Policy Analysis of Water Management for the Netherlands

Vol. XIX, Models for Salt Intrusion in the Rhine Delta

J. P. Koenis, T. F. Kirkwood

August 1982

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The Netherlands Rijkswaterstaat
PREFACE

For some time the Netherlands has had a problem with water quality, particularly salinity, eutrophication, and thermal pollution. Moreover, the future demand for fresh water is expected to exceed the supply. The growing demand for the limited supply of groundwater is leading to increased competition among its users: agriculture, industry, nature preserves, and companies that supply drinking water. The supply of surface water is sufficient except in dry years, when there is competition not only among such users as agriculture, power plants, and shipping, but also among different regions.

Facing such water management problems, the Dutch government wanted an analysis to help draft the first national water management law and to select the overall water management policy for the Netherlands. It established the Policy Analysis for the Water Management of the Netherlands (PAWN) Project in August 1976 as a joint research project of Rand (a nonprofit corporation), the Rijkswaterstaat (the government agency responsible for water control and public works), and the Delft Hydraulics Laboratory (a leading Dutch research organization).

The primary tasks of the PAWN project were to:

1. Develop a methodology for assessing the multiple consequences of water management policies.
2. Apply it to develop alternative water management policies for the Netherlands and to assess and compare their consequences.
3. Create a Dutch capability for further such analyses by training Dutch analysts and by documenting and transferring methodology developed at Rand to the Netherlands.

The methodology and results of the PAWN project are described in a series of publications entitled Policy Analysis of Water Management for the Netherlands. The series contains the following volumes:

- Volume I, Summary Report (Rand R-2500/1)
- Volume II, Screening of Technical and Managerial Tactics (Rand N-1500/2)
- Volume III, Screening of Eutrophication Control Tactics (Rand N-1500/3)
- Volume IV, Design of Long-Run Pricing and Regulation Strategies (Rand N-1500/4)
- Volume V, Design of Managerial Strategies (Rand N-1500/5)
- Volume VA, Methodological Appendixes to Vol. V (Rand N-1500/5A)
Volume VI, Design of Eutrophication Control Strategies (Rand N-1500/6)
Volume VII, Assessment of Impacts on Drinking-Water Companies and Their Customers (Rand N-1500/7)
Volume VIII, Assessment of Impacts on Industrial Firms (Rand N-1500/8)
Volume IX, Assessment of Impacts on Shipping and Lock Operation (Rand N-1500/9)
Volume X, Distribution of Monetary Benefits and Costs (Rand N-1500/10)
Volume XI, Water Distribution Model (Rand N-1500/11)
Volume XII, Model for Regional Hydrology, Agricultural Water Demands and Damages from Drought and Salinity (Rand N-1500/12)
Volume XIII, Models for Sprinkler Irrigation System Design, Cost, and Operation (Rand N-1500/13)
Volume XIV, Optimal Distribution of Agricultural Irrigation Systems (Rand N-1500/14)
Volume XV, Electric Power Reallocation and Cost Model (Rand N-1500/15)
Volume XVI, Costs for Infrastructure Tactics (Rand N-1500/16)
Volume XVII, Flood Safety Model for the IJssel Lakes (Rand N-1500/17)
Volume XVIII, Sedimentation and Dredging Cost Models (Rand N-1500/18)
Volume XIX, Models for Salt Intrusion in the Rhine Delta (Rand N-1500/19)
Volume XX, Industry Response Simulation Model (Rand N-1500/20)

Four comments about this series of publications seem appropriate. First, the series represents a joint Rand/Rijkswaterstaat/Delft Hydraulics Laboratory research effort. Whereas only some of the volumes list Dutch coauthors, all have Dutch contributors, as can be seen from the acknowledgments pages.

Second, except where noted, these publications describe the methodology and results presented at the final PAWN briefing at Delft on December 11 and 12, 1979. For Rand, this briefing marked the beginning of the documentation phase of the project and the end of the analysis phase. Rand and the Rijkswaterstaat (RWS) considered the results to be tentative because (1) some of the methodology had not become available until late in the analysis phase, and (2) the RWS planned to do additional analysis.

Third, the RWS is preparing its Nota Waterhuishouding, the new policy document on water management scheduled for publication in 1982, by combining some of the PAWN results from December 1979 with the results of considerable additional analysis done in the Netherlands with the PAWN methodology. Because the understanding gained in the original analysis led to improvements in the data—and, in some
instances, the models--used to represent the water management system in the additional analysis, the reader is hereby cautioned that the numerical results and conclusions presented in the PAWN volumes will not always agree with those presented in the Nota Waterhuishouding or its companion reports. (It has not been possible to indicate such differences in the volumes since they are being written before the Nota is published.) Thus, the present series of publications puts primary emphasis on documenting the methodology rather than on describing the policy results.

