PROTECTING AN ESTUARY FROM FLOODS — A POLICY ANALYSIS OF THE OOSTERSCHELDE

VOL. V, ANAEROBIC CONDITIONS AND RELATED ECOLOGICAL DISTURBANCES

PREPARED FOR THE NETHERLANDS RIJKSWATERSTAAT

J. H. BIGELOW, J. C. De HAVEN

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PREFACE

In February 1953, a severe storm from the North Sea flooded much of the Delta region of the Netherlands, inundating 130 thousand hectares and killing several thousand people. After this disaster, the Dutch government decided to greatly increase the region's protection from floods by constructing a system of dams and dikes, called the Delta Works, in all the Delta estuaries. By the mid-1970s, this protective construction had been completed, or was well under way, in every Delta estuary except the largest—the Oosterschelde. In the Oosterschelde, the construction work had barely begun before it was interrupted by controversy.

The original plan for protecting the Oosterschelde had been to construct an impermeable dam across the nearly 9-km-wide mouth of the estuary, thereby closing off the estuary from the sea, and then to turn the resulting basin into a freshwater lake. This, however, threatened the Oosterschelde's extremely rich and rare ecology and its thriving oyster and mussel fishing industry. As the time approached when the construction in the Oosterschelde would cause major changes, the original plan provoked strong opposition among people with a special interest in protecting the fishing industry or preserving the natural environment. For people primarily interested in safety, however, the original plan continued to receive strong support.

In 1974, in response to the growing controversy, the Dutch Cabinet directed the Rijkswaterstaat, the government agency responsible for water control and public works, to study an alternative approach—the construction, in the mouth of the Oosterschelde, of a special kind of dam called a *storm-surge barrier*. Basically, the storm-surge barrier was to be a flow-through dam containing many large gates. In a severe storm, these gates would be closed. Under normal conditions, they would be open to allow a reduced tide—somewhat smaller than the original—to pass into the Oosterschelde basin from the sea. The size of the reduced tide is governed by the size of the aperture in the barrier.

The Cabinet specified two conditions for accepting any plan for a storm-surge barrier: First, as in the original plan, the storm-surge barrier was to provide protection against a storm so severe that it might be expected to occur only once in 4000 years.[1] Second, it had to be possible to complete the barrier by no later than 1985 for no more than a stipulated cost. If these conditions could not be met, the original plan would, supposedly, be implemented.

Some opponents of the original plan were fearful that the storm-surge barrier, with its reduced tide, might also seriously damage the fishing or the ecology, even though it met the specified conditions. They pressed for yet another alternative—an open plan, where the mouth of the Oosterschelde would be left open to maintain the original tide and a system of large dikes would be built around its perimeter to protect the land.

In effect, three alternative approaches were proposed, either formally or informally, for protecting the Oosterschelde: closing it off completely, as in the original

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[1] Such a storm is called a 1/4000 exceedance frequency (or excess frequency) storm, because the frequency with which it might occur would not exceed 1/4000 per year.

plan; leaving it open and building large new dikes; or constructing a storm-surge barrier. Each approach, of course, had many possible variations; the storm-surge barrier, for example, could be built with different aperture sizes, each size producing a different reduction in the tide and hence a potentially different effect on the Oosterschelde's ecology.

It soon became clear that the process of comparison and choice among the Oosterschelde alternatives would be very difficult, for their potential consequences were many, varied, and hard to assess. To aid the decisionmaking process, the *Policy Analysis of the Oosterschelde (POLANO) Project* was established, in April 1975, as a joint research project between Rand (a nonprofit corporation) and the Rijkswaterstaat.[2]

The project began with one year of analysis, during which each organization spent about eight man-years of effort on joint research, concentrating on different but complementary tasks. Rand's primary task was to help develop and then apply a methodological framework for predicting the many possible consequences of the alternatives; most of these consequences were expressed in disparate units (e.g., money versus ecology) and some were impossible to quantify (e.g., aesthetics).[3] The Rijkswaterstaat's primary tasks were, on the basis of special engineering and scientific studies, to develop a specific design for each alternative approach, to analyze the consequences of the designs in which they had special expertise (e.g., the effects on salinity), and to provide data, as well as assistance, for the methodology being developed with Rand.[4]

The Rijkswaterstaat developed three alternative cases to analyze in the POLANO project: the closed, open, and storm-surge barrier cases. These cases embody the three alternative approaches for protecting the Oosterschelde but specify several additional features—the most important being the *compartment design*, which gives the location of the compartment dams.

Two compartment dams are incorporated in each case to aid water management and to provide tide-free navigation (required by treaty with Belgium) for the ship canal passing through the rear of the Oosterschelde. One dam merely blocks off the Oosterschelde from the Volkerak Krammer, and has the same location in all three cases. The other dam separates the Oosterschelde into two basins: a *Western Basin* located close to the mouth and an *Eastern Basin* located close to the other end. Different locations for this second dam produce different compartment designs and different Eastern Basin sizes. In *compartment C-4*, the dam is located near Wemeldinge, where it produces a larger Eastern Basin than that in compartment C-3. In *compartment C-3*, the dam is located considerably closer to the rear of the Oosterschelde, where it produces a smaller Eastern Basin.[5] In both compart-

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[2] Rand had had extensive experience with similar kinds of analysis and had been working with the Rijkswaterstaat for several years on other problems.

[3] Other Rand tasks were to help the Rijkswaterstaat staff coordinate their various study activities on the Oosterschelde by showing interrelations and identifying data problems, and by making them familiar with policy analysis techniques by participating in joint research.

[4] The Rand contract was officially with the Delta Service of the Rijkswaterstaat, which had direct responsibility for the Oosterschelde protection. The Rijkswaterstaat members of the POLANO project came from the Delta Service, the Information Processing Service, and the Economics Department of Rijkswaterstaat Headquarters. Other Rijkswaterstaat services and directorates provided data, consultation, and suggestions.

[5] The name of the dam that produces the Eastern Basin depends on its location. In compartment C-4 it is called the Wemeldingedam and in C-3 the Oesterdam.

ments, the Western Basin remains salt water while the Eastern Basin becomes fresh water.

In the *closed case*, the mouth of the Oosterschelde is completely closed with a dam, while the existing dikes are left basically unchanged. Compartment C-4 produces the larger Eastern Basin, which, in contrast with the original plan, is the only part of the Oosterschelde that becomes a fresh-water lake.

In the *open case*, the mouth of the Oosterschelde is left open, but its perimeter is surrounded by large new dikes, similar to those designed by the Province of Zeeland to withstand a 1/4000 excess frequency storm. Compartment C-3 produces the smaller Eastern Basin.

In the *storm-surge barrier case*, a storm-surge barrier[6] with an aperture of 11,500 sq m is constructed across the mouth of the Oosterschelde; this aperture reduces the tide to about two-thirds of its original value. To increase the protection during the period before the barrier can be completed, the height of the existing dikes is raised to a level that the Rijkswaterstaat believes adequate to resist a 1/500 excess frequency storm while the mouth of the Oosterschelde remains open. Compartment C-3 produces the smaller Eastern Basin.

For the alternative cases, POLANO analyzed and compared many different consequences. Indeed, even the categories for these consequences, which we shall henceforth call "impacts," are very numerous. They include the *security* of people and property from flooding; the *financial costs* to the government from the construction and operation of the works; the changes in the kinds and populations of species that constitute the *ecology* of the region; the additional employment and other *economic* impacts that occur not only in industries directly involved in the construction of the barrier but also indirectly in other interrelated industries; the quantity and quality of the *water supply* available in various locations; and various *social* impacts, including the displacement of households and the disproportionate effects on the Zeeland economy.

In addition, POLANO performed a number of sensitivity analyses to see how the impacts would change with variations in the design of the cases and in certain assumptions. These variations included different aperture sizes for the storm-surge barrier and different assumptions about the recreational investment policy for the Oosterschelde region.

