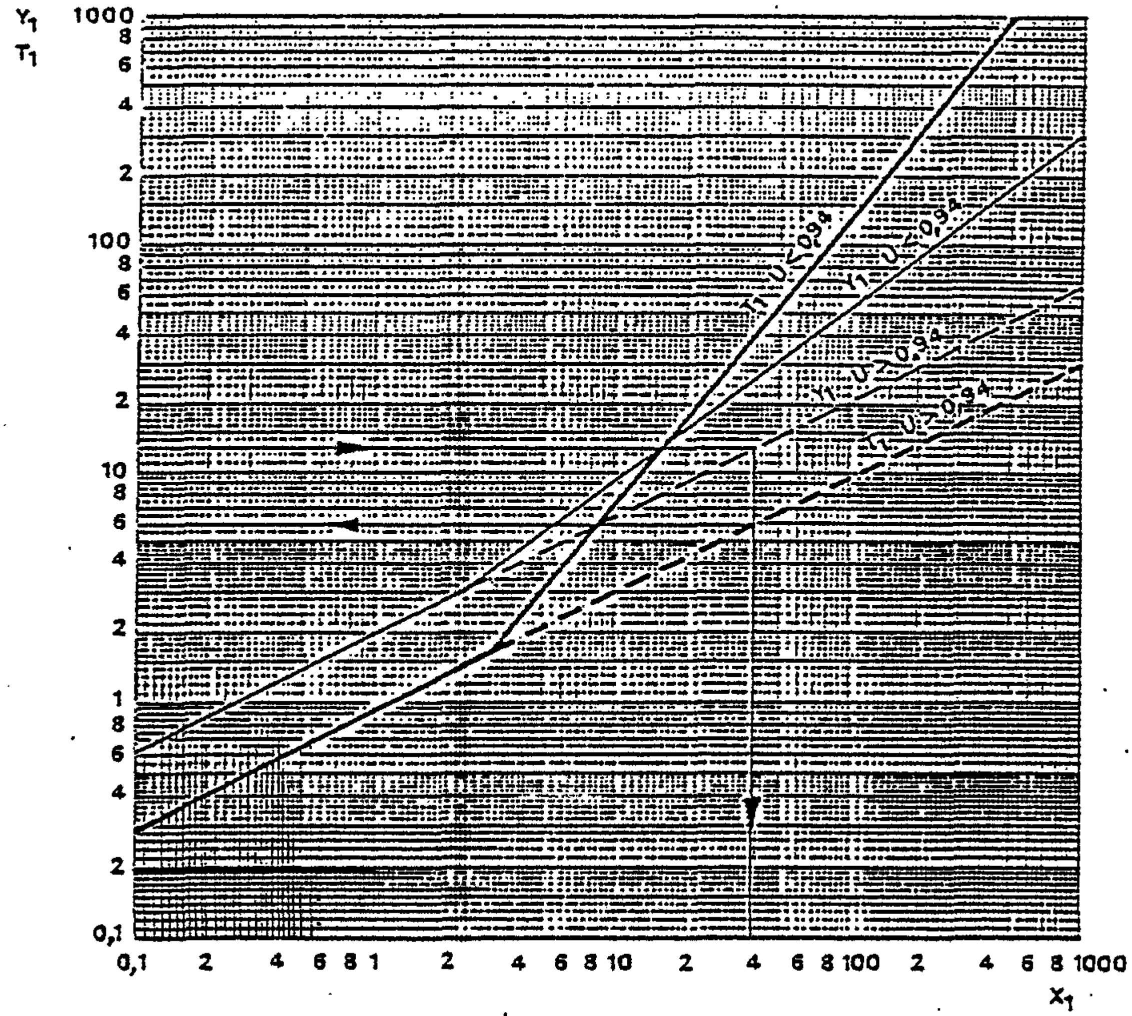
- The direction of the jet or plume inclines strongly under the action of the marine current as follows:

  X_1 of the order of $1{,}61\ (u_1F/u_o)^4$ if it is a plume
  X_1 of the order of $0{,}35\ (u_1F/u_o)^2$ if it is a jet

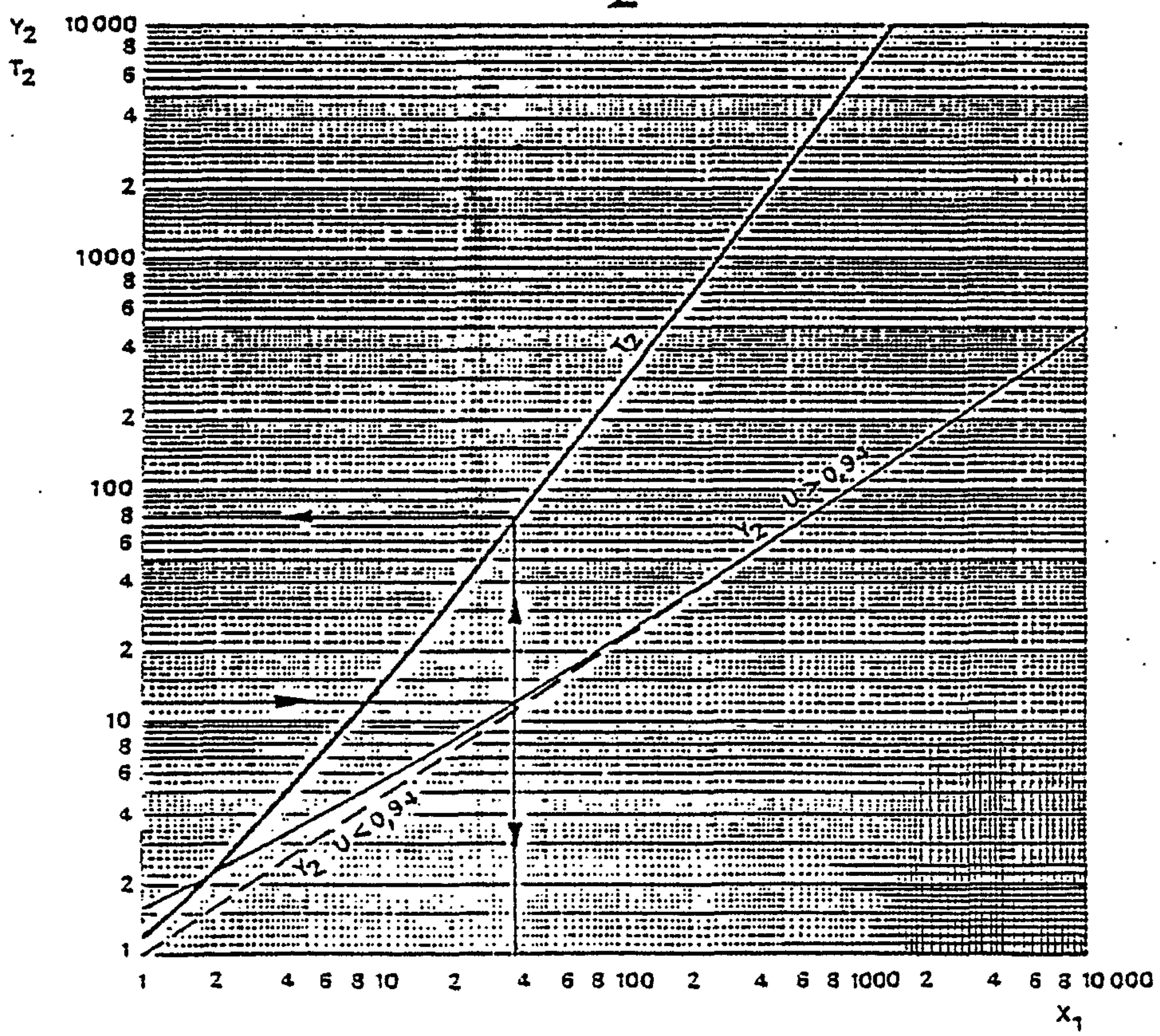
- The graphs have been established on the basis of systematic computations with the computer programme EMMA 2A (computations following the Abraham method. Schmidt number = 1,0. Entrainment coefficient = 0,5. Drag coefficient = 0,30) and were compared to the results obtained with a physical model by Wright (1977), Briggs (1975), Chu and Goldberg (1974).

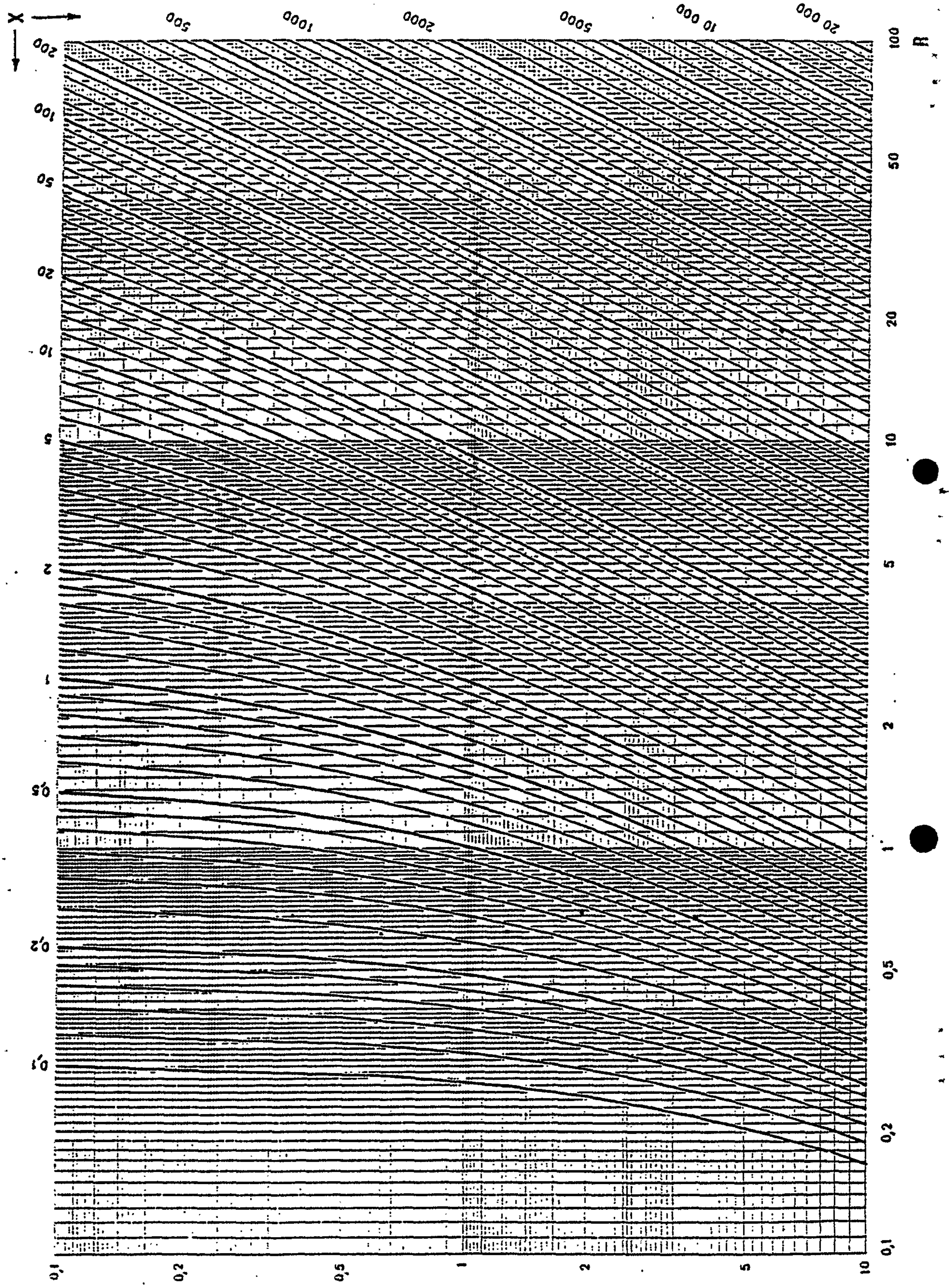
- If u_1F/u_o becomes greater than 2,5, the plume divides into two co-axial horizontal eddies. The graphs remain valid and the distribution of concentrations remains Gaussian only on the vertical plane containing the jet trajectory. On the other hand, there are two maxima of concentration outside this plane which are higher by 50 to 70% than that calculated. (see figure).