Fourth, Vols. II through XX are not intended to stand alone, and should be read in conjunction with the Summary Report (Vol. I), which contains most of the contextual and evaluative material.

When PAWN tactics extract large amounts of water from rivers in the Rhine Delta, the reduction in river flows causes an increase in the salt intrusion from the North Sea into the Nieuwe Waterweg and (potentially) the rivers that feed it (the Oude Maas and the Nieuwe Maas). If this salt intrusion reaches sufficiently far upstream, it can increase the salt concentration in the main irrigation supply to one of the Netherlands' richest agricultural areas and cause large financial losses.

To investigate how the choice of tactics affects salt intrusion, PAWN developed several models for salt intrusion in the Rhine Delta that are described in this volume. These models were primarily used as subroutines in two other PAWN models--the Water Distribution Model (documented in Vol. XI) and the Managerial Strategy Design Model (documented in Vol. V)--that estimated the costs and benefits of PAWN tactics.

The primary audience for this volume is the Dutch engineers and policy analysts who are using the PAWN methodology and need to understand it. However, both in the Netherlands and elsewhere, this volume should also be of interest to hydraulic engineers who are interested in problems of salt intrusion and to policy analysts and policymakers who are concerned with assessing the costs and benefits of water management policies.

NOTES

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

2. The Rand contract was officially with the Rijkswaterstaat, Directie Waterhuishouding en Waterbeweging (Directorate for Water Management and Water Movement), but numerous other parts of the Rijkswaterstaat contributed to the analysis.

3. Delft Hydraulics Laboratory research was performed under project number R1230, sponsored by the Netherlands Rijkswaterstaat.

4. Each water management policy involved a mix of tactics, each a particular action to affect water management, such as building a
particular canal or taxing a particular use. Four kinds of tactics were considered: building new water management facilities (infrastructure) or applying various treatments to the water (called technical tactics); using managerial measures (called managerial tactics) to change the distribution of water among competing regions and users; and imposing taxes or quotas to affect the quantity of water extracted or discharged by different users (called price and regulation tactics, respectively). A mix of tactics of the same kind is called a strategy. Thus, the overall policy could be conceived as a combination of technical, managerial, pricing, and regulation strategies.
SUMMARY

S.1. INTRODUCTION

The Rijn River's major outlet to the sea is the Nieuwe Waterweg, which is fed by the Oude Maas and the Nieuwe Maas. As the ocean tide rises and falls, salt water ebbs and flows into these rivers and causes an increase in salt concentration, which, under some conditions, extends as far upstream as the mouth of the Hollandsche IJssel in the Nieuwe Maas and threatens to enter the mouth of the Spui in the Oude Maas. Salt intrusion into the mouth of the Hollandsche IJssel is of particular interest in PAWN, as water extracted from the Hollandsche IJssel at Gouda forms the main irrigation supply for the agriculturally rich Zuid Holland area. Saltwater intrusion into the Spui is undesirable as it may then enter the fresh water of the Haringvliet. Early investigations showed that the salt wedge would not enter the Spui even under conditions of extremely low river flows. (It could enter as a result of storms at sea, but this rarely occurs, and so was not considered to be of interest in PAWN.) Consequently, PAWN concentrated on salt intrusion into the Hollandsche IJssel.

The extent to which salt intrudes into the rivers is determined by a balance between the river flow and the inflow of salt water that occurs as the tide rises. Some of the water management tactics considered in PAWN (those involving large extractions for agricultural uses) will result in reduction in the river flows and a consequent increase in salt intrusion. To estimate how the choice of tactics affects salt intrusion, we developed the Rotterdam Salt Wedge Model and the Gouda Inlet Salinity Model.

S.2. ROTTERDAM SALT WEDGE MODEL

The Rotterdam Salt Wedge Model calculates the average salt concentration as a function of the distance upstream from the mouth of the Nieuwe Waterweg into both the Oude Maas and the Nieuwe Maas. "Average" salt concentration is that observed at a particular location averaged over the flow cross section and over the tidal cycle. Our model finds the equilibrium value that would exist if many tide cycles had occurred while the river flow remained constant. PAWN uses this model to calculate the change in average salt concentration at the mouth of the Hollandsche IJssel caused by changes in river flows. The model will also handle two different river geometries; one is the present configuration, and the other represents a PAWN tactic in which the mouth of the Oude Maas is closed with a dam.