On April 5.1976, one year after POLANO began, Rand presented a final report in the form of an all-day briefing at the Rijkswaterstaat Headquarters; this briefing described the methodological framework that had been developed and summarized the results of the POLANO analysis. After this, Rand helped the Dutch members of the POLANO team synthesize the jointly obtained POLANO results with the results of several special Rijkswaterstaat studies. This work became the foundation of the Rijkswaterstaat's May 1976 report, *Analysis of Oosterschelde Alternatives*, that was presented first to the Cabinet and then to Parliament, along with the Cabinet's recommendation for a decision. Based on the Rijkswaterstaat report, the Cabinet recommended the storm-surge barrier case to Parliament, which accepted it in June 1976. (The Parliament also requested additional analysis by the Rijkswaterstaat to establish the best aperture size for the barrier.)

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[6] In the design concept selected by the Rijkswaterstaat, the barrier receives its vertical support from large pillars founded on top of pits, a kind of piling driven deep into the Oosterschelde bottom. This barrier concept has been called "pillars on pits."

The methodology and results of the POLANO project are described in a series of Rand reports entitled *Protecting an Estuary from Floods—A Policy Analysis of the Oosterschelde.*

Volume I, *Summary Report* (R-2121/1), describes the approach and summarizes the results of the complete analysis. It presents and compares, in a common framework, the many impacts of the different cases. It also shows how these impacts vary with changes in the designs of the alternatives and in certain assumptions.

Volume II, *Assessment of Security from Flooding* (R-2121/2), describes the methodology that was developed to estimate the likelihood and severity of flood damage in the Oosterschelde region. It also presents a detailed analysis of the security offered by the three cases in both the long-run and the construction period, showing how security varies with changes in the alternatives and assumptions.

Volume III, *Assessment of Long-Run Ecological Balances* (R-2121/3), describes how the abundances of the Oosterschelde's different species would change in the long run with variations in the alternatives and certain assumptions; the variations include different apertures for the storm-surge barrier, different sizes for the Western (salt) Basin, and different rates for fishing and detritus import. The report also discusses in detail the ecology model that was developed using mathematical concepts new to ecology. In addition, the report presents the results of our attempt to validate the model: For Grevelingen, an estuary adjacent and similar to the Oosterschelde, the model's abundance estimates were compared with observations made both before and after Grevelingen's tide was reduced to zero by its 1971 transformation to a salt-water lake.[7]

Volume IV, *Assessment of Algae Blooms, A Potential Ecological Disturbance* (R-2121/4), describes a mathematical model that was developed to estimate the risk of algae blooms and presents the results that were obtained by applying the model to the present Oosterschelde and the different cases. When algae have a large population increase, from favorable conditions, the resulting bloom may seriously reduce the dissolved oxygen levels in the water. This, in turn, can cause the death of desirable fish and also produce bad odor. Because an upper bound on the risk of algae blooms is desired, the model uses linear programming techniques to predict the maximum algae biomass that could occur, subject to various constraints on growth (such as the availability of several nutrients).

Volume V, *Anaerobic Conditions and Related Ecological Disturbances* (R-2121/5), describes a mathematical model that was developed for estimating the potential for anaerobic conditions in an Eastern Basin and applied to the different cases. Oxygen-free (anaerobic) water is created in the Eastern Basin during its conversion from salt water to fresh water. By interfering with the normal action of certain bacteria, this oxygen-free water causes bad odors and murky water. Using the model, this report shows that the large and small Eastern basins—and thus the cases that contain them—differ greatly in their potential for anaerobic conditions and related disturbances.

Volume VI, *Selected Social and Economic Aspects* (R-2121/6), considers a variety of impacts for the different cases. These include the effect on jobs and value

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[7] An *Addendum* to Vol. III, published subsequently, will present the raw data on species abundances that were used to calibrate the model.

added in the fishing industry; the changes in recreational opportunities and demand; the savings to the carriers and customers of the canal shipping industry; the total (direct plus indirect) changes in production, jobs, and imports for the 35 industrial sectors of the national economy; and, finally, as social impacts, the displacement of households and activities, and the disproportionate effects on the Zeeland economy.

Several comments about this series of reports should be noted. First, although formally published by Rand, the series is a joint Rand/Rijkswaterstaat research effort; whereas only a few of the reports list Dutch coauthors, all have Dutch contributors, as can be seen from the acknowledgment pages.

Second, the methodology and results described therein are expanded and refined versions of those presented in the April 1976 final-report briefing. The improvements in methodology and results have come not only from the leisure to experiment and reflect, but also from exposure to Rand's rigorous review process; each report has been reviewed by at least two, often three, technical reviewers who are unaffiliated with the POLANO project.

The present report, Vol. V in the POLANO series, considers the possibility that oxygen-free (anaerobic) water will be created in the Eastern Basin by flora and fauna that were killed during its construction. This oxygen-free water can lead to several ecological disturbances during the time the Eastern Basin is being converted into a fresh-water lake. Without certain bacteria that need oxygen, the decay of the dead organisms produces bad odors and murky water and retards the growth of organisms suited to the fresh-water environment.

This report describes a mathematical model that was developed for estimating the potential for anaerobic conditions in an Eastern Basin, shows how this potential varies with the velocity of the wind and the size (and other characteristics) of the basin, and then identifies anaerobic safety conditions for the desalinization of both a large and a small Eastern Basin. It is shown that the potential for anaerobic conditions and related ecological disturbances is very different in the large and small Eastern basins.

SUMMARY

During creation of one or another of the fresh-water basins associated with construction being considered in the Oosterschelde in the Netherlands, oxygen-free water may be produced during the change from salt to fresh water as the rearward basin is dammed off from the rest of the estuary. Anaerobic conditions in the water and bottom of these basins can result from the sudden death of flora and fauna, especially on the bottoms, as the fresh-water basin is created. The decay of dead organisms under these conditions results in highly objectionable odors and retards the growth of organisms suited to the fresh-water environment.

Two sizes of such fresh-water basins have been considered, depending upon whether the compartment-dividing dam is constructed to the rear, close to the Rhine-Schelde Canal, or further forward, near Wemeldinge. In the latter designs, the fresh-water basin is considerably larger and deeper than in the former case.

An analysis of the possibilities for anaerobic conditions for the two basins uses models that include parameters relating to wind velocities, fetch, water depth, and water viscosities for each average month of the year. Those conditions establish the rapidity with which the water can be reoxygenated by the atmosphere in these shallow basins. The reoxygenation rates are compared with rates at which bacteria require oxygen from the water to remineralize the dead flora and fauna. When oxygen is not available for this purpose, mechanisms of decay create bad odors.

The analysis of this report, using the pertinent features of the two basins and the appropriate average meteorological conditions associated with each month, indicates that anaerobic conditions are not likely to occur in the smaller basin, regardless of its month of closure. However, sustained below average wind velocities could cause transient anaerobic conditions if this basin is desalinated in the summer. Anaerobic conditions are likely to be encountered if the large lake is closed off during the months of June through September. If this condition is to be avoided, then closure must be undertaken well before or after this season. An alternative is to be prepared with extensive mechanical aeration equipment to supplement natural aeration should it be necessary to close off the larger basin and freshen it during the summer months. This propensity of the larger basin toward anaerobic conditions is a definite point in favor of compartment plans that involve only the smaller basin.

In situ measurements of mineralization rates for dead bottom organisms are sorely needed to improve the reliability of predicting anaerobic conditions. Measurements of monthly bottom biomass concentrations in the affected regions are also required.

ACKNOWLEDGMENTS

The authors are indebted to their Dutch colleagues J. C. H. Peeters and B. A. Bannink of the Environmental Division of the Rijkswaterstaat's Delta Service for assistance in this study. Peeters brought the problem of potential anaerobic disturbances to our attention and helped to set the focus of the analysis. Bannink not only assisted with the compilation of necessary environmental input data, but also made useful suggestions for improving the content and clarity of an early draft of this report.