1


Y_1
T_1
1000
100
10
1
0,1
0,1 2 4 6 8 1 2 4 6 8 10 2 4 6 8 100 2 4 6 8 1000
X_1
T1 U<0,94
Y1 U<0,94
Y1 U>0,94
T1 U>0,94

2


Y_2
T_2
10 000
1000
100
10
1
1 2 4 6 8 10 2 4 6 8 100 2 4 6 8 1000 2 4 6 8 10 000
X_1
T2
Y2 U>0,94
Y2 U<0,94


X
500
1000
2000
5000
10 000
20 000
200
100
50
20
10
5
2
1
0,5
0,2
0,1
R
100
50
20
10
5
2
1
0,5
0,2
0,1
U
0,1
0,2
0,5
1
2
5
10

HORIZONTAL ADVECTION AND THREE-DIMENSIONAL DISPERSION ON THE SURFACE OF THE SEA

Assumptions

It is only the marine currents that ensure the transport (advection) and the dispersion of the waters contaminated by the rising plume.

These currents are constant in intensity and direction (see remarks).

The vertical density gradients are negligible (see remarks).

There is no interference between the polluted layer and the solid walls, the coast or the sea floor.

It is assumed that the characteristic parameters of the turbulence-induced diffusion are constant.

On the surface of the sea, the radius of the rising plume is assumed to be equal to $r = 1{,}5\,\sigma$ (circle containing 90% of the pollutant).

Principle

If the emission of the pollutant is from a point source in the mathematical sense of the word, the equation of diffusion has an analytical solution. The contamination patch produced on the surface of the sea by a rising plume is far removed from this concept. The principle proposed here consists in finding which continuous discharge point source situated upstream in the sea water flow is equivalent to the rising plume when it reaches the water surface (see diagram). This approximation assumption is validated by the Gaussian character of the distributions of concentration in the rising plume and in the field of contamination produced by the point source.

Formulation (see description of symbols on page 143 at the end and estimates for K_x, K_y and K_z on page 139)

Calculate:

$$U = u/\sqrt{K_x} \qquad R = r/\sqrt{K_y}$$

For these values, read in the graph on the opposite side:

$$X_o \qquad \text{whence} \qquad x_o = X_o\sqrt{K_x}$$

Beyond the impact of the rising plume on the free surface of the sea, dilutions are minimal on the trajectory passing through the fictitious point source and through the centre of this impact. These dilutions at any point x beyond the peak of the rising plume are (see figure):

$$D_m = x/x_o = (d + x_o)/x_o$$

The effects of this dilution D_m are added to the dilution T_m in the rising plume and give the total dilution: $D_m \; T_m$. Outside this trajectory, total dilutions (including the rising plume) can be calculated on the basis of the following formulae:

$$X^2 = (d + x_o)^2/K_x \qquad Y^2 = y^2/K_y \qquad Z^2 = z^2/K_z \qquad U^2 = u^2/K_x$$

$$c = \frac{1}{D} = \frac{X_o}{T_m}\,\frac{1}{\sqrt{X^2 + Y^2 + Z^2}}\,\exp\left[\frac{U}{2}\left(X - \sqrt{X^2 + Y^2 + Z^2}\right)\right]$$

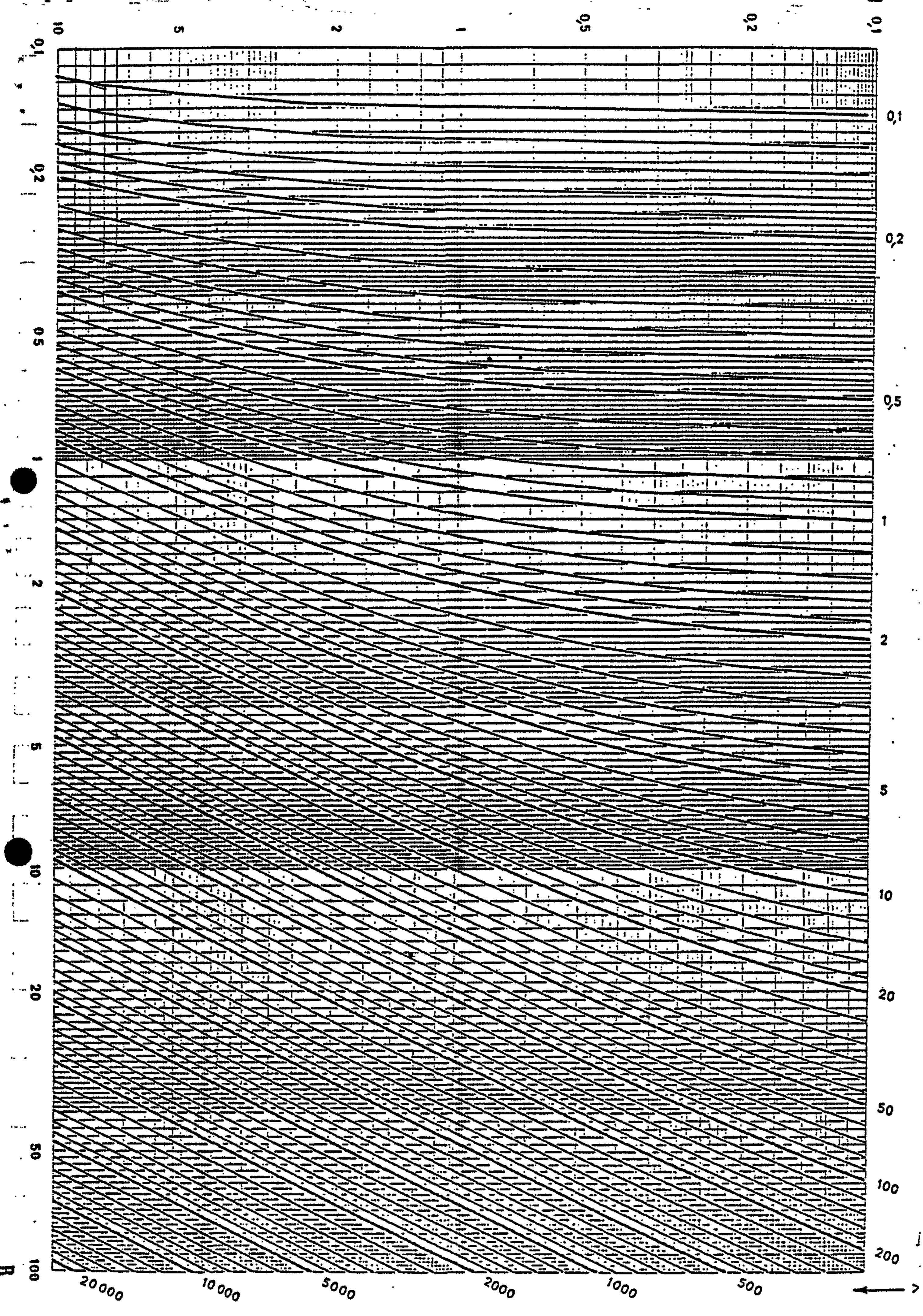
Remarks

The above formulae can give acceptable results, provided some caution is exercised in selecting the parameters, if the trajectory has a moderate curving or in the case of tidal seas, by respecting the boundaries of movement of the water masses. Outside the central trajectory (axis of symmetry), precision decreases on account of differential convections. The exact solution can be obtained through complex mathematical models.

- A thermocline, or a saline stratification, can play a role similar to that of a wall.

- If the dilutions in the rising plume are small and the residual density gradients significant, gravity spreading of the contaminated waters may increase the width of the horizontal plume on the water surface. If one wants to take this phenomenon into consideration and combine it with turbulent diffusion, one cannot use simple computations.

- The vertical gradients of the horizontal velocity and the deviations of the latter due to the Coriolis effect further complicate the problem.


U
R
0,1
0,2
0,5
1
2
5
10
20
50
100
200
20 000
10 000
5000
2000
1000
500

HORIZONTAL ADVECTION AND BIDIMENSIONAL DISPERSION AT THE WATER SURFACE

Assumptions

In certain cases (very considerable discharge from the outfall, small dépth etc), the thickness of the contaminated patch at the surface can almost equal total depth ($z \sim H$). In that case vertical diffusion plays no role whatsoever and dispersion becomes a bidimensional problem.

All the other assumptions made for tridimensional dispersion are applicable in this case as well.

Formulation (see description of symbols on page 143 at the end)

Calculate the reduced magnitudes:

$$U = u/\sqrt{K_x} \qquad R = r/\sqrt{K_y}$$

For these values, read in the graph on the previous page:

$$X_o \qquad \text{whence} \qquad x_o = X_o\sqrt{K_x}$$

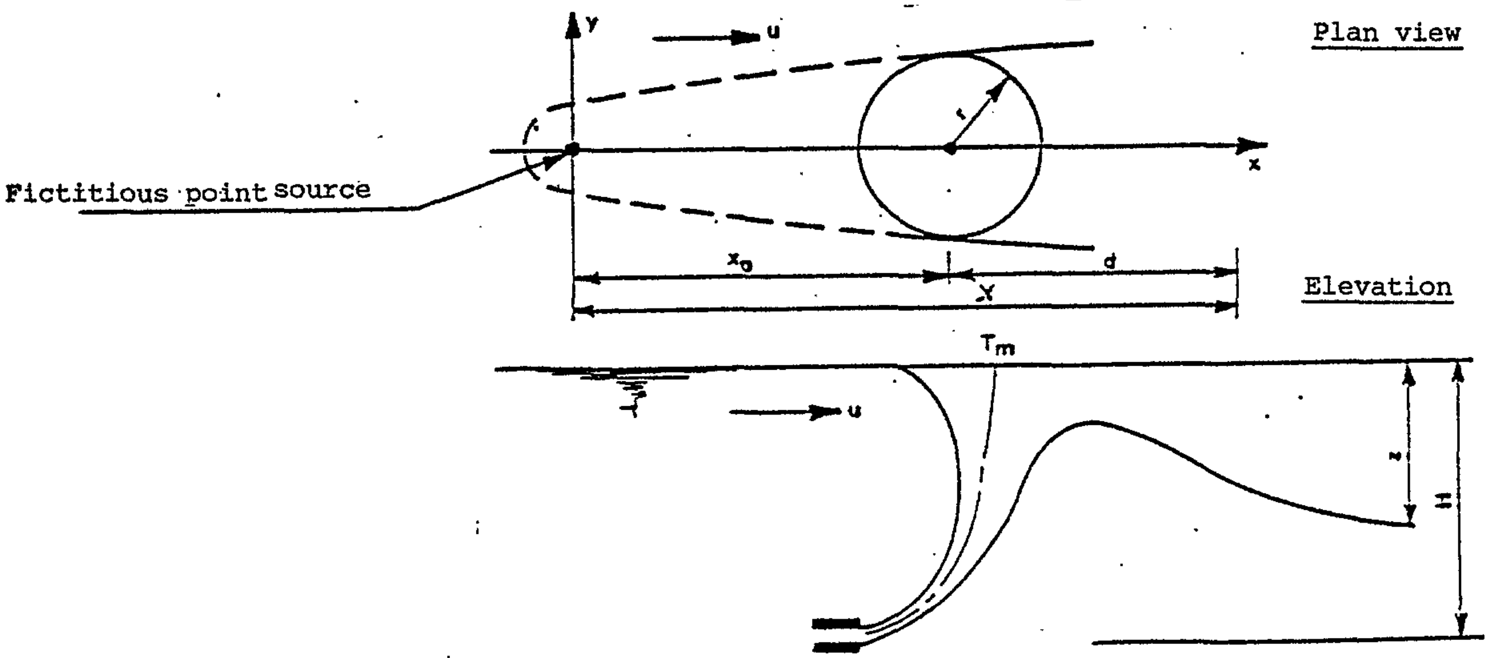
Beyond the impact of the rising plume on the free surface of the sea, dilutions are minimal on the trajectory passing through the fictitious point source and through the centre of this impact. These dilutions at any point X beyond the peak of the rising plume are (see figure):