The model is based on physical principles, although it must be calibrated with measured data. We have chosen this type of model over a statistical model because the statistical data on salt intrusion are clouded by configuration changes made over the years, such as modifications to Rotterdam Harbor and the dredging and filling of the
Nieuwe Waterweg and the Nieuwe Maas. We have used a modified version of a model first developed by Van der Burgh. This model has the advantage of being simple and well known to the Rijkswaterstaat. Its limitations are that it is a one-dimensional model, and that past experience has shown that it will not always predict the effects of changes in river geometry.

To best reproduce the available measured data, we modified the original Van der Burgh model in two ways. First, Van der Burgh related the salt concentration in the river mouth to the concentration in the sea using the flood number, which is determined by the river discharge and the flood volume (the volume of water that flows into and out of the river mouth due to the tide at sea). For the modified model, we found that the available data were better represented by using an expression that involved only the river discharge.

Second, Van der Burgh's model was developed for a single river branch and contained two empirically derived calibration constants for calculating salt dispersion. We modified the model by adding a third calibration constant and then determined the values of the three constants separately for the Nieuwe Waterweg, the Nieuwe Maas, and the Oude Maas. This modification not only improved the fit to the available data but made it possible to calculate salt concentration in all three branches.

We used three sources of data to calibrate the model. The first data set consists of a large number of data points obtained from measurements of salt concentration by instruments permanently installed along the river branches at a number of locations and at different depths. These instruments were necessarily located near the bank of the rivers, so they do not provide information on the distribution of salt over the flow cross section.

The second data set consists of a series of measurements made to calibrate the Delft Hydraulics Laboratory's scale model of the river system, as well as various computer models. Measurements were used for two years (1973 and 1974) when the configuration of the river channels was essentially the same as it is at present.

The third data set consists of a series of new experiments conducted by the staff of the Delft Hydraulics Laboratory with their scale model of the Rotterdamsche Waterweg system. Tests were made both with the existing configuration and with Oude Maas closed (these tests provided the only data available with the Oude Maas closed). Unfortunately, the model was not large enough to allow reliable measurements to be made at the point of greatest interest, the mouth of the Hollandsche IJssel.

To calibrate the model, we calculated the variation of salt concentration along all of the three rivers, using an initial set of estimates for the three calibration constants to measure salt dispersion. This was done for flow conditions and tide heights appropriate for each set of observed data. We observed the agreement.
between the calculated and measured data and adjusted the calibration constants to improve it. Different constants were used in each river branch, and for cases with the Oude Maas open and closed, but we found that good agreement could be obtained when the constants were considered independent of river flows. This was important in PAWN, because it showed that our model could be used to calculate the effect of changes in river flow on salt intrusion. We found a single set of calibration constants that gave good agreement with all three data sets.

S.3. GOUDA INLET SALINITY MODEL

Water is extracted from the Hollandsche IJssel at Gouda for level control and agricultural use. The extraction point is some 15 km upstream from the mouth of the Hollandsche IJssel. The Hollandsche IJssel ends near this point, so that, except for the tide, the only flow into it results from the extraction of water at Gouda. To estimate the salinity of the extracted water, we had to relate the salt concentration at the mouth of the Hollandsche IJssel to that at the Gouda extraction point.

A model was developed at the Delft Hydraulics Laboratory that calculates the equilibrium salt concentration at the Gouda extraction point as a function of the salt concentration at the mouth of the Hollandsche IJssel and the rate of extraction at Gouda. The equilibrium concentration is the concentration that would exist after many tide cycles if the river discharges and the extraction rate remained constant. Thus, the equilibrium salt concentration is an upper bound on the actual concentration in situations in which the change in river flow results in an increase in salt concentrations at Gouda.

The average location of the salt wedge during a tide cycle is obtained from Rotterdam Salt Wedge Model. Using this average location and measured data on the tidal variation at the mouth of the Hollandsche IJssel, the Gouda Inlet Salinity Model calculates the flow of water and salt in and out of the Hollandsche IJssel during a tide cycle. When there is a net inflow of salt, the model calculates the movement of salt up the Hollandsche IJssel. This movement is caused by the diffusion of salt from the higher concentration at the mouth of the Hollandsche IJssel and by the transport of salt from the current caused by the extraction. We investigated the effects of different extraction rates at Gouda and found that (at least for the extraction rates of interest) salt concentrations at Gouda were insensitive to the extraction rate and depended only on the average salt concentration at the mouth of the IJssel. The extraction rate, however, does influence the time that elapses before the salt water reaches the inlet at Gouda.