The draft report was also reviewed by our colleagues at Rand, D. S. K. Liu and P. F. Morrison. They both made highly useful suggestions for improving the accuracy and lucidity of the final report. We are also grateful to H. B. Turin for carefully editing and guiding this report through the publication process.

CONTENTS

Chapter 1

INTRODUCTION

During creation of one or another of the fresh-water lakes associated with construction being considered in the Oosterschelde, the possibility arises that oxygen-free (anaerobic) water will be created as rearward lakes are dammed off from remaining portions of the basin (which are to be maintained saline). Many salt-water organisms are unable to survive in fresh water. The sudden death of flora and fauna, especially on the bottom, as these fresh-water lakes are created can cause the water to lose its oxygen. The decay of the dead organisms without certain bacteria that need oxygen results in highly objectionable odors and murky water, and retards the growth of organisms suited to the fresh-water environment.

We have considered two classes of fresh-water lakes, depending upon whether the compartment-dividing dam is constructed to the rear, close to the Rhine-Schelde Canal, or further forward, near Wemeldinge. In the latter designs, the lakes are considerably larger and somewhat deeper than in the former case and may be subdivided in a complex fashion to preserve water quality.

The desalinization of the lakes that starts immediately after closure may take place rapidly (through special management procedures) or slowly (through natural replenishment by fresh water) [1]. Most organisms have a range of tolerance for salinity and die only when exposed to waters below this range, not continuously in phase with the salinity as it is gradually reduced. The rate of desalinization is not at issue. Rapid introduction of fresh water with its dissolved oxygen may in fact partly ameliorate the trend toward the undesirable anaerobic conditions.

The creation of fresh-water lakes in previous salt basins is sufficiently unusual that few studies have been made of the transition phenomena, especially of mechanisms that permit the construction of predictive ecological models. We have therefore been forced to use data and models not entirely suited to the situations that may occur during the creation of one or another of the fresh-water lakes. To compensate for the predictive uncertainties, we have attempted to make conservative assumptions and examine worst-case anaerobic disasters.

Chapter 2

GENERAL ECOLOGICAL FACTORS AND ASSUMPTIONS

When organisms die in a natural environment, biochemical decay starts immediately and ultimately results in minerals that are used as nutrients by primary producers or that become entrapped in geological formations. This highly important process is called "mineralization" or "remineralization." Bacteria and similar microorganisms play a crucial role in mineralization by producing enzymes and other biochemical pathways and environments for the organic degradation process.

Different mineralization pathways exist in aerobic and anaerobic environments. Generally, the aerobic pathways yield unobjectionable, ecologically useful products; the output of anaerobic pathways, if not subject to subsequent oxidation, can be aesthetically unpleasant in odor and appearance and sometimes toxic. Therefore, it is desirable to prevent the environments in which mineralization takes place from losing oxygen.

Sources of oxygen to be used in mineralization in the aquatic environment are (1) absorption from the atmosphere, (2) dissolution in input waters, and (3) production *in situ* by photosynthetic organisms. Sinks for oxygen are (1) mineralization; (2) respiration, growth, and reproduction of organisms; and (3) entrapment in sediments or return to the atmosphere. In most natural environments these sources and sinks have reached a balance. When these balances are perturbed by man's activities, however, an ecological disaster may occur. Compartmentation and the creation of fresh, still lakes will affect all of the oxygen balances mentioned above to different degrees.

We hope to show that the amount of dissolved oxygen contained in input water will be small relative to demand during crucial periods and that production from photosynthetic organisms will be insignificant under the expected conditions of changes in salinity, because salt-loving phytoplankton crops will have died off and brackish or fresh-water varieties will not yet have appeared. Amounts of oxygen required for respiration, growth, and reproduction will be small because mobile organisms will move away, following favorable salinities, and sessile organisms will be dead or dying. Oxygen trapped in sediments will also be small during the crucial period. Our model will consider the return of oxygen to the atmosphere, even though this will be reduced because the oxygen content of the water is lowered. Reaeration by absorption of oxygen from the atmosphere is the remaining important source, and mineralization and oxygen loss to the atmosphere are the important sinks for oxygen. We therefore examine the balances between this source and these sinks for oxygen to determine if the oxygen level becomes too low as various conditions occur during the months when desalinization may be brought about.

2.1. REAERATION RATE

The rate of reaeration of water by oxygen from the atmosphere depends upon such factors as the concentration of oxygen already in the water; physical circulation of the water as caused by flow, tides, or wind; surface roughness; temperature; and salinity. A discussion of the mechanical details of reaeration is beyond the scope of this report. Extended treatments of the subject may be found in Refs. 2 and 3. Because of this complexity, there are no generalized models of reaeration that permit computation of oxygen input rate from the atmosphere for all bodies of water. Rather, available models are mostly specific for a particular type (e.g., river, tidal estuary, or still lake) and use parameters derived from empirical observations of similar bodies. The bodies of water of greatest concern here have predominantly wind-induced water circulation, and circulation caused by flow will be of lesser importance. A model for reaeration of water bodies of this nature is, therefore, adapted from Ref. 2 for computation of the reaeration rate for the several configurations of shallow lakes of this type.

The reaeration coefficient, r, may be defined according to a large number of empirical observations as

$$r = 29G^{2/3}/H. \tag{2.1}$$

Here r is the reaeration coefficient in days^{-1}, G is the mean temporal water velocity gradient in seconds^{-1}—i.e., dv/dz averaged over both time and space. H is the mean or hydraulic depth of the receiving water in feet. In bodies of water like those of interest here, winds sweeping over water surfaces create the zone of circulation. Here, we may consider a strip of water of unit width and of length F in the direction of the wind and call the velocity of the wind-induced water currents pW, where W is wind velocity and p is the proportionate surface velocity of the water. The square of the mean temporal velocity gradient [2] becomes:

$$G^2 = 9.3 \times 10^{-3}(pW)^3/(\mu gF), \tag{2.2}$$

where W (wind velocity) is in miles per hour, F (the fetch) is in miles, μ (absolute viscosity) and g (acceleration of gravity) are in ft-lb-sec units,[1] and G is in seconds.

To compute both p, the proportionate surface water velocity with respect to wind velocity, and D, the depth of frictional resistance, the classic empirical formulas of Ekman are used. According to [2] these are,

$$p = V_0/W = 0.0127/\sqrt{\sin \phi}, \tag{2.3}$$

$$D/W = 11.1\sqrt{\sin \phi}, \tag{2.4}$$

where ϕ is latitude in degrees, V_0 (surface water velocity) and W are in miles per hour, and D is in feet. For the Dutch latitude, 52° N, $p = V_0/W = 1.43 \times 10^{-2}$, and D, the depth of frictional resistance, is always greater than the average, actual depths of water in the lakes, so these latter are determining. The more general equations from which Ekman's were derived take into account the influence on surface water velocity of both the deflecting force of the earth's rotation and the eddy viscosity. In the form given above, the results are applicable only to conditions in the Northern Hemisphere. (In the Southern Hemisphere sin ϕ is negative, therefore D is imaginary. For a solution valid in the Southern Hemisphere, the

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[1] Inasmuch as values of r, the reaeration coefficient we wish to compute, are independent of units, we did not convert these formulas as given in [2] to metric units.

direction of the y-axis in the derivation must be reversed.) These formulas are empirical in that values for certain parameters present in the original general equations were obtained from empirical observations. Note that the influence of temperature on the reaeration coefficient is imposed through its effect on water viscosity in Eq. (2.2).

2.2. MINERALIZATION RATE

We are concerned not only with the total biological oxygen demand (BOD) but with the rate at which this demand occurs because, as will become apparent, the load of organic material to be presented for mineralization far exceeds the store of oxygen normally occurring in the overlaying water. As is the case for reaeration, there are no generalized models that may be used to compute mineralization rate. Rather, rates of mineralization vary widely with such factors as temperature; age, type, and source of organic load; concentration of proteolytic microorganisms; salinity; and whether mineralization takes place in the pelagic zone or within sediments in the bottoms. The rates of mineralization within the pelagic zone are more than an order of magnitude faster than when mineralization takes place within bottom sediments.