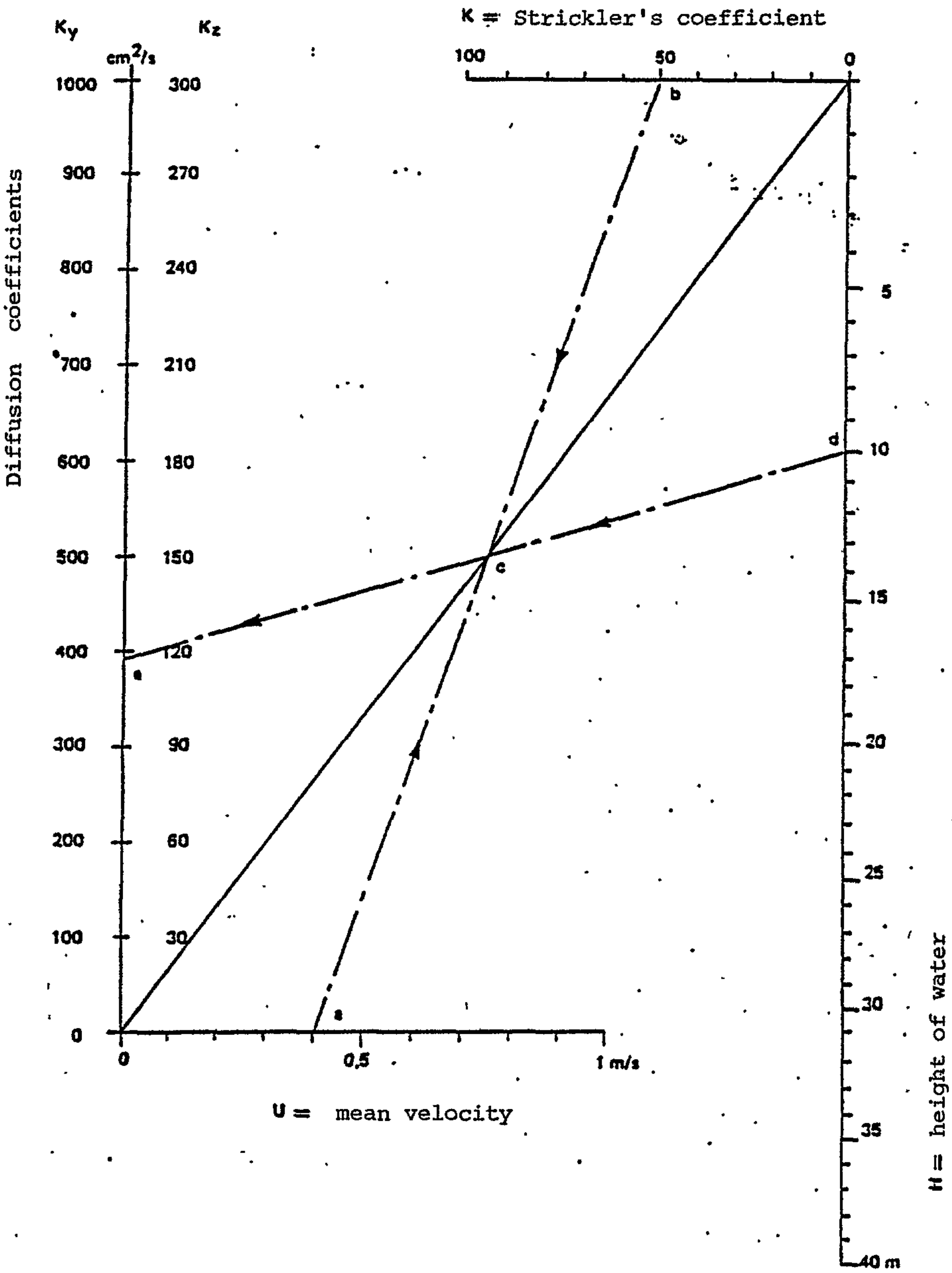
$$D_m = x/x_o = (d + x_o)/x_o$$

The effects of this dilution D_m are added to the dilution T_m in the rising plume and give the total dilution: $D_m \cdot T_m$. Outside this trajectory, total dilution (including the rising plume) can be calculated on the basis of the following formulae:

$$X^2 = (d + x_o)^2/K_x \qquad Y^2 = y^2/K_y \qquad U^2 = u^2/K_x$$

$$c = \frac{1}{D} = \frac{1}{T_m}\sqrt{\frac{X_o}{\sqrt{X^2 + Y^2}}}\ \exp\left[\frac{U}{2}\left(X - \sqrt{X^2 + Y^2}\right)\right]$$





join ab whence c

join cd whence e

Graph of Elder's formula (diffusion coefficients in a canal)

COEFFICIENTS OF TURBULENT DIFFUSION

Assumptions

These coefficients depend on the flow itself and on the influence of the walls on the distribution of velocities. It is only through field data that one can obtain values. *If field measurements have not been carried out,* one can use the following formulae derived by Elder and established on the basis of tests in a laboratory canal.

Thus these formulae can only be applied to flows where the vertical distribution of velocities depends on the friction on the bottom (shear flows).

The structure of these formulae can also be adapted to wind generated flows, but the numerical coefficients to be applied in that case probably differ from those given here (and have not been established as yet).

Formulae (see description of symbols on pages 143 and 144 at the end)

Calculate: $A = 3{,}13\ H^{5/6}\ u/K$

whence: $K_x = 5{,}9\ A$ $K_y = 0{,}23\ A$

$K_z = 0{,}067\ A$ $K_z = 0{,}4\ AZ(H - z)/H^2$

K stands for the friction coefficient in the classic law of STRICKLER. Take for instance: 30 to 40 for a sandy bottom and 20 to 30 for a rocky bottom.

These formulae are translated in the graph on the opposite page.

The total depth H to take into consideration shall always be limited to the surface layer which is density homogeneous. For any extrapolation beyond 40 metres caution should be exercised and justification given.

STANDARDS CONCERNING BACTERIAL POLLUTION

Mandatory standard: limit quality of water acceptable for bathing.
Guiding standard : values to take into account for the computation of the characteristics in designing new outfalls.

BATHING WATERS (E.E.C. Standards)	Number of germs in volume of water	Guiding Standards	Mandatory Standards
Total coliforms	100 millilitres	500	10 000
Faecal coliforms	100 millilitres	100	2 000
Faecal streptococci	100 millilitres	100	-
Salmonella	1 litre	0	0
E.Coli	10 litres	0(UFP)	0(UFP)

SHELLFISH GROWING WATERS (French Standards)	Number of faecal coliforms contained in 100 millilitres of shellfish flesh. Sampling frequency: 26 over 12 months	Tolerance
Area suitable for public health	$\leqslant$ 300	3 measurements $\leqslant$ 1 000 2 measurements $\leqslant$ 3 000
Area unsuitable for public health	(a) $>$ 300 and $\leqslant$ 10 000 (b) $>$ 10 000 in 25% of the samples	under provision of effluent treatment and permission of Aff. Maritimes and I.S.T.P.M. under authorisation of D.D.A.S.S.

BACTERIAL DECAY AT SEA

Assumptions

The mechanisms explaining bacterial decay in the sea are very poorly understood. Temperature, salinity, ultra-violet radiation, antagonism among living organisms, which fight for survival, probably play a direct or indirect role. Some scientific studies (BRISOU-CRAS-June 1980) have shown a privileged adsorption of bacteria on suspended solids. The bacteria would then follow the movements of the solids supporting them and would float, settle or enter the food chain.

Bacterial decay is thus a poorly identified phenomenon, which however should be distinguished from mortality.

The characteristic parameter of this decay, or the time needed to divide by 10 the number of bacteria present (i.e. a 90% reduction) designated by T_{90} is a random variable following (as experience shows) a log-normal law. We are dealing with a living environment, there is uncertainty concerning the explanatory phenomena, the marine environment is heterogeneous, the measurements are subject to errors in the quantitative analysis, the samplings may not be precise, etc.

Formulation (see description of symbols on pages 143 and 144 at the end).

Simple law of population dynamics $N = n_0 \exp(-2{,}3\, t/T90)$

Log-normal law

$$p\left[\mathrm{Log}\,(T90)\right] = \frac{1}{\sigma\sqrt{2.\pi}} \exp\left[-\frac{1}{2}\left(\frac{\mathrm{Log}\,(T90) - m}{\sigma}\right)^2\right] \qquad m = \mathrm{Log}\,(\overline{T90})$$

whence by combining the two:

$$N = (N_o/\sqrt{2\pi}) \int_{-\infty}^{\infty} \exp\left[-(2{,}3t/\overline{T90}) \exp(-\sigma x) - x^2/2\right] dx$$

can be computed solely with the help of the graph on the opposite page following the procedure:

- Calculate the abscissa $X = t/\overline{T_{90}}$
- Read on the diagram, on the referenced curve σ the ordinate $Y = N/N_o$
- Deduce from it the residual value $N = YN_o$
- Equivalent dilution $D_b = 1/Y$

The minimal total dilution on the trajectory passing through the point source (pages to) is the product of the three dilutions produced by the jet, by the advection -dispersion and by the bacterial decay:

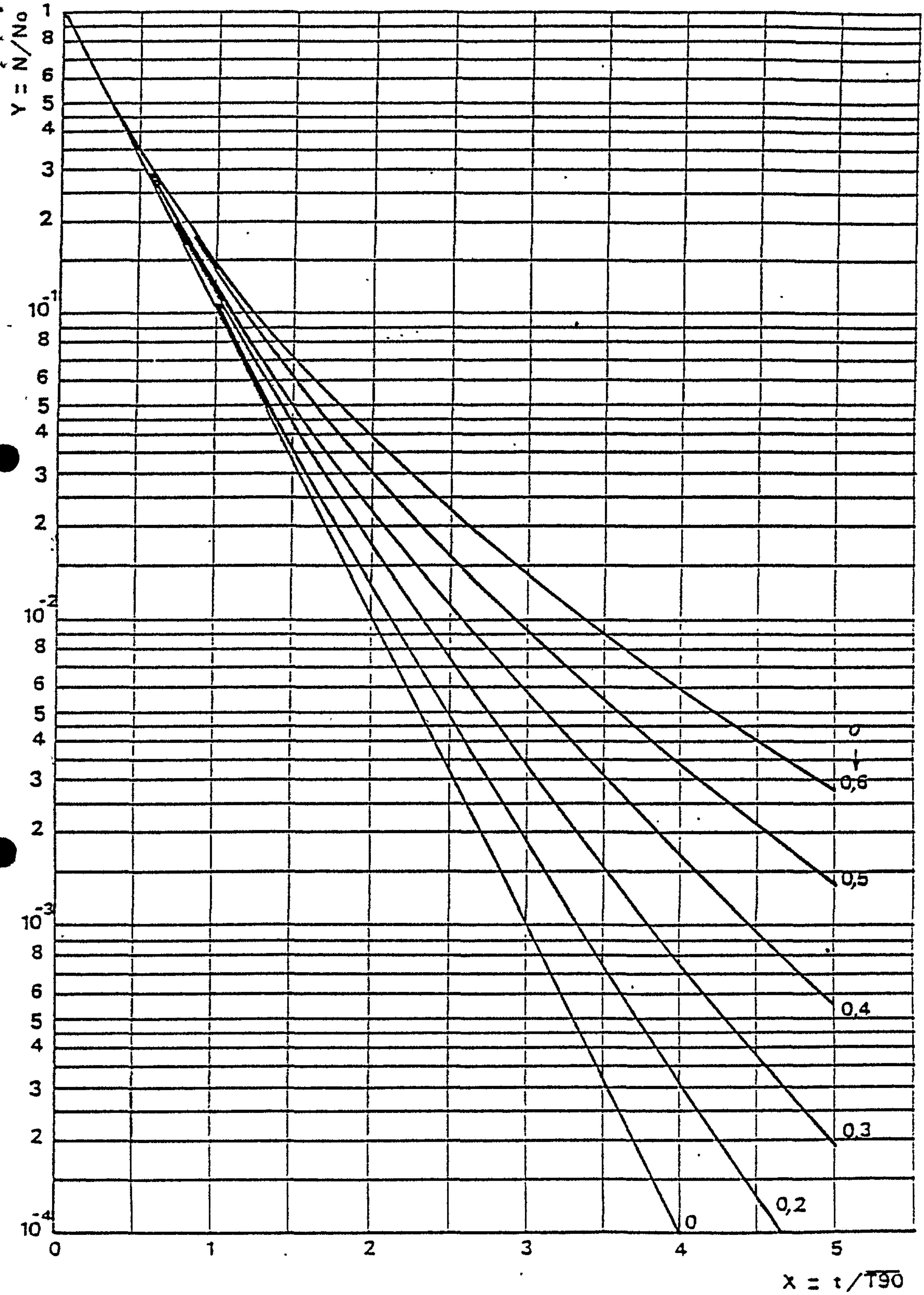
$$T_m \cdot D_m \cdot D_b$$

Outside this trajectory it is only equal to $D.D_b$ (since D comprises the effect of the jet T_m).

NUMERICAL VALUES

Measurement Site	Authors	Date	Temperature of sea water	Total Coliforms		Faecal Coliforms		Faecal Streptococci	
				$\overline{T_{90}}$ hrs	σ	$\overline{T_{90}}$ hrs	σ	$\overline{T_{90}}$ hrs	σ
Marseille Courtiou	SOGREAH	Jul.1977	16,9	2,63	0,35	2,61	0,43	2,88	0,56
Gulf of Giens	SOGREAH	Jun.1977	19,5	2,00	0,81	2,02	0,92	2,03	0,93
La Rochelle	SOGREAH	Jun.1978	15,8	1,00	0,50	1,00	0,50	1,60	0,60
Royan (Terre Nègre)	SOGREAH	Sep.1978	18,1	1,70	0,45	1,70	0,40	1,83	0,57
U.K. (Plymouth)	Gameson & Gould	1969-1973	17,0	2,43	0,38				
Brazil (Sao Paulo)	Occhipinti	-	18to28	1,25	0,65				
USA (California)	Foxworthy&Kneeling	-		2,00	0,72				
Abidjan(Ivory Coast)	SOGREAH - CRO	1977	20,0	2,16	0,47				

LAW OF BACTERIAL DECAY



DESCRIPTION OF SYMBOLS

Rising jets and plumes

Reference: Origin at the centre of the port of jet emission, vertical axis Y oriented upwards, horizontal axis X oriented in the direction of the velocity of the flow of the receiving water or in the direction of the emission of the jet horizontally emitted.

c = concentration at any given point
c_o = initial concentration of effluent prior to discharge
c_m = concentration on the plume axis
g = acceleration due to gravity
r = distance from the plume axis

s = curvilinear abscissa along the jet axis
u_o = velocity of emission of jet
u_1 = velocity of flow in the receiving water
D = diameter of port of emission of jet
F = Froude number

M = quantity of pollutant in a section of the jet
M_o = quantity of pollutant in the initial section of the jet
T_m = dilution on the axis of the jet or plume
X = abscissa of the axis of the jet or plume
Y = ordinate of the axis of the jet or plume

ϵ = vertical density gradient in the receiving water
ρ = density at a given point in the plume
ρ_o = initial effluent density
σ = standard deviation in the section of the jet
$\Delta\rho$ = $\rho_m - \rho_o$
ρ_m = sea water density (if homogeneous)
ρ_1 = sea water density at depth z_1
ρ_2 = sea water density at depth z_2

$D_3, N_3, T_1, T_2, T_3, U, X_1, X_m, Y_2, Y_3, \zeta, \eta, \lambda, \xi$

adimensional variables which simplify the various formulae and ensure the connection with the various graphs.

Horizontal advection and dispersion

Reference: Origin at point of impact of the axis of the rising jet with the water surface, axis O_x oriented in the direction of sea water flow, vertical axis O_z oriented upwards, axis O_y perpendicular to the other axes.

c = concentration at any given point
g = acceleration due to gravity
r = radius of the plume at the surface of the sea
u = velocity of the flow of sea water
x_o = distance from the fictitious point source

x = real abscissa
y = real horizontal coordinate
z = real vertical coordinate
D = dilution at any given point
D_m = dilution on the axis of horizontal field

H = total height of sea water
K = Strickler's friction coefficient
K_x = longitudinal diffusion coefficient
K_y = transversal diffusion coefficient
K_z = vertical diffusion coefficient

T_m = final dilution on the axis of the rising plume

R, U, X_o, X, Y, Z: Reduced values of the quantities r, u, x_o, x, y, z

Bacterial decay

m = logarithmic average of T_{90}
= probability density
t = time
N = residual number of bacteria at t

N_o = initial number of bacteria
T_{90} = time needed to divide N by 10
$\overline{T_{90}}$ = geometric average of the T90s
σ = standard deviation of the logarithms of T_{90}

APPENDIX E

PRECISE COMPUTATION OF THE DENSITY OF SEA WATER

The precision which is indispensable in the expression of sea water density is: 10^{-5} to 10^{-6}, or 5 to 6 decimals.

One should stress in effect that a density difference of 10^{-6} corresponds to a mass variation of 1 gram per m^3 of water and that a variation of 1 degree centigrade modifies the density by approximately 0,00025, or 250 grams per m^3. Such differences are sufficient to break the balance of a mass of water which is always at the limit of its buoyancy.

Precise computations of turbulence, which are also confirmed by field experiments, show that a density difference of 10^{-5} inhibits vertical turbulent diffusion, whose representative coefficient k_z may be reduced by a factor of 100.

It is thus highly advisable to use the computation formulae given here. They are order 3 polynomials presented in a form which reduces to the minimum the number of arithmetical operations to carry out and is well suited to electronic calculators of any size.

Let:

$\rho(S,T)$ be Density of sea water (t/m^3)
S total salinity (g/l)
T Temperature (°C)

Oceanographers define the following practical magnitude:

$$\sigma(S,T) = 1000\,[\rho(S,T) - 1]$$

(whence for instance: $\rho = 1{,}026132$ hence $\sigma = 26{,}132$).

Thus we have:

$$\sigma(S,T=0) = \left[\left[6{,}8 \times 10^{-6}\,S - 4{,}82 \times 10^{-4}\right]S + 0{,}8149\right]S - 0{,}093$$

$$\sigma(S,T) = \sigma(S,T=0) + \left[\left[a_1\,(T-10) + a_2\right](T-20) + a_3\right](T-30) + a_4$$

The following table gives the coefficients a_1 to a_4 as a function of the value of salinity S.

Regardless of the error made on S and T, precision is of the order of 10^{-2} on σ, thus of 10^{-6} on ρ.

Salinity S	Coefficients of the polynomial in T			
	$(10^5 \times a_1)$	$(10^3 \times a_2)$	a_3	a_4
37,5 à 42,5	5,7166	-3,600	-0,3050	-6,6470
32,5 à 37,5	2,3400	-4,250	-0,3020	-6,3696
27,5 à 32,5	4,5166	-4,225	-0,2965	-6,0888
22,5 à 27,5	2,4250	-4,750	-0,2930	-5,7945
17,5 à 22,5	5,5500	-4,400	-0,2810	-5,4566
12,5 à 17,5	5,5833	-4,700	-0,2780	-5,1850
7,5 à 12,5	1,9233	-5,300	-0,2720	-4,8646
2,5 à 7,5	4,1616	-5,250	-0,2650	-4,5503
0 à 2,5	5,5500	-5,100	-0,2550	-4,2557

APPENDIX F

PRINCIPLE OF THE SCHEME FOR THE IMPROVEMENT OF COASTAL WATERS (SAEL)

We stated in the beginning of this study (foreword, page 2) that in the form called "2nd problem" a particular approach to the problem of effluent discharge into the sea could be used in order to establish what we called "the receiving capacity" of a coastal zone to a specific pollutant.

The methodology developed in this context is that of the "Schemes for the improvement of coastal waters" (SAEL). It is especially suitable to the Mediterranean coastal areas and their special conditions: absence of tides, mostly wind-generated coastal currents, both of which make for a better computation of effluent dilution as a function of the sole geographic and meteorological conditions.[1]

The methodology is based on the following principle:

The dispersion-dilution of an effluent from the offshore end of an outfall depends on:

- the particular features of the discharge: flow, port diameter
- the current prevailing in the receiving water; its direction and velocity may be considered as a direct function of the direction and the velocity of the wind.

At a particular site, the meteorological statistics give us, in the form of a "wind rose", the corresponding frequencies of the directions and intensities for the 8 directional sectors generally considered.

Since the SAEL has been established for a particular type of pollution, which is generally urban sewage, the parameters that must be introduced into the model are:

- the nature of the concentration of the critical pollutant,
- the maximum acceptable concentration of it, in other words the "standard", in the usage area most immediately threatened by the discharge.

For instance, it will be the "bathing water" standard if all or part of the coastal area is used for bathing. In that case the critical pollutant will be one of the test germs of faecal contamination (total or faecal coliforms).

The abatement coefficient for this pollutant between the outfall port and the sensitive area will be the ratio between the concentration of the pollutant in the discharged effluent and that of the standard, e.g.:

$$C.A. = \frac{10^8}{500} = 2.10^5$$

---

(1) This methodology has been applied in France in all the coastal areas between the Spanish and the Italian borders. SAEL Mediterranée Provençale - March 1978, SAEL Languedoc-Roussillon - March 1979.