The model is operated in a series of time steps, and the calculation is carried through enough tide cycles that the equilibrium salt concentration at Gouda is reached (the concentration that would exist if the river flows remained constant indefinitely).
In the real world, however, the river flows vary significantly in a period of ten days. This variation results not only from variations in Rijn flow, but also from the "Haringvliet effect." Over the two-week period from neap to spring tide, there is a variation in the mean sea level that causes a corresponding variation in the water level—and hence the amount of water stored—in the Haringvliet and the Hollandsche Diep. This in turn causes a periodic variation in the river flows. On the basis of available information, which is quite limited, we have represented the Haringvliet effect as a sinusoidal variation in river flow. The variation has a period of approximately two weeks and amounts to about 250 m³/s in the Nieuwe Maas in the present configuration. It is estimated that the variation will be about 150 m³/s if the Oude Maas is closed.

PAWN is interested in the salt concentration at the Gouda extraction point averaged over a decade (ten days). Consequently, the Gouda Inlet Salinity Model was designed to average the equilibrium salt concentration at Gouda over a ten-day period, taking into account the ten-day variation in Rijn flow and the two-week variation in river flows caused by the Haringvliet effect.

There are limited data on salt intrusion into the Gouda extraction point to use in verifying the model. For July and August 1976, the model results are fairly close to the measured salt concentrations at Gouda. Other than this, the model's credibility rests on the fact that it is based on physical principles. The primary uncertainty in the model is the estimation of salt diffusion. However, there are theoretical and experimental data to help in this estimation, and a sensitivity analysis showed that the results of the model were insensitive to variations within the range of uncertainty that the Rijkswaterstaat considered reasonable.
ACKNOWLEDGMENTS

The modeling was performed in close cooperation with the Rijkswaterstaat, Directie Waterhuishouding en Waterbeweging, District Zuidwest. Major contributions were made by J. van Weerden in formulating the model and in supplying data obtained through in situ measurements. For two aspects of the problem, special investigations have been carried out by the Delft Hydraulics Laboratory. First, DHL's investigation of the salt intrusion into the Rotterdamsche Waterweg, if the Oude Maas were to be closed, was carried out in the tidal salinity model "Rijnmond" under the supervision of P. de Jong. Second, N. Nederveen used a mathematical model to determine the relationship between the salt concentration of the water at the mouth of the Hollandsche IJssel and that at the extraction point at Gouda.

B. F. Goeller, Project Leader of PAWN at Rand, provided broad guidance throughout the project, as well as helpful administrative support.

We express our gratitude to S. Wildhorn at Rand for the considerable effort he expended in reviewing the first draft. We have done our best to incorporate all of his comments, as they have resulted in significant improvements in both substance and clarity.

Our sincere thanks to E. T. Gernert, Managing Editor of PAWN at Rand, for her editorial acuity in reading the manuscript, and to her colleagues in the Publications Department for their care in guiding our study to press.

Even though we were heavily dependent on other people's contributions, we take sole responsibility for any errors that appear in this volume.
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Chapter 1

INTRODUCTION

The modeling described in this volume is part of the activities conducted within the framework of the PAWN project (Policy Analysis for the Water Management of the Netherlands). Briefly, the objective of the study is to develop sufficient information to help the Netherlands Government select one of a number of promising water management policies. The term "policies" means a specific combination of actions (tactics) in the field of water management. The study compares the various possible policies by providing straightforward and unambiguous information on the consequences (impacts) of such tactics. The tactics include actions relating to the current water management infrastructure, as well as to changes in that infrastructure. Detailed information on the PAWN study can be found in Refs. 1-3.

1.1. PROBLEM STATEMENT

Salt intrusion into the Rotterdamsche Waterweg (see Fig. 1.1) plays a major role in the water management of the Netherlands. The surface-water supply to the midwestern part of the country is provided mainly through the extraction point at Gouda on the Hollandsche IJssel River. The Hollandsche IJssel has a direct connection with the Nieuwe Maas River and the Nieuwe Waterweg. At low discharge rates in the Rijn and Maas rivers, the saline water (the salt wedge) from the sea penetrates toward the mouth of the Hollandsche IJssel. Any resulting salt intrusion into the Hollandsche IJssel has implications for both water consumers and the various water boards.¹ The current infrastructure offers the water boards limited possibilities to transport water to their regions by other means (emergency supply facilities). In the event that this emergency supply is insufficient, the boards are forced to take in water from the salinated Hollandsche IJssel to provide the requisite level control of the boezem and polder areas, for example, in the southwest of Holland. Salt intrusion into the boezems and polders seriously affects the regional water consumers, particularly those engaged in glasshouse agriculture.