All of the quantitative studies of mineralization we have found have been undertaken in the context of water pollution from sewage wastes, mostly as discharged into rivers [4,5,6]. We have adapted the results of these empirical studies to evaluate the mineralization and oxygen demand rate that will result from the death and decay of naturally occurring organisms residing mostly on the bottoms of the lakes that may be created. We shall make conservative assumptions about the phenomena involved so as to err on the safe side with regard to the rate of oxygen demand.

Several processes exert their demands for oxygen during the mineralization of organic material, and rates for these processes can vary markedly. The fastest process appears to be the oxidation of the carbonaceous material, ultimately to carbon dioxide and water. The production of ammonia by deamination and hydrolysis of macromolecular nitrogen compounds and the oxidation of phosphorous compounds appear to occur at nearly the same speed as does the oxidation of the carbonaceous material. The oxidations of ammonia to nitrite and nitrate are slower processes when examined in the laboratory under controlled conditions [7]. In these laboratory studies, ammonia forms first and most rapidly, followed by nitrite, followed by nitrate. In all cases, the earlier nitrogen compound becomes greatly reduced in amount before the peak occurs for the following compound. At all times, after initial ammonia production, the total nitrogen in one or another available form is about the same. This nitrogen compound succession is believed to be caused by the different rates of growth of separate microorganisms responsible for the several different nitrogen compounds in these laboratory experiments. In other laboratory experiments, more nearly representative of natural conditions where all necessary microorganisms are simultaneously present in varying stages of mineralization, the different stages of nitrification occur simultaneously [8].

For our purposes, we use values for rate coefficients determined for the so-called first stage, more rapid mineralization process. For a given sample of water, this reaction rate increases with temperature. The observed temperature effect can be formulated in terms of the Van't Hoff-Arrhenius relationship, namely,

$$d(\ln \eta)/dT = E/RT^2, \tag{2.5}$$

where η is the first-stage mineralization coefficient, T is temperature in degrees Kelvin, E is the activation energy for the biochemical mineralization process, and R is the gas constant. Using appropriate values for E and R, Davidson and Bradshaw [9] derive the following formula for representing the variation of the mineralization coefficient, η, with temperature:

$$\eta = 2.35 \times 10^{-7} \exp(0.0464T). \tag{2.6}$$

Figure 2.1 is a graph of this influence of temperature on mineralization rate.

Rates of mineralization in saline water may be somewhat greater than in fresh water but not significantly so [5]. Delay in mineralization may be induced by a lag in the seeding and buildup of mineralizing microorganisms that are viable in fresh water as the salinity is reduced. Any such lag would tend to reduce the possibilities for anaerobic conditions.

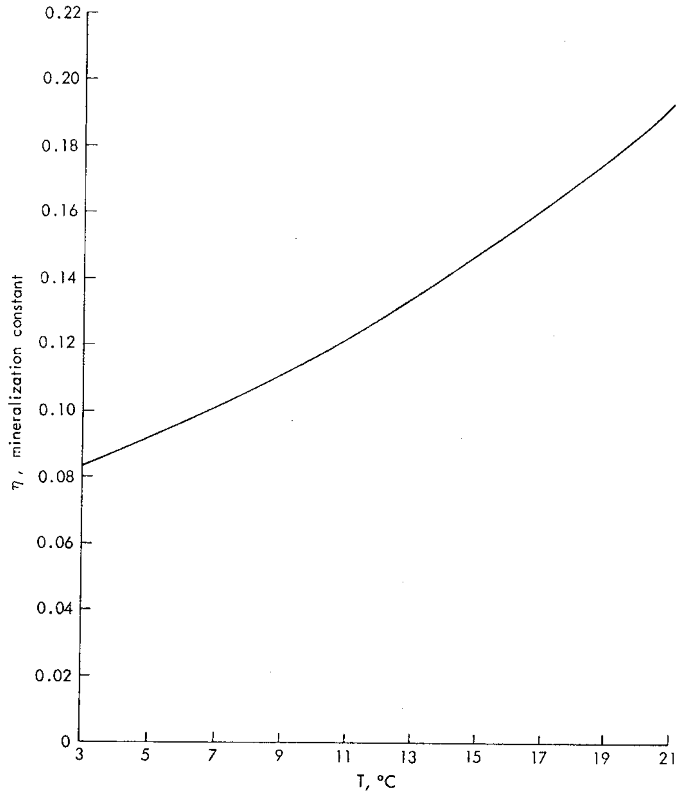

Fig. 2.1—Mineralization coefficient, η, versus temperature [9]

To justify our use of the faster remineralization rates given above and associated with mineralization in the pelagic zone rather than the slower rate in the benthos where most of the dying organisms will be situated, we assume that the active decomposition will result in an upward movement of products and residues for an appreciable fraction of the bottom organisms [4]. Along with Vegter [1], we assume that the organisms residing in the upper 5 cm of the bottom may be subjected to this mineralization. Vegter estimated the BOD of these organisms based on a total requirement of 1.42 gram of oxygen for each gram of ash-free dry biomass substance. These estimates are shown separately for the Volkerak-Krammer and small Eastern Basin areas in Table 2.1 for different average months of the year.

Table 2.1

OXYGEN NEED OF THE BIOMASS FOR THE VOLKERAK-KRAMMER AREA AND THE OOSTKOM (EASTERN BASIN)

(Figures are given in g O_2/m^3 or as in mg O_2/ℓ) [1]

	Volkerak-Krammer											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Macrozoobenthos	2.8	2.7	2.0	2.7	3.3	4.2	4.8	4.9	4.6	4.1	3.5	3.0
Microphytobenthos	3.0	2.5	2.1	3.0	4.2	4.2	3.0	2.1	3.4	4.1	3.1	2.9
Macrophytobenthos	---	---	---	---	---	---	---	---	---	---	---	---
Total	5.8	5.2	4.7	5.7	7.5	8.4	7.8	7.0	8.0	8.2	6.0	5.9
	Oostkom (Eastern Basin)											
Macrozoobenthos	19.5	18.7	18.1	18.9	22.2	29.2	33.7	33.9	32.1	28.4	24.5	21.0
Microphytobenthos	20.7	17.3	14.6	20.7	29.5	29.5	20.9	14.8	23.8	8.5	21.9	20.2
Macrophytobenthos	2.7	2.1	2.7	4.2	6.3	8.4	9.8	10.4	9.8	8.4	6.3	4.2
Total	42.9	38.1	35.4	43.8	58.7	67.1	68.4	59.1	65.7	65.3	52.7	45.4

In connection with the total BOD values listed in Table 2.1, it is instructive to examine the values for dissolved oxygen in fresh and saline water at saturation shown in Table 2.2 (from [2]). A comparison of these two sets of values lends credence to some of the assumptions that have been made in this study. For example, the BOD for the small Eastern Basin is about 65 mg of oxygen per liter in the summer months; it would take about seven refillings with oxygen-saturated input water containing about 9 mg of oxygen per liter to meet this BOD from an input water source. This is many times any conceivable input water flow during a period of mineralization (10 to 28 days), so this source for oxygen is likely to be of minor importance. The BOD loadings estimated in Table 2.1 emphasize the potential requirements for large amounts of oxygen by reaeration in this lake. This table also shows the moderate BOD for the Volkerak-Krammer area. This small BOD can

Table 2.2

SATURATION VALUES OF DISSOLVED OXYGEN IN FRESH AND SEA WATER EXPOSED TO AN ATMOSPHERE CONTAINING 20.9 PERCENT OXYGEN UNDER A PRESSURE OF 760 mm OF MERCURY[a] [2]