Finally, one should establish a limiting condition in order that the problem has a definite solution. It is conceivable in effect that the receiving capacity one seeks to determine is as large as one wishes, if no limit is set to the distance from the discharge point. The limiting condition may be either maximum length of the outfall pipe (which means establishing a ceiling to the cost of the project or constraints of a technical nature), or a condition such as non-trapping of the effluent plume at a certain depth by a thermocline, given the disadvantages already discussed. The first type of limiting condition will be seen in flat coasts, the second in steep ones where the phenomenon of thermocline generates the risk of trapping.

Thus stated, the problem has a defined solution, which is that for a given emission point at the offshore end of the outfall pipe there is, in the most unfavourable meteorological conditions (wind, current), a maximum effluent flow compatible with the limiting condition. Since the value of this maximum flow varies with the position of the discharge point, it is for a specific position that the maximum flow will reach its highest value.

In order to define the outfall system which, along a coast frontage, will correspond to the highest discharge possible, i.e. to the limit receiving capacity for the pollution under consideration, one must draw the outline comprising the greatest number of discharge points capable of maximum flows on condition that the effects of contiguous discharge points on the sensitive areas under protection remain separate from one another.

On this basis, the objective that was set was to develop a method leading to a practical, quick and simple solution of the problem theoretically defined in this way. The goal was reached thanks to the purely graphic character of the solution proposed and this made possible the computation, made in advance and presented in the form of tables, graphs and diagrams, of all the necessary numerical elements concerning a coastal front defined by its geographic and current-related characteristics; the latter are established on the basis of meteorological statistics which are also used for the theoretical establishment of the seasonal thermocline and its development in time.

Concerning each one of the phases of mixing and advection of the effluent distinguished in the previous chapters (vertical ascension, horizontal transport, decrease of degradable pollutants), the laws of dilution have been approximated by mathematical models called EMMA 1, 2 and 3 which were developed for this occasion; one of them gives the development characteristics of the thermocline.

Thus, a coastal area of a determined length is physically described and put into memory in a multiple series of graphs and tables; the figures following show what they look like, in the case taken as an example, where the non-trapping of effluents by the thermocline is the limiting condition of the depth of discharge.

In this case, each of the tables of the type shown in figure 1 correspond to the following series of parameters:

- depth of discharge
- discharge flow per diffuser port
- initial velocity of discharge
- number of diffuser ports
- objective of dilution.

Thus each table gives, as a function of the maximum statistical velocity of the wind in each of the 8 directions of the rose, 11 characteristics of the dilution of the effluent plume; the most important is the distance at which, in the direction of the current corresponding to the direction of the wind, the objective of dilution is reached. In other words, it is the distance at which the water quality standard for the most threatened sensitive area will be met in the diluted effluent itself.

Thus one can trace, for instance on a transparent rhodoid, for each numerical series of the 5 parameters mentioned above an oriented octagon (figure 5) for which the distance between each peak from the centre represents, at the scale of a sea chart, the minimum distance that must be kept between the discharge point and the limit of a sensitive area, whose standard as regards the critical pollutant was the basis for the computation for the dilution objective for that pollutant.

In order to define àn acceptable discharge point, represented by the centre of the octagon, it is sufficient to place this centre on the bathymetric curve of the sea chart corresponding to the depth of discharge for which the octagon was traced while respecting the geographic orientation of the octagon and provided that the internal surface of the polygon does not encroach upon the surface of the sensitive area to be protected.

The discharge flows, for which the octagons have been drawn and which are given next to them, correspond to the minimum flows for which the effluent rises to the surface as a function of the theoretical computations of the thermocline. If, all other things being equal, the discharge is higher than this minimum, one must determine a larger octagon that would correspond to that flow. One could accomplish this either by using the EMMA models or more simply by one of the methods given in the previous chapters.

SAEL comprises moreover three series of graphs (figures 2 to 4) which furnish for each of the meteorological sectors into which the coastal section was divided:

- the depth of effluent trapping,
- the dilution at the level of trapping
- the plume diameter at the level of trapping

in relation to flow, depth of discharge and initial jet velocity.

Let us mention here, without entering into details, that to another type of coast characterised by an underwater shallow will correspond another type of graphs and tables derived from similar principles but not exactly identical, since in that case there will be no risk of effluent trapping by the thermocline; in that case one must set a different limiting condition for the distance from the discharge point, for instance maximum length or cost ceiling for the outfall(s).

Let us add that, although the SAEL methodology was developed primarily for the establishment of limit receiving capacities of coastal sections (for a relatively low cost but also a rather rough approximation of results), it can also be used, if SAEL has already been developed for a particular coast, at no cost whatever, in order to trim down the search for a site suitable for the installation of an outfall and the particular design features of an individual outfall project.

The SAEL methodology, if not accompanied by a field survey of the local marine environment, cannot give precise results; however, it has the advantage over the other graphical method given in Appendix D of incorporating in the graphs a theoretical study of the real thermocline on the basis of the local meteorological statistics, whereas the general graphs in Appendix D incorporate only a schematic linear thermocline.

Each one of these methods has its own specific applications.

This is then a very brief summary of the principle of the methodology which can be called "extensive" in the sense that it can cover large coastal areas without any thought of applying it to immediate projects.

It has been described in detail in many published studies to which one can refer if additional information is needed.

METEOROLOGICAL ZONE X . . . .

YHEJ = 20.0 M Q0/N = 0.046 M3/S.UH PAN = 62.5

10-PORT DIFFUSER - TOTAL FLOW:0,460 m^3/s, objective of dilution:10.000

	VENT (M/S)	DISTANCE (M)	V SUPER (M/S)	LARGEUR (M)	HAUTEUR (M)	ME	DANZHO	TEMPS (S)	DIF	BAC	DIL.OCO	DIL.BAC
N	2.50	720.	0.027	2191.	0.52	2.091	[illegible]	29100.	1.	101.	82.	10000.
M	0.0	610.	0.0	*********	0.61	10.037	[illegible]	29100.	1.	101.	82.	10000.
E	4.36	910.	0.050	1491.	1.36	0.575	[illegible]	21532.	3.	53.	105.	10070.
SE	5.51	960.	0.057	1200.	2.56	0.350	[illegible]	17425.	6.	29.	250.	10120.
S	5.05	970.	0.050	1109.	2.05	0.470	[illegible]	19285.	9.	39.	291.	11307.
SO	0.0	610.	0.0	*********	0.61	10.037	[illegible]	27100.	1.	101.	82.	10000.
O	9.35	1090.	0.093	750.	5.63	0.185	[illegible]	11721.	35.	11.	935.	10451.
NO	6.00	955.	0.060	1202.	1.81	0.500	[illegible]	19105.	[illegible]	41.	255.	10000.

10-PORT DIFFUSER - TOTAL FLOW o,460m^3/s, objective of dilution:200.000

	VENT (M/S)	DISTANCE (M)	V SUPER (M/S)	LARGEUR (M)	HAUTEUR (M)	ME	DANZHO	TEMPS (S)	DIF	BAC	DIL.OCO	DIL.BAC
N	2.50	1187.	0.025	3160.	0.30	1.130	[illegible]	56470.	1.	3210.	82.	200000.
M	[illegible]	[illegible]	[illegible]	*********	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	82.	200000.
E	4.36	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	190.	527.	[illegible]
SE	5.51	1735.	0.057	1705.	5.61	0.250	[illegible]	31000.	10.	410.	700.	200007.
S	5.05	1670.	0.050	1897.	3.05	0.290	[illegible]	32867.	11.	262.	703.	205600.
SO	0.0	892.	0.0	*********	0.55	11.000	[illegible]	56470.	1.	3210.	82.	200000.
O	9.35	2596.	0.093	1120.	9.37	0.090	[illegible]	26025.	29.	113.	1813.	205645.
NO	6.00	1655.	0.060	1960.	3.52	0.122	[illegible]	36190.	11.	302.	712.	214781.

Fig 1

METEOROLOGICAL SECTOR : X . . . .

STUDY OF DISCHARGE IN STRATIFIED WATERS, DEPTH OF TRAPPING AS A FUNCTION OF THE FLOW, THE DEPTH OF DISCHARGE AND INITIAL VELOCITY.

—— 25 —— Trapping depth for initial velocity of 2 m/s and for discharge at a depth of 25m

— — 25 — — Trapping depth for initial velocity of 0,5 m/s and for discharge at a depth of 25m