Basically, it is possible to change the current infrastructure so that either the risk of salt intrusion into the Hollandsche IJssel is reduced (e.g., by closing the Oude Maas branch) or an alternative supply route is made available for water supply (e.g., construction of a canal through the Krimpenerwaard polder). Besides tactics (actions) that may be used by the water boards, others may be used by consumers. The PAWN study's major tasks are to compile an inventory of such tactics, combine them into strategies, and then compare the strategies by assessing their consequences (impacts).
Fig. 1.1 - The Rotterdamsche Waterweg (Nieuwe Waterweg, Oude Maas, Nieuwe Maas, Hollandsche IJssel etc.)
Although salt intrusion into the Hollandsche IJssel is regarded as the top-priority problem arising from the inflow of saline water from the sea, other extraction points are located on the Oude Maas and Nieuwe Maas branches where an increase of the salt concentration of the water may present problems for water consumers. To be able to determine the consequences of salt intrusion from the sea for the consumers, information is needed on salt concentrations at the various extraction points on the Nieuwe Waterweg, Oude Maas, Nieuwe Maas, at the mouth of the Hollandsche IJssel, and at the withdrawal point at Gouda. These salt concentrations must be known for all combinations of river discharges in the Rotterdamsche Waterweg area that result from

- Variations of the Rijn and Maas discharges.
- Various withdrawals that are made (e.g., flushing the freshwater Zoommeer).
- Management tactics providing for water distribution within the water management infrastructure in the Netherlands (e.g., by the selection of the weir program at Driel).
- Technical tactics changing the current infrastructure (e.g., closing the Oude Maas branch).

The salt concentration in this area, however, is not determined only by the discharge distribution over the Oude Maas, Nieuwe Maas, and Nieuwe Waterweg. The tides at sea play a significant part. In addition, storms have a major effect on the mean water levels at sea and, consequently, on salt intrusion into the Rotterdamsche Waterweg.

The distribution of water within the water management infrastructure in the Netherlands is simulated in the PAWN study by the Water Distribution Model.

1.2. OBJECTIVE OF THE MODELING

The objective of the modeling described in this volume is to estimate the salt concentration caused by salt intrusion from the sea (rather than salt flowing down the rivers) of water at various points on the Nieuwe Waterweg, Oude Maas, Nieuwe Maas, at the mouth of the Hollandsche IJssel, and at the extraction point at Gouda. The model is intended as a tool for PAWN and not as a generally applicable one-dimensional model for salt intrusion problems in estuaries.

1.3. ORGANIZATION OF THIS VOLUME

The following chapter gives an overview of the modeling. The sources of the data used are reviewed in Chap. 3. Chapters 4 and 5 describe the development of the Rotterdam Salt Wedge Model and the Gouda Inlet Salinity Model, respectively. The Rotterdam Salt Wedge Model's applicability to PAWN is demonstrated in Chap. 6. Chapter 7 discusses both models' limitations and sensitivity. Two supporting appendixes
present listings of computer programs for the open and closed case for the Oude Maas.

The reader should be aware of two items of nonstandard mathematical notation dictated by typographical limitations. First, the symbols \(<\) and \(\geq\) are represented by \(<-\) and \(\rightarrow\), respectively. Second, an asterisk (*) is used to indicate multiplication.

NOTE

1. Water boards are agencies set up by provinces to assume responsibility for water defenses, water level and drainage, and the supply of water at the local level. Some of these water boards date from the 12th century, making them among the oldest forms of government in Europe. Many of the tactics studied by PAWN contain elements proposed by the various water boards.
Chapter 2

MODELING OVERVIEW

2.1. THE PROBLEM

The PAWN study uses two macro-models, the Water Distribution Model and the Managerial Strategy Design Model, to evaluate alternatives. The Water Distribution Model simulates the water movement through the water management infrastructure in the Netherlands. This simulation is based on, among other factors,

- A specific water supply (Rijn, Maas, and rainfall).
- A specific water demand by consumers.
- A certain state of the infrastructure (e.g., canalization of the IJssel River or no canalization).
- A specific strategy (combination of tactics).

In addition to water movement, the model estimates water quality, including the salt concentration of the water at the various extraction points.