	Dissolved Oxygen (mg/ℓ) for Stated Concentrations of Chloride (mg/ℓ)					
Temperature, °C	0	5000	10000	15000	20000	Difference per 1000 mg/ℓ Chloride
0	14.7	13.8	13.0	12.1	11.3	0.165
1	14.3	13.5	12.7	11.9	11.1	0.160
2	13.9	13.1	12.3	11.6	10.8	0.154
3	13.5	12.8	12.0	11.3	10.5	0.149
4	13.1	12.4	11.7	11.0	10.3	0.144
5	12.8	12.1	11.4	10.7	10.0	0.140
6	12.5	11.8	11.0	10.4	9.8	0.135
7	12.1	11.5	10.8	10.2	9.6	0.130
8	11.8	11.2	10.6	10.0	9.4	0.125
9	11.6	11.0	10.4	9.7	9.1	0.121
10	11.3	10.7	10.1	9.5	8.9	0.118
11	11.0	10.4	9.9	9.3	8.7	0.014
12	10.8	10.2	9.7	9.1	8.6	0.110
13	10.5	10.0	9.4	8.9	8.4	0.107
14	10.3	9.7	9.2	8.7	8.2	0.104
15	10.0	9.5	9.0	8.5	8.0	0.100
16	9.8	9.3	8.8	8.4	7.9	0.098
17	9.6	9.1	8.7	8.2	7.7	0.095
18	9.4	9.0	8.5	8.0	7.6	0.092
19	9.2	8.8	8.3	7.9	7.4	0.089
20	9.0	8.6	8.1	7.7	7.3	0.088
21	8.8	8.4	8.0	7.6	7.1	0.086
22	8.7	8.3	7.8	7.4	7.0	0.084
23	8.5	8.1	7.7	7.3	6.8	0.083
24	8.3	7.9	7.5	7.1	6.7	0.083
25	8.2	7.8	7.4	7.0	6.5	0.082
26	8.0	7.6	7.2	6.8	6.4	0.080
27	7.9	7.5	7.1	6.7	6.3	0.079
28	7.7	7.3	6.9	6.6	6.2	0.078
29	7.6	7.2	6.8	6.5	6.1	0.076
30	7.4	7.1	6.7	6.3	6.0	0.075

[a] For barometric pressures other than 760 mm of Hg, the solubilities vary approximately in proportion to the ratio of the actual pressure to the standard pressure.

probably be satisfied safely by the oxygen dissolved in the overlaying water plus any additional amounts that should accrue through reaeration and input water. For this reason, primary attention is given only to conditions that may occur in the several larger sized Eastern Basins.

Chapter 3

A MODEL FOR ESTIMATING THE POTENTIAL FOR ANAEROBIC CONDITIONS IN EASTERN BASINS

Having presented means for computing the rate coefficients for reaeration and remineralization, we require a method for evaluating the net effects of changes in these phenomena, given the pertinent characteristics of the several basins that may be created and seasonal changes in related meteorological and hydrological conditions that occur.

3.1. MODEL ASSUMPTIONS

In constructing this evaluation model we made the following assumptions, some of which have been discussed previously in greater detail.

1. As a basin turns fresh, the entire stock of living organisms dies simultaneously. This creates an initial demand for oxygen of y_0. This demand is for first-stage mineralization—i.e., mineralization of carbonaceous material.
2. Mineralization, and hence uptake of oxygen from the water by the dead organisms, takes place at a rate proportional to the remaining demand for oxygen. This rate is independent of how much oxygen is actually available, so long as there is some oxygen present. This assumption leads to more conservative model results than an assumption that oxygen uptake rate depends on the level of oxygen present.
3. Oxygen is distributed throughout the water so that if there is oxygen anywhere in the water, there is oxygen available everywhere that mineralization occurs because the water is shallow. Only if the total oxygen in the water is zero will anaerobic conditions be encountered.
4. The oxygen in the water is either used for mineralization or it escapes to the atmosphere at a rate proportional to the amount of oxygen in the water. On the average and in the long term, oxygen is assumed to enter the water from the atmosphere at a constant, unidirectional rate.[1]

3.2. THE MODEL

Define the symbols:

$x(t)$ = the amount of oxygen in the water at time t (the initial value is x_0);

---

[1] We will, of course, use the model to evaluate the effects on the state of the basin system of different *net* reaeration rates that depend on factors such as wind velocity, water temperature, depth, fetch, etc.

$y(t)$ = the requirement for oxygen for mineralization that remains at time t (the initial value is y_0);

x_{EQ} = the equilibrium amount of oxygen in the water;

r = the reaeration rate constant;

η = the rate constant of oxygen utilization because of mineralization.

The equilibrium oxygen content of the water, x_{EQ}, is the amount that $x(t)$ will approach as t becomes very large. In some applications, this will be the same as the saturation value for oxygen content. In other applications, there will be one or more sources or sinks for oxygen other than reaeration from the atmosphere and mineralization. For example, algae might produce oxygen as a byproduct of photosynthesis. In these other applications, x_{EQ} will differ from the saturation value for oxygen. Taking these factors into account then, the model is expressed in the following linear differential equations:

$$\begin{aligned} dx/dt &= r(x_{EQ} - x) - \eta y, \\ dy/dt &= -\eta y. \end{aligned} \tag{3.1}$$

These equations have the general solution:

$$x(t) = x_{EQ} + [x_0 - x_{EQ} - (\eta y_0)/(\eta - r)]\, e^{-rt} + [(\eta y_0)/(\eta - \mu)]\, e^{-\eta t}, \tag{3.2}$$

$$y(t) = y_0 e^{-\eta t}. \tag{3.3}$$

Note that as required, the solution $x(t)$ approaches x_{EQ} as $t \rightarrow \infty$.

3.3. SPECIAL CASES RELATED TO ANAEROBIC CONDITIONS

We now ask the question, under what circumstances will the basin experience anaerobic conditions? By assumption 2, this occurs only if $x(t) = 0$. Whether it does so is fairly simple to calculate in two special cases:

Case I: Assume $x_0 = 0$. That is, the basin is completely depleted of oxygen at the time all the organisms die. In this case, $x(t)$ must begin increasing immediately to avoid anaerobic conditions. Thus, the danger condition is:

$$r x_{EQ} \leq \eta y_0. \tag{3.4}$$

Clearly, x_0 will never equal zero. However, even if it should, if condition (3.4) is not satisfied, there is no danger of anaerobic conditions occurring.

Case II: Assume $x_0 = x_{EQ}$. In this case, it can be shown that $x(t)$ will first decrease and then increase. It will have a unique minimum that occurs when $dx/dt = 0$. But, from (3.2), and substituting, we find:

$$dx/dt = (\eta y_0)/(\eta - r)(- \eta e^{-\eta t} + r e^{-rt}). \tag{3.5}$$

So, the minimum of x(t) occurs at:

$$t_{min} = (\log y/r)/(\eta - r). \tag{3.6}$$

Substituting this into (3.2), we find that the minimum value of x (which must be $x(t_{min})$) is:

$$x_{min} = x_{EQ} - y_0(\eta/r)^{-r/\eta - r}. \tag{3.7}$$

The basin will turn anaerobic unless $x_{min} > 0$. Thus, the danger condition is:

$$(\eta/r)^{1/(\eta/r)-1} \leq y_0/x_{EQ}. \tag{3.8}$$

3.4. SAFE AND DANGEROUS REGIONS

Define the two quantities:

$$\rho = \eta/r, \tag{3.9}$$

$$s_0 = y_0/x_{EQ}. \tag{3.10}$$

Any set of initial conditions that obtains in the basin may be described by three quantities. These are: ρ, the ratio of the mineralization rate coefficient to the oxygen diffusion rate coefficient; s_0, the ratio of the initial demand for oxygen for mineralization to the equilibrium amount of oxygen present in the water; and x_0, the initial amount of oxygen present in the water. That is, the initial conditions in the basin can be described as a point in the ρ - s_0 plane, plus an initial amount of oxygen x_0.

Now, partition the ρ - s_0 plane into three regions.

Region 1: $s_0 < 1/\rho$.