depth of the layer with constant temperature 12,2m

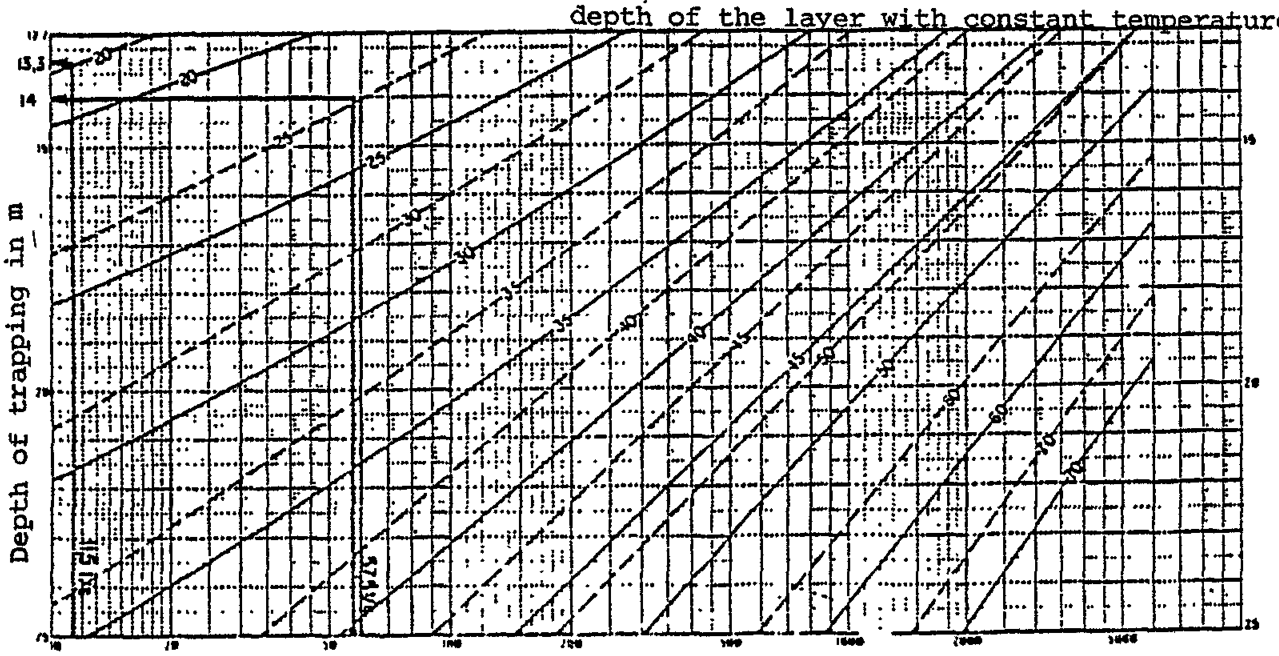


Fig. 2

Flow in 1/s

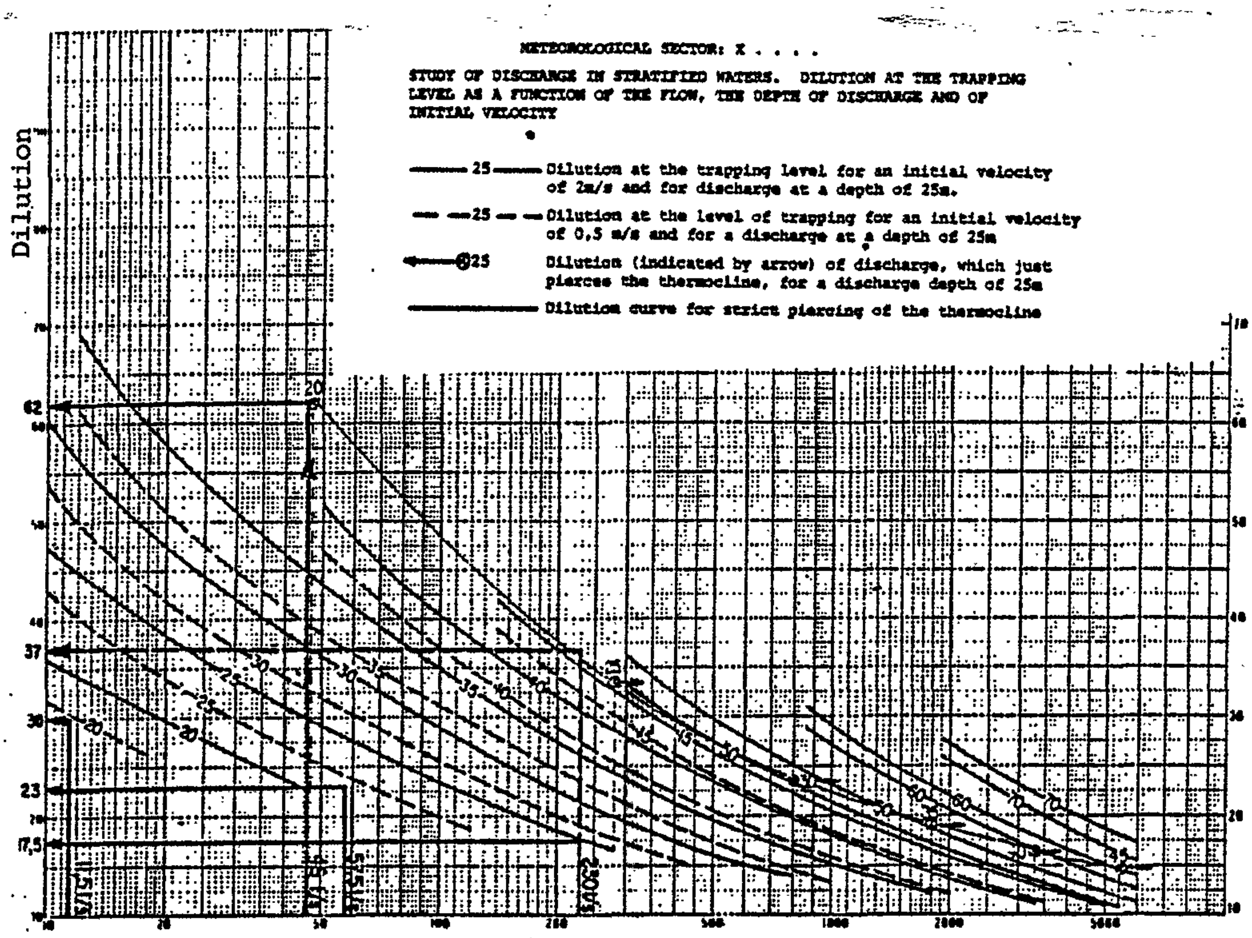

METEOROLOGICAL SECTOR: X . . . .
STUDY OF DISCHARGE IN STRATIFIED WATERS. DILUTION AT THE TRAPPING LEVEL AS A FUNCTION OF THE FLOW, THE DEPTH OF DISCHARGE AND OF INITIAL VELOCITY
25 Dilution at the trapping level for an initial velocity of 2m/s and for discharge at a depth of 25m.
25 Dilution at the level of trapping for an initial velocity of 0,5 m/s and for a discharge at a depth of 25m
25 Dilution (indicated by arrow) of discharge, which just pierces the thermocline, for a discharge depth of 25m
Dilution curve for strict piercing of the thermocline
Dilution
62
37
30
23
17,5
11,5 l/s
46 l/s
57,5 l/s
230 l/s
flow in l/s

Fig. 3

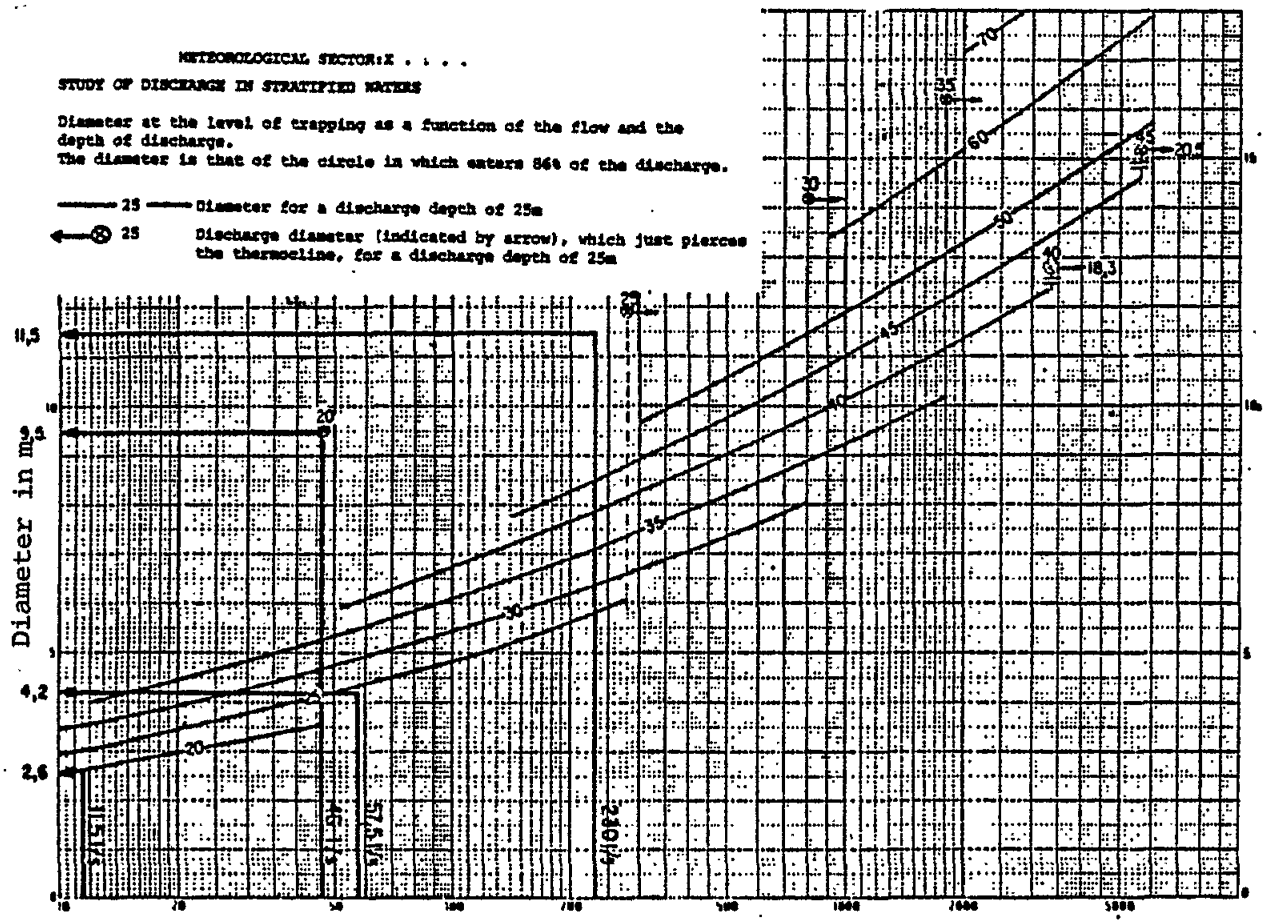
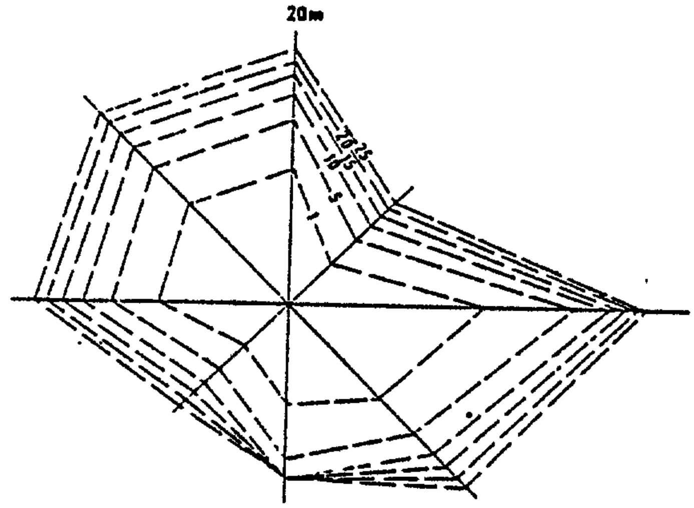

METEOROLOGICAL SECTOR: X . . . .
STUDY OF DISCHARGE IN STRATIFIED WATERS
Diameter at the level of trapping as a function of the flow and the depth of discharge.
The diameter is that of the circle in which enters 86% of the discharge.
25 Diameter for a discharge depth of 25m
25 Discharge diameter (indicated by arrow), which just pierces the thermocline, for a discharge depth of 25m
Diameter in m
11,5
9,5
4,2
2,6
20,5
18,3
11,5 l/s
46 l/s
57,5 l/s
230 l/s
flow in l/s

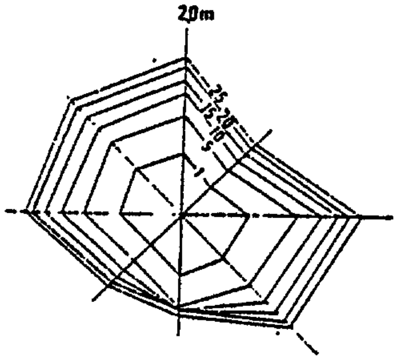
Fig. 4

METEOROLOGICAL ZONE X......