The Managerial Strategy Design Model selects the combination of tactics that optimizes the water distribution tactics, while meeting standards for water quality. The optimization considers, among other factors,

- A specific water supply (Rijn, Maas, and rainfall).
- A specific water demand by consumers.
- A specific infrastructure.

Water quality is also estimated in this model in order to compare the estimate to the water quality standards.

In both models, we need to determine the salt concentration values of the water in the Rotterdamsche Waterweg area as a function of the discharge distribution and other important factors. To do this, we have developed the two models that are described in this volume. The first model, generally referred to in PAWN as the Rotterdam Salt Wedge Model, relates the salt concentration at the mouth of the Hollandsche IJssel (and at other locations) to the flows in the Oude Maas and Nieuwe Maas. As will be explained, this model was obtained by modifying an existing model developed by Van der Burgh, which in this volume will be referred to as the "modified Van der Burgh model." The second model, generally referred to in PAWN as the Gouda Inlet Salinity Model, relates the salt concentration in the inlet at Gouda to that at the mouth of the Hollandsche IJssel.
The computation procedure to calculate these salt concentration values should be as simple as possible to allow us to examine many alternatives. On the other hand, salt intrusion into the Rotterdamsche Waterweg is a highly complex physical problem. Measurements and investigations have already yielded much information on in situ developments. But that information is still insufficient to answer many questions about the water movement, and even less adequate to answer questions about salt movement in the area. However, investigations on the movements of water and salt in the Northern Delta area are continuing. This research employs all available means, such as measurements in situ, the tidal salinity model "Rijnmond" (see below), and mathematical computer models for water and salt movement. Both categories of models have their advantages and limitations. Mathematical computer models have limited applicability, because mathematical formulation of the important physical mechanisms (especially the mixing processes) in only one or two dimensions is still insufficient. The tidal salinity model Rijnmond is a distorted physical scale model for reproducing water and salt movement in the Rotterdamsche Waterweg area. The distortion introduces scale effects for the mixing of salt. Nevertheless, investigations up to this point have shown that the reproduction of the movement of water and salt in the tidal salinity model Rijnmond is good [13]. That means that the most relevant mixing mechanisms are reproduced correctly in the tidal model.

2.2. SELECTING THE APPROACH

For PAWN, we selected the modeling approach that made optimum use of available in situ measurements. Moreover, several in situ measurements were reproduced in the tidal salinity model Rijnmond. Measurements made during experiments with this model were also used. In addition, the Rijnmond model was used to simulate the situation in which the Oude Maas branch is closed. All of these measurements together served as the basic material to estimate the salt concentration of the water in the Rotterdamsche Waterweg area.

The measurements, whether made in situ or in the tidal salinity model, yield the salt concentration values under a specific set of boundary conditions (e.g., tide at sea, volume and distribution of river discharges averaged over one tidal period). Because we needed to investigate various combinations of boundary conditions that may occur in the real world, a model was required that was able to interpolate between specific values measured and to extrapolate outside the range of values measured.

We selected the salt intrusion model developed by Van der Burgh and modified his equations and coefficients to best reproduce the measured data. The advantages of the modified version of Van der Burgh's model are
-7-

- The model uses a simple computation procedure to calculate the salt concentration values at points on the Nieuwe Waterweg, Nieuwe Maas, and Oude Maas.
- The outcome of the computation is a mean salt concentration value for the full cross section of the river branch, averaged over one tidal period (a one-dimensional, pseudo-stationary model). More detail is neither required by the two macro-models used in PAWN, nor is such detail practical to obtain.
- The PAWN models estimate the salt concentration due only to the effect of seawater. The so-called background salt concentration, which comes from the Rijn, Maas, and other inland salt sources, is not included in these models but is accounted for when used with other PAWN models.
- The structure of the model makes it possible to adapt it so that all basic data (in situ and model measurements) are reproduced with an acceptable degree of accuracy.

The experiments with the tidal salinity model Rijnmond, in which the Oude Maas was closed, permitted us to calibrate the modified Van der Burgh model for both the situation where the Oude Maas is closed (using only model measurements) and the existing situation (using in situ measurements as well as results from the tidal salinity model). However, we found that other technical tactics that would significantly change the tidal movement in the Rotterdamsche Waterweg area cannot be examined with a modified version of the Van der Burgh model, because measurement data are not available to recalibrate the model to the new situation. (An example of a technical tactic is the closing of the Nieuwe Maas branch.)