If the initial values of ρ and s_0 fall into region 1, then the situation is absolutely safe. Even if $x_0 = 0$, anaerobic conditions cannot occur.

Region 2: $s_0 \geq 1/\rho$,

but

$s_0 < \rho^{(1/\rho - 1)}$.

If the initial values of ρ and s_0 are in this region, the situation is only conditionally safe. For sufficiently low values of x_0, anaerobic conditions will occur. However, if x_0 is sufficiently close to x_{EQ}, aerobic conditions will persist.

Region 3: $s_0 \geq \rho^{(1/\rho - 1)}$.

If the initial values of ρ and s_0 are in this region, x_0 must exceed x_{EQ} or anaerobic conditions are sure to result.

These three regions are pictured in Fig. 3.1. The individual points on this figure are computed for the small Eastern Basin. We used conservative assumptions about the various parameters as described in previous sections.

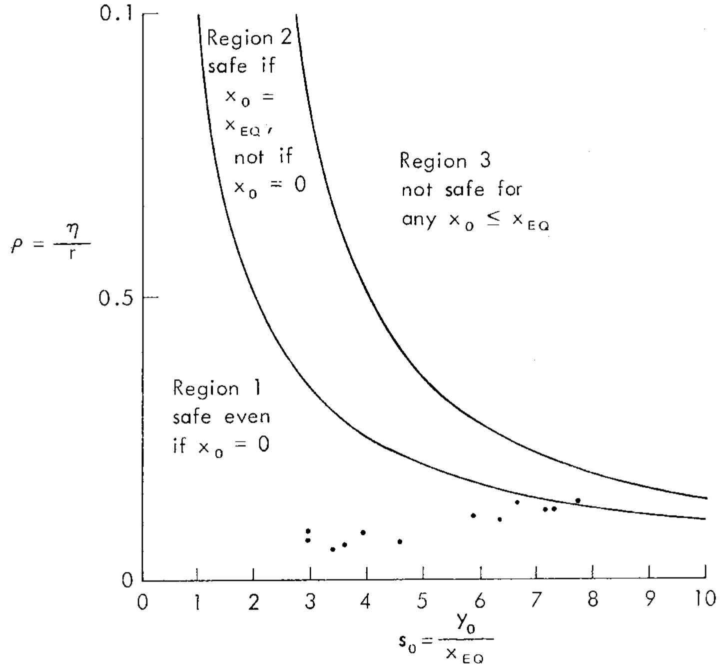

Fig. 3.1 — Regions of safety with respect to anaerobic conditions (individual points are average-month values for small Eastern Basin)

Chapter 4

ANAEROBIC SAFETY CONDITIONS FOR DESALINIZATION OF A SMALL EASTERN BASIN

Figure 4.1 shows the planned location and configuration of this basin. Table 4.1 has been constructed to show the data assembled and necessary to compute the susceptibility of this small Eastern Basin to anaerobic conditions at different periods of the year. The meteorological data shown are monthly averages derived from information supplied by the Environmental Division, Rijkswaterstaat [10]; water viscosities as related to temperature are from the standard texts in our references. The small Eastern Basin is sufficiently symmetrical that it may be assumed to be

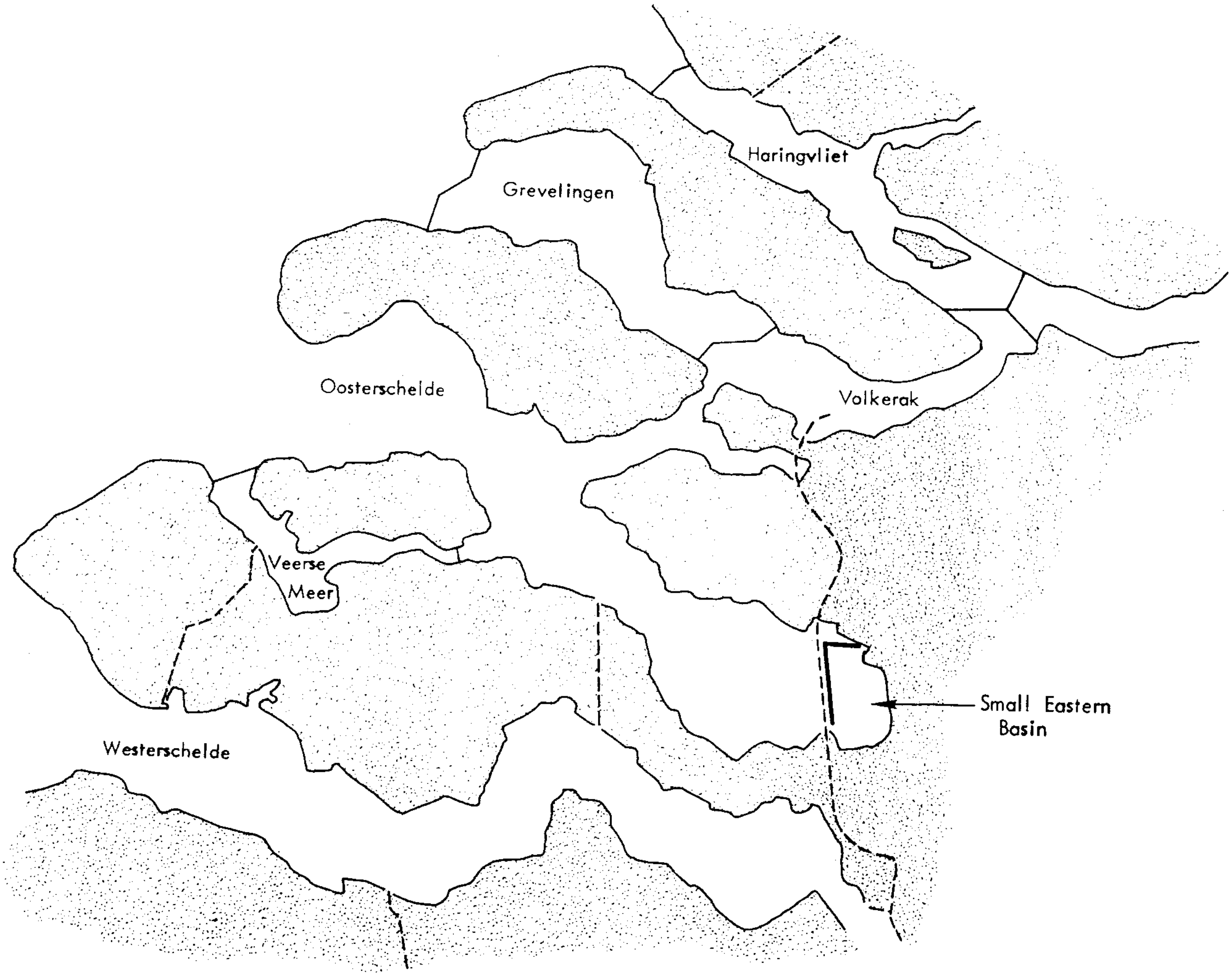

Fig. 4.1—Location of small Eastern Basin

Table 4.1

REAERATION PARAMETERS AND COMPUTED VARIABLES--SMALL EASTERN BASIN[a]

Month Average 4.25 Years	Average Wind 1971-1975		T,°C	$\mu \times 10^5$	G	r	η	η/r	s_0
	Meters per Second	Miles per Hour							
Jan.	6.82	15.26	3.0	3.382	.2185	1.283	.0834	.065	3.35
Feb.	5.98	13.38	2.8	3.405	.1788	1.122	.0827	.0737	2.98
Mar.	5.51	12.33	4.8	3.193	.1633	1.057	.0911	.0862	2.92
Apr.	6.34	14.18	8.4	2.862	.2127	1.260	.1080	.0857	3.94
May	5.36	11.99	13.4	2.486	.1774	1.117	.1365	.1222	5.90
June	5.34	11.95	14.8	2.395	.1799	1.127	.1455	.1291	7.27
July	5.28	11.81	19.2	2.141	.1870	1.157	.1770	.1530	7.73
Aug.	5.30	11.86	18.8	2.162	.1876	1.159	.1740	.1501	6.65
Sept.	5.36	11.99	16.6	2.486	.1774	1.117	.1575	.1410	7.07
Oct.	5.38	12.35	12.1	2.576	.1823	1.137	.1290	.1135	6.37
Nov.	7.32	16.37	7.1	2.967	.2592	1.438	.1020	.0700	4.56
Dec.	7.64	17.09	3.6	3.318	.2614	1.446	.0880	.0609	3.60

[a] Average fetch is 3000 m (1.87 miles) in all directions. Average depth is 2.5 m (8.2 ft).

circular. This means that the fetch length is independent of wind direction. Average depth was estimated by a grid count on a depth-contour map.