——— Objective of dilution 10.000

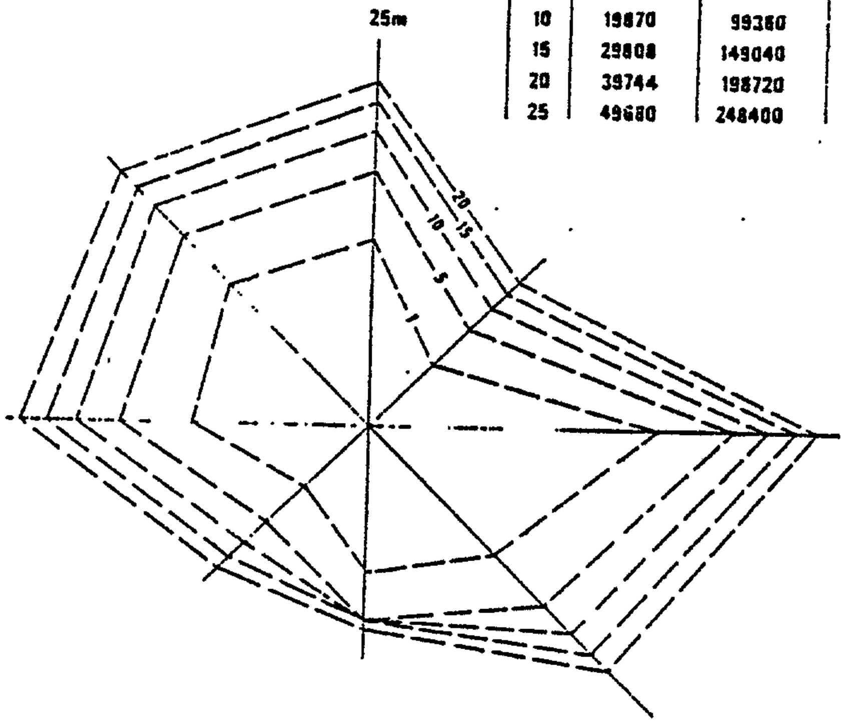
— — Objective of dilution 200.000

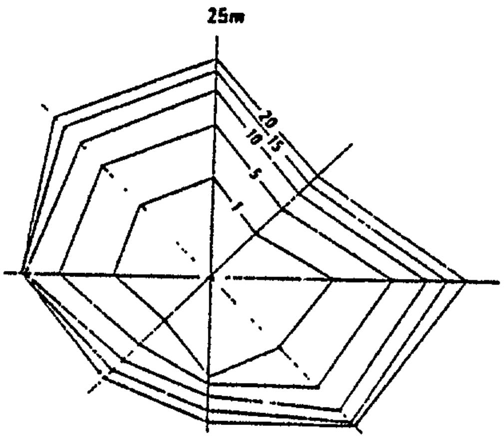




YR=20m Qmax/n=46l/s Do=62

n	Qmoy. (m³/j)	Eq. hab.
1	1987	9936
5	9936	49680
10	19870	99360
15	29808	149040
20	39744	198720
25	49680	248400





YR=25m Qmax/n=280l/s Do=33

n	Qmoy (m³/j)	Eq. hab.
1	12096	60480
5	60480	302400
10	120960	604800
15	181440	907200
20	241920	1209600

Fig. 5

APPENDIX G

SOME IDEAS ON THE ESTABLISHMENT AND IMPLEMENTATION AT NATIONAL SCALE OF A THEORY FOR THE DISCHARGE OF SEWAGE INTO THE SEA

We devoted the previous parts of this study to a description of the methods by which one can determine the most favourable characteristics of the outfall for the discharge into the sea of sewage from a determined source.

In order to complete this study we are proposing to give here some general ideas on the organization and implementation at national scale of the regulatory and technical programme with a view to defining a general doctrine on discharge into the sea of polluted effluents.

The suggestions presented herein have been drafted primarily for the benefit of countries which have not advanced very far in dealing with the problem; thus they may be of lesser or no interest to the countries which have already defined their own theory on the matter. Therefore, each country can take only those elements that are useful.

Our approach comprises of necessity two parts:

- The establishment of the doctrine, an administrative task but based on technical data.

- The implementation of the doctrine in the field, a task primarily technical.

1. ESTABLISHMENT OF THE DOCTRINE

1.1 Administrative regulations

It is with this that the whole procedure should begin, since nothing can be imposed on a third party concerning effluent discharge into the sea if it is not based on legislative texts or on regulations having the force of law.

These texts, which may in certain cases be part of a more general existing body of legislation concerning fresh water and marine resources, shall establish a procedure for the issuance of permits for outfall discharge to the sea.

1.1.1 Procedure for the issuance of permits for marine discharge

This procedure must in all cases comprise the following:

a - The characteristics of the effluents to be discharged for which a permit is obligatory and those that are exempted from such obligation.

b - The contents of the application file that the petitioner must file with the administrative authority for the issuance of the permit.

c - The designation of the competent service for the examination of the application file.

d - The procedure for the examination and evaluation of the file.

e - The designation of the authority with the power to deliver discharge permits.

f - The establishment, in the form of a standard type of discharge authorisation, of all the indications that must appear in such an authorisation.

g - The conditions for the initial control and the periodic monitoring of the conformity of the outfall system and of effluent composition with the characteristics established in the authorisation.

h - The affirmation that the authorisation may be revised as well as the conditions for such revision, either on the initiative of the administration, or as a result of an application by the petitioner to modify the characteristics of the discharge.

i - The transitional regulations applicable in the case of outfalls existing prior to the promulgation of the regulations. The former shall as a rule comprise the obligation to declare within a determined period of time all existing discharge schemes and to submit a regularisation dossier identical to that mentioned in "b" above.

Concerning "c" and "e" above, it seems inevitable that, for the examination of the dossiers and for the issuance of discharge permits, a central administrative service and a central administrative authority respectively be appointed, since in most cases the petitioners will be the local political/administrative authorities and it would not seem proper that they be both the petitioner and the permit-granting authority.

The evaluation of the application for discharge authorisation and the issuance of the permit must both be based on the technical regulations which should allow the establishment of the limits to be imposed on effluent discharge into the sea.

1.1.2 Receiving capacity - Uses - Standards

In the past and for reasons of convenience, these regulations were based often on a uniform limitation on the concentration of the various pollutants (DBO, DCO, MES, N, P, detergents, toxic substances, etc.) in the effluent prior to discharge.

However, especially in cases where the sole limitation of the "concentrations", without any consideration for the "volumes" discharged, led to totally uninhibited "flows" of pollutants, it was soon recognised that such a regulatory context was totally inadequate and that only regulations based on the impact of discharge on the receiving marine environment could effectively ensure its protection.

The result was to develop the notion of the "receiving capacity" of the marine environment for each of the potentially noxious pollutants and since this nocivity obviously varies with the "use" to which the environment is put, the appropriate regulations now comprise:

- The definition of "uses",

- The list of pollutants potentially noxious in the context of each use,

- The limit on concentration for each pollutant acceptable for each use. The contents expressed in terms of volume concentration constitute the "standards".

Even though one can easily think of quite a high number of "uses" for the marine environment, for most of them one cannot define quantitative standards; the result is that in most cases the uses officially regulated are the following two:

- Bathing
- Shellfish growing

This is then the minimum regulatory context necessary for every country which has taken the decision to protect its coastal waters against the risks of pollution from land-based sources.

In order to establish the various regulatory texts and define the uses and relevant standards, the countries concerned can, if they so wish, look into what has already been promulgated in this connection in the countries which have such regulations in force.

We refer especially to the bathing water standards established by the European Economic Community and the French standards for shellfish growing waters, as concerns the pollution measured by means of bacterial indicators, which were given as examples in Chapter 3, paragraph 3.10.1 above.

1.1.3 Remarks on the delimitation of "bathing areas"

In our opinion it would be useful, as concerns the esssentially microbial standards for the protection of the quality of sea water in the bathing areas, to discuss a gap due to recent developments in sports activities in inshore waters; intellectual honesty on the part of the national authorities entrusted with protecting public health would oblige them to examine this gap openly and take a responsible position; however, as far as we know, this does not generally seem to be the case in the countries which already enforce regulations concerning effluent discharge into the sea.

The problem is the following:

From the point of view of compliance with standards, at the present time "a bathing area" is defined (and exclusively admitted as such) as a narrow coastal strip (even though its width has never been established) adapted to the use of summer bathing on the part of vacationers who have none of the sophisticated navigational equipment.

However, at the present time, and especially in the most popular tourist resorts along the Mediterranean coasts which are blessed in the summer with a calm and warm sea, we have seen the introduction and considerable proliferation of sailboats and motorboats, water skiing, wind and body surfing; tomorrow there will be water motorcycles (which were recently announced) and everything else that the fertile (and not disinterested) imagination of sports equipment manufacturers will create. As a result, the geographical map showing the use of the sea on the part of vacationers becoming bolder by the day is no longer limited to a narrow coastal strip adjacent to the beach; it resembles rather (not without danger of course, but this is a different question) a huge flock of sheep occupying a vast and very wide "marine pasture area" to a distance from the coast definitely extending to the offshore end of most outfall pipes today, the maximum length of the latter being limited on account of both financial and technical constraints.

Since the length of outfalls is computed for the conditions described in the preceding chapters and in such a way as to ensure that the dilution of pollutants conform with standards at a distance from the emission point almost equal to the length of the pipe, it is quite obvious that, within a radius of the same order of magnitude as that around the discharge point, there can be no compliance with the standards, while the number of persons bathing within that circle may almost be equal to the number of those swimming quite close to the beach.

We must be honest and admit that the former category of users is "sacrificed" without even so much as a warning.

If the characteristics of the coast are such that allow the installation of the outfall in such a way as to make the area where the pollution is injected into the sea inaccessible to users, the disadvantage disappears; however, for many coastal fronts in the Mediterranean this solution is not available: very long stretches of coast are used continuously.

Certainly, it is generally admitted that the microbial risk incurred while bathing in polluted waters is not evident and very much lower than the risk incurred by eating polluted shellfish; however, if we adopt this reassuring point of view, we must come to the logical conclusion that one cannot justify the allocation of very considerable funds for the construction of a marine outfall system if it is going to protect (and while the usefulness of such protection is not proven) the majority at most but in no case all of those using the particular marine area.

If one refuses this line of thinking and adopts a cautious approach then one of two things will happen: either the outfall pipe must be given an enormous length which one will never be sure to establish in such a way as to be absolutely certain that it is adequate and which can never be implemented for technical as well as financial reasons; or one must fence off (and prohibit the entry to users) a circle around the discharge point which could reach several kilometres in diameter, something that would be unacceptable for political and phychological reasons.

One is then in the horns of a dilemma which must be solved by taking a courageous decision in order to put an end to the present contradictory situation, before the users themselves start acting on it (which has already happened in certain areas) and exploit it in a rather spiteful manner which would put the responsible authorities in an embarrassing situation.

It may seem peculiar to raise such questions on the risks for bathers, given that such risks are mainly of microbial origin and that they can theoretically be removed if one uses chemical disinfection.

In this connection we must refer back to what was said earlier in the study about the chancy and even deceiving character of chemical disinfection; it is this character that has prompted qualified public health officials to state that it is preferable to accept the microbial risk of bathing in waters where there is insufficient dilution of effluent (a risk that is not considered serious), than to have a sense of false security after carrying out chemical disinfection. On the other hand, if natural disinfection in storage tanks is possible then this would be a truly satisfactory solution.

2. IMPLEMENTATION OF THE DOCTRINE

This important parenthesis having been closed, let us move on to the phase where the national authorities of a country have in place the regulatory framework which enables them to control the effluents discharged into the sea.

In order to carry out the implementation of the programme proposed above, the next step will consist in defining the areas in which there will be mandatory monitoring of the quality of sea water, bathing areas, shellfish growing areas (and any other areas for which a similar decision will have been taken) and in establishing their borders.

Then a list of existing discharges must be drawn up, by applying for instance the regulations in point "i" of the procedure above; then one shall proceed to assessing the impact of effluents on the sensitive areas which are likely to come in their zone of influence.

From that point on, in order to meet the technical specifications of the files concerning marine outfalls, one should collect all the elements, especially meteorological, cartographical and hydrographical in order to determine the currents, the tides (if it is a tidal sea), the density stratifications and in general all the pertinent data listed in Chapters 2 and 3 above.

While this work of regularisation (and of closing down or modification) of existing outfall systems is going on, there may be requests for the examination of application dossiers for new outfalls.

Depending on their size, it may be necessary to carry out large or small scale surveys of the local marine environment.

The preceding chapters, aimed at giving all the indications on the way to proceed and especially on how to decide which method to use (more precise or less so) for the computation of the residual concentration of pollutants at the borders of the areas under protection.