2.3. COMPUTATION PROCEDURE

We applied the following computation procedure:

- Water movement is computed by means of either the Water Distribution Model or the Managerial Strategy Design Model. Water movement depends on the river discharges in the various branches in the Rotterdamsche Waterweg area and on withdrawals in the area. Discharges and withdrawals are averaged over several tidal periods at average tidal conditions. The averaging interval applied in these models is a minimum of one week to 10 days.
- Given this water movement (in particular, the average river discharges through the Oude Maas, Nieuwe Maas, and Nieuwe Waterweg), the modified Van der Burgh model computes the salt concentration values of the water in these three river branches, averaged over the cross sections and tidal period.
Using a diffusion analysis, we determined a mathematical relationship between the salt concentration of the water at the extraction point at Gouda and that of the water at the mouth of the Hollandsche IJssel as computed using the modified Van der Burgh model. This relationship applies to the situation without the use of the existing storm-surge barrier near the mouth of the Hollandsche IJssel. Exact information on the effect of the barrier on salt intrusion into the Hollandsche IJssel is still lacking.

We used the modified Van der Burgh model to compute the salt concentration of the water at the various withdrawal points on the Oude Maas, Nieuwe Maas, and Nieuwe Waterweg.

The modified Van der Burgh model and the mathematical relationship for the salt concentration at Gouda were not built directly into the Water Distribution and Managerial Strategy Design models because that would have unduly increased the computation time. Instead, we made the computations separately and then incorporated them into the two models in the following way. For several combinations of river discharges through the Oude Maas, Nieuwe Maas, and Nieuwe Waterweg, and with a specific infrastructure, the salt concentration at the extraction point at Gouda was computed using the modified Van der Burgh model and the relationships between the salt concentration at the mouth of the Hollandsche IJssel and the salt concentration of the water at Gouda. For each of the two infrastructures (with and without closure of the Oude Maas), we summarized the computed results in several equations and incorporated them into both models. The salt concentration can be determined by these equations for a specific combination of discharges. If necessary, comparable equations could also be produced for other withdrawal points in the area.

The next chapters provide a detailed discussion of the items described in general terms above.
Chapter 3
SURVEY AND SOURCES OF DATA

3.1. ACTUAL INFRASTRUCTURE

For the actual infrastructure of the Rotterdamsche Waterweg area, we calibrated the modified Van der Burgh model on the basis of measurement data collected in situ for the period 1971-1976 and in the tidal salinity model Rijnmond. The measurements of salt concentrations can be subdivided into three categories:

- In situ measurements (1973-1976), which were also reproduced in the tidal salinity model.
- Measurements taken only with the tidal salinity model.

These three data categories are discussed in detail below.

3.1.1. In Situ Measurements (1971-1974)

During the 1970-1978 period, the Rijkswaterstaat (RWS) made extensive measurements at regular intervals (about six times) in the Rotterdamsche Waterweg. On each occasion, measurements were taken during both weekend days as follows: In the course of one day, 4 cross sections of the Nieuwe Waterweg and 3 of the Oude Maas were measured. On the second day, 4 cross sections of the Nieuwe Maas and at least one cross section of both the Nieuwe Waterweg and the Oude Maas were taken. For each cross section, during one tidal period of about 12.5 hours, 3 to 4 verticals were measured over the full water depth. Salt concentration and the velocity were derived for each measuring point. Thus, by combining the data collected on both days, a fairly complete picture was obtained of the salt concentration and the velocity field as a function of time and location on the Rotterdamsche Waterweg, under the tidal and discharge conditions prevailing during the weekend.

These measurements were collected to calibrate and verify the models that are being used or developed to simulate salt intrusion. Although the primary model currently in use is the salinity model Rijnmond, various mathematical models are being developed but are not yet sufficiently verified.

In addition to the information collected on weekends, several measurements were taken over the whole cross section at different times and locations. At several points along the Nieuwe Waterweg, Oude Maas, Nieuwe Maas, and along other river branches of the Lower Rivers area, instruments are located that continuously record the salt
concentration values at one or more depths. Measurements made at river banks or at bridge piers are not representative of the average salt concentration of the full cross section of the river at that location. But measurements at locations where the cross section is well mixed, such as at Van Brienenoordebrug and Spijkenisserbrug, are more representative of the whole cross section. Therefore, data from such locations were used to supplement the available measurements of the cross sections.