The points η/r vs. s_0 from Table 4.1 have been plotted in Fig. 3.1. They indicate that, given our conservative assumptions, this small Eastern Basin can probably be desalinated any month of the year without causing a serious anaerobic condition if the average meteorological conditions pertain for each month. The use of average criteria, however, masks meteorological variations that occur within a month, and such extremes may persist sufficiently long to cause anaerobic conditions. Of these factors, the wind velocity is both most variable and most critical in determining the supply of oxygen for meeting BOD.

We note from Table 4.1 and Fig. 3.1 that June and July are the most critical months on the average with respect to safety from anaerobic conditions. From Fig. 3.1, η/r must be $\leq .2$ in July and $\leq .21$ in June for safety. Using Eqs. (2.1) and (2.2) and knowing the values for η for both months, we can compute the minimum wind velocity to provide aerobic conditions. These values are 9.03 mph (4.03 meters per second) for July and 7.32 mph (3.27 meters per second) for June. These required average wind velocities are well below the measured averages for these months. However, Table 4.2 shows percent frequencies of wind velocities by decade for four years (1971-74), and there are considerable periods when wind velocities fall below these critical values. These critical wind velocities and their frequencies (summed from all directions) are given for June through October. Also shown in Table 4.2 are the minimum times required to reach anaerobic conditions, computed by using Eq. (3.6) and appropriate values for η and r for the several months.

If winds blow continuously below critical velocities without interruption by higher velocity winds for the fraction of the time indicated in Table 4.2, there could be one period in June (2nd decade 1973), five periods in July, two periods in August,

Table 4.2

DISTRIBUTION OF AVERAGE WIND CONDITIONS BY YEAR AND DECADE AND CRITICAL CONDITIONS REQUIRED TO MAINTAIN AEROBIC CONDITIONS (EASTERN BASIN)

Year and Decade	Percent Frequency of Wind Velocity Less than Critical				
	June	July	Aug.	Sept.	Oct.
1971					
I	1	45	5	33	6
II	0	44	13	83	0
III	13	32	10	22	1
1972					
I	8	1	6	0	13
II	12	10	0	1	0
III	13	8	5	91	4
1973					
I	0	26	16	44	8
II	35	21	23	8	6
III	6	15	9	5	14
1974					
I	7	1	0	3	0
II	0	5	12	66	27
III	0	9	33	0	0
Minimum time to reach anaerobic condition, days	2.12	1.92	1.93	2.04	2.16
Critical wind velocity to maintain aerobic conditions, meters per second	3.27	4.03	3.31	3.59	2.57

six periods in September, and one period in October in which anaerobic conditions might occur if past wind records are indicative of future conditions.

If low wind velocities only occur continuously half of the time uninterrupted by higher velocities, then there are two periods in July and four periods in September in which difficulties might have been encountered.[1] Although far from definitive, the above analysis indicates there are sufficient possibilities for anaerobic conditions to occur during transient conditions that desalinization schedules should be arranged if possible to avoid the summer months. If this is not possible, then standby aeration equipment should be on hand in the event anaerobic conditions do occur.

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[1] We had no data on the distribution of continuous lengths of times winds blow at different velocities.

Chapter 5

ANAEROBIC SAFETY CONDITIONS FOR DESALINIZATION OF A LARGE EASTERN BASIN

Plans for subcompartment dams in the back of the Oosterschelde include the possibility for constructing a second, larger Eastern Basin in addition to the one considered above. This additional subcompartment dam would protect fresh-water quality in a basin isolated from the pollution discharged from shipping that passes through the Rhine-Schelde and Wemeldinge Canals. The position considered for this dam and the enclosed larger Eastern Basin to be formed is shown in Fig. 5.1.

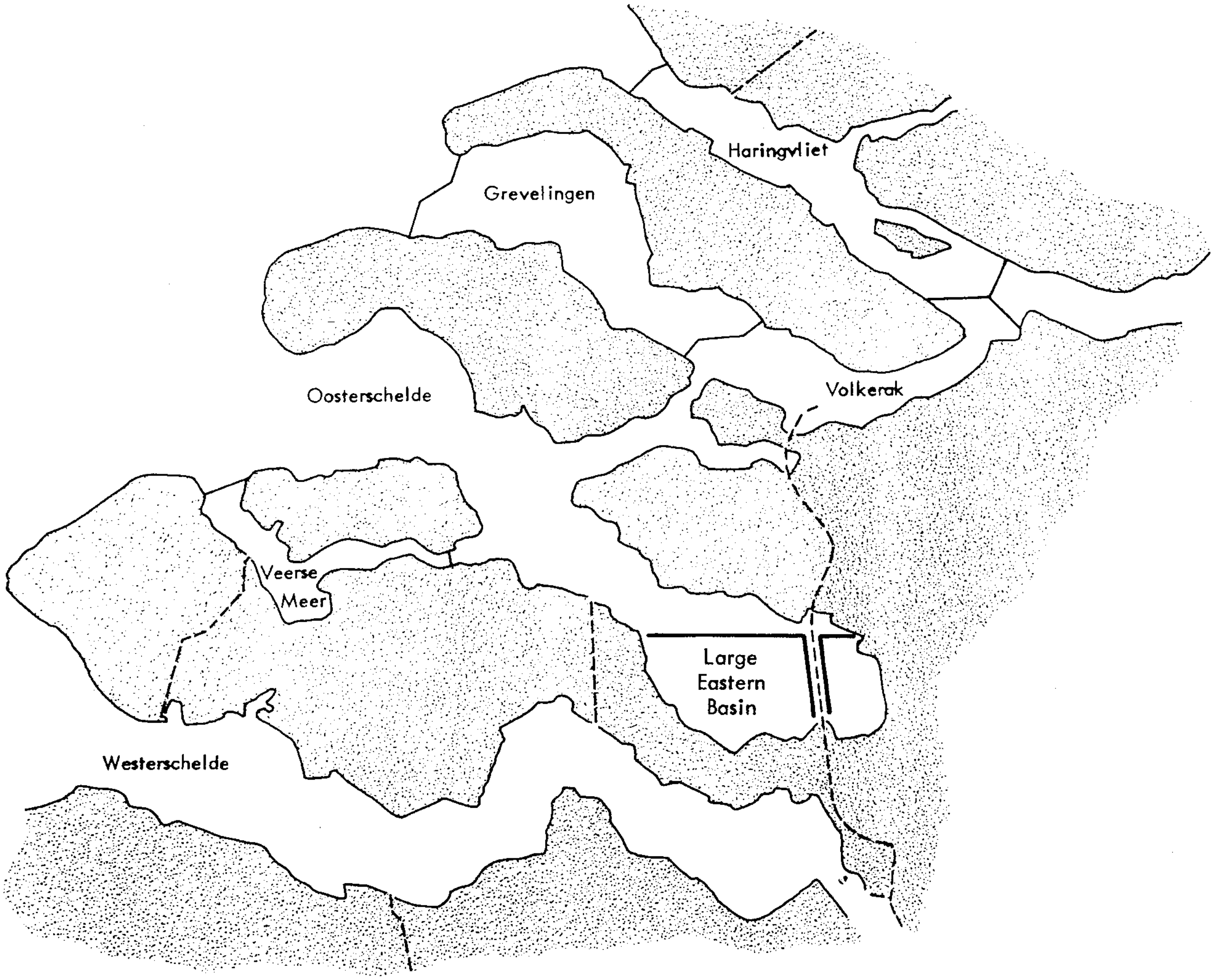

Fig. 5.1 — Location of large Eastern Basin

This basin would be 5 km × 11.6 km in extreme dimensions and have an average depth of 3.27 meters. Table 5.1 contains the necessary data and computed variables to analyze the hazards of anaerobic conditions occurring during desalinization. The biomass concentrations and mineralization rates are assumed to be the same as for the smaller Eastern Basin.