If the problem to be solved goes beyond the case of single discharge or of a small number of individual discharge projects and concerns for instance a project for a large urban or industrial complex, then it may be useful to determine in advance the receiving capacity of the whole coastal section concerned, by using for example the SAEL method (an outline of which is given in Appendix "F" above), by which, it is possible, especially if the coast is free from construction as yet, rationally to establish a priori the most economical configuration of a system of outfalls taking the best advantage of the receiving capacity of the coastal section; it is on the basis of such a configuration that one can decide on where to locate the installations on land.

3. POSSIBLE NUISANCES - OTHER THAN MICROBIAL - FOR MAN AND FOR THE MARINE ENVIRONMENT

We have devoted the greatest part of this study to the monitoring of the quality of sea water from the point of view of the risk for man resulting from microbial pollution; we should not forget however that (a) the microbial risk is not the only one and (b) that the marine environment can itself be affected by the pollution discharged into the sea and thus must be protected against such pollution.

This means that for man and for the marine fauna one must look at the toxic elements, especially those that do not degrade in the sea and tend to accumulate in the living organisms according to the laws of their metabolism. For the marine flora there is the risk of eutrophication through excessive discharges of nitrogen and phosphorus containing nutrients in a confined ambient that one must monitor, but fortunately the critical circumstances for such a phenomenon to occur are rarely all present in open coasts.

Unfortunately, in both cases it is very difficult to come up with anything but partial rules; one can only recommend an examination of the problem on a case by case basis.

However, let us mention that in France there has been an experimental survey, both in a confined area (experiment Biolaigue) and in various marine sites, in an attempt to determine the flow of nutrients of the urban sewage type that a particular volume of sea water can digest without suffering any irreversible physico-chemical degradation.

Many successive campaigns led to the tentative conclusion that the acceptable flow limit of the urban sewage type is of the order of 1 gram per m^3 per day in the case of an experimental confined area which was deprived of any renewal of the water, thus under conditions that are more unfavourable than those generally prevailing at sea, but quite similar to those prevailing near the sea floor with no current and isolated by a very pronounced thermocline.

4. REMINDER OF SOME IMPORTANT POINTS AND WATCHWORDS

In conclusion we will recall some important points most of which have already been discussed in this document, as watchwords against methods or lines of reasoning at times established by custom but nonetheless erroneous.

4.1 The dilemma of chemical disinfection of effluents before discharge into the sea

Even if one accepts the idea that chemical disinfection of the effluent is not advisable when the use of the marine area to be protected is bathing (and it is an opinion held by more and more specialists), one is forced to admit that the same position cannot be adopted if a shellfish growing area is threatened by microbial pollution issuing from an outfall.

However, when one recommends (or even imposes) in this case chemical disinfection one should not ignore that one rests on false security and that the control of the effectiveness of the method by counting the faecal coliforms is particularly deceiving if a local epidemic breaks out in which case an exceptional discharge of pathogens would be discharged by the outfall under consideration.

The honest conclusion is that in order truly to protect the shellfish growing areas one should prohibit any discharge likely to reach them. Outside this radical solution, the risk will always exist, even if it should manifest itself rarely.

4.2 Should one favour or avoid in depth trapping of the effluents issuing from an outfall?

The problem is especially acute in the Mediterranean, where a pronounced density stratification of the water, permanent in summer season, is often associated with coasts sloping abruptly under water. Thus the two conditions of low depths (20 to 25m) and adequate distance from the discharge point are frequently incompatible. In this case, it is the second condition that must prevail. However, when one can avoid effluent trapping it is preferable to do so because of the very poor conditions of biodegradation of the organic matter under a thermocline which inhibits oxygen renewal and in the presence of nitro-phosphorous compounds which favour eutrophication.

In the Mediterranean these disadvantages are aggravated by both the absence of tides and the calm seas in the summer which create the conditions favouring effluent stagnation. Moreover, if land winds which are strong enough occur in the summer they cause destratification and rising to the surface (on the side of the land) of the polluted water mass.

In sum, the disadvantages of a trapped effluent prevail over the advantages. However, the picture can be reversed if one has the assurance that there are deep currents both permanent and adequate to renew the water around the pipe opening and to remove the discharge toward the open sea, something that happens in seas with a considerable range of tides.

During the course of an outfall study, if one wants to verify with a certain amount of precision the trapping risks, it may not be sufficient to use the simplified graphic methods, because all the graphs have been established on the basis of linearised vertical profiles of density, i.e. thermoclines with a constant gradient.

In extreme cases, the necessary precision can only be obtained by means of very sophisticated mathematical models into which one can introduce the most unfavourable real thermoclines measured in the field during the study of the marine environment.

4.3 Utilisation of the coefficients of turbulent diffusion

The computation of the dilution of the effluent during the phase of its horizontal transport from the point of emergence of the plume implies that one knows the value of two coefficients of turbulent diffusion: that of the transversal horizontal diffusion and that of vertical diffusion.

Now, measuring these two coefficients in the field is very chancy and the results vary greatly depending on the conditions of the sea (whether it is calm or not).

This is why it is good to remember that:

- The horizontal diffusion brings a very small contribution (no more than a factor of 2) to the total dilution that must be undergone by the effluent for which the factor to be attained is 10^4 to 10^6.

- Theoretically, the vertical diffusion contributes to dilution by a factor greater than that of the horizontal, but in practice it is limited by the fact that the critical entrainment direction is that which carries the plume landwards. Thus, the dilution by vertical carrier diffusion is limited, as is the vertical excursion of the mixture, by the depth of water which gradually decreases.

If we put those two effects together we see that in most cases the dilution varies between 5 and 20; thus it is often sufficient to assign to it a number estimated in advance and which will introduce an error which is negligible and in any event not as high as that which may result from field measurements that are difficult and quite unreliable.

As concerns the debate on whether the coefficients of turbulent diffusion are constant or variable, the famous law, which states that these coefficients vary by the power of 4/3 of the dimension of the phenomena, is only valid in isotropic three-dimensional geometry, in other words not limited vertically by a floor of low depth. Near the coasts, the dominant role is played by the friction both on the sea floor and that of the wind on the surface. Thus the diffusion coefficients are primarily governed by laws where the principal role is played by the internal shear. The result is that the vertical coefficient varies as a function of depth in the conditions depicted in graphs 22 and 23.

As regards the coefficient of horizontal diffusion it can be considered constant in terms of the distance in relation to the length of the outfall.

4.4 Law of bacterial decay

Simple mathematical formulae have been proposed with the claim that they take into account both hydraulic dilution and the decay of the bacteria themselves from the point of discharge on the sea floor.

Now this is a totally unrealistic integration of phenomena which, because they are governed by independant laws, are incommensurable.

In effect, hydraulic dilution depends solely on hydraulic data: flow, initial velocity, densities, turbulent coefficients, distances; the majority of them does not appear in the proposed formulae, whereas the self "die away" of bacteria, the mechanism of which is poorly understood, can only be linked to the decrease time by a classic law of the exponential type in a very general and rough way. Therefore, there is no relationship between these two types of phenomena and no one formula can express them simultaneously. The only valid procedure would be to calculate the dilutions by hydraulics methods and the bacterial decay on the basis of laws resulting from data collected in the field. Since the bacteria receive the two effects of the abatement of concentration, the factor of global abatement is the product of both.

B I B L I O G R A P H Y

B I B L I O G R A P H Y

1. 1959 - ELDER J.
The dispersion of marked fluid in turbulent shear flow - Journal of fluid mechanics - 5 (4) p. 544 to 560.

2. 1963 - ABRAHAM G.
Jet diffusion in stagnant ambient fluid
Delft Hydraulics Laboratory - Report No.29.

3. 1965 - LACOMBE
Cours d'Océanographie physique - Gauthier - Villars.

4. 1966 - NEUMAN - PIERSON
Principles of physical Oceanography - Prentice Hall Inc.

5. 1971 - ABRAHAM G.
The flow of round buoyant jets issuing vertically into ambient fluid flowing in a horizontal direction.

6. 1972 - ABRAHAM G.
Jets and plumes issuing in a stratified fluid
IAHR International symposium on stratified flows NOVOSIBIRSK.

7. 1972 - de ROUVILLE - RODIER - LAPORTE
Capacité d'acceptation du milieu récepteur marin et programmation de l'assainissement dans les zones littorales
(Commission internationale pour l'exploration de la Méditerranée - Athènes 1972).

8 1973 - Etude expérimentale No.1 sur la dilution des jets.
Rapport SOGREAH - R. 11473.

9 1974 - Auteurs divers
Discharge of sewage from sea outfalls (Actes du symposium international de Londres) - Pergamon Press.

10. 1974 - CHU et GOLDBERG
Buoyant forced plumes in cross flow
Journal Hydraulics Division - ASCE 100 (HY9) September.

11. 1974 - LEPETIT - SEBATON
Emissaires en mer : efforts exercés par la houle et le courant sur la conduite - Laboratoire National d'Hydraulique de Chatou - Rapport LNHH HC 042/74-50.

12. 1975 - Etude expérimentale No.2 sur la dilution des jet à la sortie des émissaires en mer. - Rapport SOGREAH R. 12011.

13. 1975 - Emissaires en mer - Memento de calcul des jets et panaches - SOGREAH.

14. 1975 - Pollution des zones littorales - Etude des phénomènes hydrauliques de dispersion des polluants - Rapport SOGREAH R. 12320.

15. 1975 - Hydrodynamique des écoulements créés par le vent en zone côtière. Rapport SOGREAH R. 11980.

16. 1976 - GAUTHIER - QUETIN
Utilisation des traceurs pour les études d'implantation des émissaires en mer - La Houille Blance No. 3-4.

17. 1976 - Emissaires en mer - Calcul pratique des diffuseurs - Memento SOGREAH.

18. 1976 - Ministère de l'Equipement.
Introduction à l'étude des schémas d'Amélioration des Eaux Littorales - M. de ROUVILLE.

19. 1977 - Ministère de l'Equipement.
Schéma d'Amélioration des Eaux Littorales : rejets en milieu stratifié - M. de ROUVILLE.

20. 1977 - Mesures de la diffusion turbulente en mer à :

Toulon - Rapport SOGREAH R. 12669
Calvi - Rapport SOGREAH 35.0554 R1
Bastia - Rapport SOGREAH 35.0554 R2

21. 1977 - GAUTHIER - QUETIN
Modèles mathématiques de calcul des écoulements induits par le vent - AIRH - Congrès de Baden-Baden.

22. 1978 - GRACE
Marine outfall systems - Prentice Hall Inc.

23. 1978 - RODIER
L'Analyse de l'Eau - DUNOD.

24. 1979 - FISHER - LIST - KOH - IMBERGER - BROOKS
Mixing in Inland and Coastal waters - Academic - Press.

25. 1980 - Rejets en mer - Memento de calcul de la disparition des bactéries - SOGREAH.

26. 1980 - de ROUVILLE - CHEVEREAU - QUETIN
Utilisation de modèles mathématiques dans la mise au point d'une méthodologie de calcul de la capacité d'acceptation du milieu récepteur littoral marin (programm Water Technics. Vol.12 No.1 - Pergamon Press 1980).

27. 1981 - Mesures de la diffusion turbulente en mer. Rapport de synthèse - SOGREAH.
Rapport SOGREAH 35 0554 R3

28. 1982 - LAPORTE - De ROUVILLE - RODIER - RODI
Approche expérimentale de la capacité d'acceptation du milieu marin pour la charge biodégradable des eaux usées urbaines.
"Techniques et Sciences Municipales" - Janvier 1982.

29. 1983 - QUETIN
Modèle mathématique de simulation de la turbulence - Destruction par le vent des stratifications densimétriques.
(AIRH - Moscou 1983).