Table 5.1

REAERATION PARAMETERS AND COMPUTED VARIABLES--LARGE EASTERN BASIN

Month Average 4.25 Years	Average Wind 1971-1975				Short Fetch[a]					Long Fetch[a]			
	Meters per Second	Miles per Hour	T,°C	$\mu \times 10^5$	G	r	η	η/r	s_0	G	r	η	η/r
Jan.	6.82	15.26	3.0	3.382	.1694	.8266	.0834	.1009	3.35	.1113	.6250	.0834	.1335
Feb.	5.98	13.38	2.8	3.405	.1386	.7229	.0827	.1144	2.98	.0911	.5465	.0827	.1514
Mar.	5.51	12.33	4.8	3.193	.1267	.6810	.0911	.1338	2.92	.0832	.5146	.0911	.1771
Apr.	6.34	14.18	8.4	2.862	.1649	.8118	.1080	.1330	3.94	.1084	.6135	.1080	.1761
May	5.36	11.99	13.4	2.486	.1376	.7196	.1365	.1897	5.90	.0904	.5442	.1365	.2508
June	5.34	11.95	14.8	2.395	.1395	.7261	.1455	.2004	7.27	.0917	.5489	.1455	.2651
July	5.28	11.81	19.2	2.141	.1450	.7454	.1770	.2375	7.73	.0952	.5632	.1770	.3143
Aug.	5.30	11.86	18.8	2.162	.1455	.7467	.1740	.2330	6.65	.0957	.5623	.1740	.3095
Sept.	5.36	11.99	16.6	2.486	.1376	.7196	.1575	.2189	7.07	.0904	.5440	.1575	.2896
Oct.	5.38	12.35	12.1	2.576	.1414	.7325	.1290	.1761	6.37	.0928	.5533	.1290	.2332
Nov.	7.32	16.37	7.1	2.967	.2010	.9264	.1020	.1101	4.56	.1321	.6895	.1020	.1480
Dec.	7.61	17.09	3.6	3.318	.2027	.9316	.0880	.0945	3.60	.1332	.7037	.0880	.1251

[a] Fetch is 5.0 km (3.11 miles) in short direction; 11.6 km (7.21 miles) in long direction. Average depth is 3.27 m (10.73 ft).

This larger Eastern Basin is asymmetrical, so we have separately analyzed the conditions that may occur for winds blowing along the shortest and longest fetches. Computed values for ρ vs. s_0 for the longer fetch are shown with respect to the several safety regions in Fig. 5.2 in a similar manner as these same values were shown in Fig. 3.1 for the smaller Eastern Basin. Figure 5.2 indicates that this larger Eastern Basin presents a much greater potential for anaerobic conditions. Even using average monthly values for wind velocities (which as we demonstrated greatly understate the hazard), the months of June, July, August, and September are in the unsafe region. The months of May and October are marginal.

If this larger Eastern Basin is to be constructed, then most certainly the crucial desalinization must be scheduled for the winter months.

In certain circumstances, a dam is to be constructed near Wemeldinge, separating the main Oosterschelde basin from the rear subcompartments. The canal way and small lake thus formed between the Wemeldinge dam and the subcompartment dam shown in Fig. 5.1 may also be a source of anaerobic problems upon desalinization. This water body has a somewhat longer fetch in one direction and is considerably deeper than the Eastern Basin considered above. In our judgment these physical disadvantages to reaeration are probably balanced by a smaller population of organisms that occur in these deeps (as in the Volkerak-Krammer [1]) plus the fact

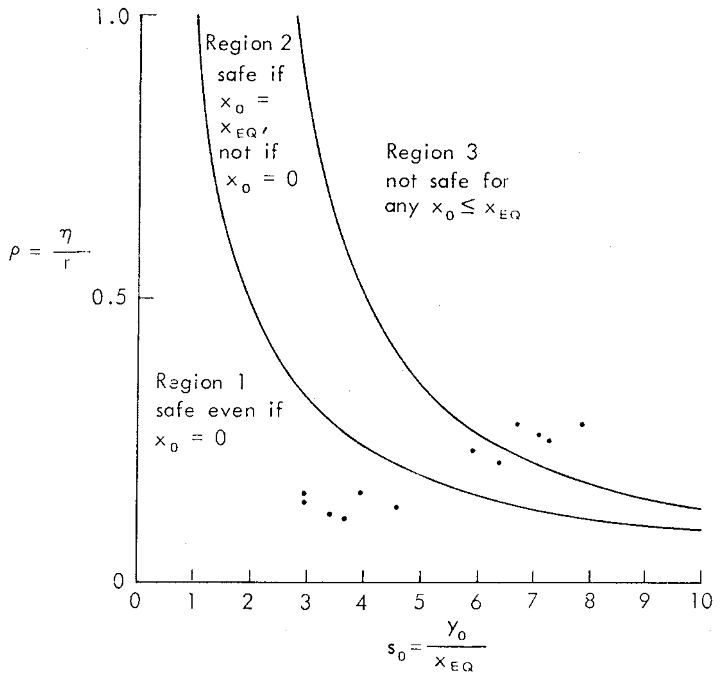

Fig. 5.2 — Regions of safety with respect to anaerobic conditions (individual points are average-month values for large Eastern Basin)

that this body will receive flow from the canals. The flow will both aid in reaeration and provide some dissolved oxygen from the incoming waters. Thus, this body should not be any worse a threat than the more rearward, large Eastern Basin analyzed above.

Chapter 6

POLICY IMPLICATIONS FOR AVOIDING ANAEROBIC DISASTERS

This analysis highlights actions that should be taken if anaerobic conditions are to be avoided during desalinization of the Oostmeer in any of its possible configurations. First, the basin configurations resulting from the subcompartment dams proposed for the larger Eastern Basin pose a considerably greater risk of encountering anaerobic conditions during desalinization than does the smaller Eastern Basin.

Second, there is a much greater hazard in allowing desalinization to occur during summer months than during the winter. If it is essential to desalinate during the summer, then artificial aeration equipment must be available for use in anaerobic emergencies as they occur. Extensions of the methodology used here (plus additional data described below) could be used to determine the amount and type of such equipment that might be required and where it might be needed.

Third, there are no data on the expected rate of mineralization for bottom organisms dying during rapid desalinization. Estimates of mineralization rates based on data for sewage-polluted rivers were used in this analysis. These estimates are believed to be conservative for the situations analyzed, but it is important to make some actual *in situ* measurements of mineralization rates (BOD) for dying bottom organisms. *In situ* measurements are required because part of the uncertainty involves the question of mixing of dead organic matter with the water. Taking of bottom samples for subsequent laboratory analysis would obscure the role of this mixing in determining mineralization rates.

An additional reason for making such mineralization measurements is that mineralization rates twice as large as those used here might occur. Such high rates are encountered in waters receiving strong wastewater or primary effluent from sewage treatment. It is believed these large mineralization rates occur because of the large numbers of bacteria associated with these sources of organic matter. But, in the absence of any measurements of the decay of bottom organisms, the possibilities for such high rates cannot be completely discarded.

Another data deficiency relates to the few actual measurements of bottom biomass for the region in question. Most of the biomass data used here from [1] were derived by extrapolation from supposedly similar regions. Bottom biomass sampling should be started for each month for the regions where desalinization is expected to occur.

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