The RWS combined and averaged all of the measurement data of the 1971-1974 period and produced a data set for three different levels of river discharge through the Nieuwe Waterweg: 600, 1000, and 1600 m³/s. These averages are shown in Table 3.1. The discharge through the Oude Maas and Nieuwe Maas corresponding to the Nieuwe Waterweg discharges was determined from the results of a systematic study of the water movement in the Northern Delta area. This study considered different discharges from the Rijn and Maas rivers and different withdrawals. The water distribution resulting from this study is called "NLP-70" (Normaal Lozingsprogramma 1970 or Normal Discharge Program 1970). NLP-70 gives the discharge program of the Haringvliet outlet sluices and assumes that the weir at Driel uses the S 300 weir program. The weir at Driel controls, within specific limits, the distribution of the discharge of water from the Rijn over the IJssel, Neder-Rijn (and Lek), and Waal rivers. The S 300 weir program implies that the weir has been set to maintain a discharge rate of 300 m³/s through the IJssel as long as possible when the Rijn discharge is low. The discharge distribution of NLP-70 is representative of the discharge distribution during the period in which measurements were made.

3.1.2. In Situ Measurements Reproduced in the Tidal Salinity Model Rijmmond

Several of the in situ weekend measurements discussed in the previous section were reproduced in the tidal salinity model Rijmmond. These were for June 16 and 17, 1973, June 22 and 23, 1974, and April 24 and 25, 1976. The experimental results of the tidal model for April 24 and 25, 1976, however, were not available to us in the calibration of the modified Van der Burgh model, and thus are not considered any further. Each measuring day was reproduced individually in the model, and the agreement between in situ measurements and model measurements was good.

To calibrate the modified Van der Burgh model, we used the measured values from experiments in the tidal salinity model for the dates mentioned above. The experimental data were preferred to the results of the in situ measurements for the following reasons:

- Salt intrusion in the model was a good reproduction of the in situ measurements [13].
Table 3.1
IN SITU MEASUREMENTS, 1971-1974

<table>
<thead>
<tr>
<th>River discharges (m³/s)</th>
<th>600</th>
<th>1000</th>
<th>1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nieuwe Waterweg</td>
<td>435</td>
<td>700</td>
<td>975</td>
</tr>
<tr>
<td>Oude Maas</td>
<td>165</td>
<td>300</td>
<td>625</td>
</tr>
</tbody>
</table>

Tidal conditions

Tidal difference (m). The mean value of all tidal conditions is used

<table>
<thead>
<tr>
<th>Flood volume (10⁶m³)(a)</th>
<th>71.3</th>
<th>64.7</th>
<th>54.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nieuwe Waterweg (kmr 1030.100)</td>
<td>20.8</td>
<td>16.5</td>
<td>11.6</td>
</tr>
<tr>
<td>Oude Maas (kmr 1006.450)</td>
<td>43.1</td>
<td>40.8</td>
<td>35.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chloride concentration (kg Cl⁻/m³)(b)</th>
<th>15.1</th>
<th>13.0</th>
<th>10.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nieuwe Waterweg kmr 1029.00</td>
<td>14.7</td>
<td>12.4</td>
<td>9.6</td>
</tr>
<tr>
<td>1024.75</td>
<td>12.8</td>
<td>9.8</td>
<td>6.6</td>
</tr>
<tr>
<td>1023.00</td>
<td>10.7</td>
<td>7.4</td>
<td>4.2</td>
</tr>
<tr>
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<td>11.9</td>
<td>8.8</td>
<td>5.6</td>
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<td>6.0</td>
<td>2.9</td>
</tr>
<tr>
<td>1015.75</td>
<td>8.7</td>
<td>5.1</td>
<td>-</td>
</tr>
<tr>
<td>1013.60</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chloride concentration (kg Cl⁻/m³)(b)</th>
<th>7.4</th>
<th>5.6</th>
<th>2.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nieuwe Maas kmr 1012.00</td>
<td>5.6</td>
<td>3.8</td>
<td>1.5</td>
</tr>
<tr>
<td>1010.00</td>
<td>4.6</td>
<td>2.6</td>
<td>0.7</td>
</tr>
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<td>1006.50</td>
<td>3.7</td>
<td>1.6</td>
<td>0.2</td>
</tr>
<tr>
<td>1002.60</td>
<td>3.9</td>
<td>1.7</td>
<td>0.2</td>
</tr>
<tr>
<td>999.30</td>
<td>3.6</td>
<td>1.2</td>
<td>0</td>
</tr>
<tr>
<td>998.60</td>
<td>2.7</td>
<td>0.6</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chloride concentration (kg Cl⁻/m³)(b)</th>
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<th>1.7</th>
<th>0.65</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oude Maas kmr 1005.40</td>
<td>2.1</td>
<td>0.6</td>
<td>0.10</td>
</tr>
<tr>
<td>999.00</td>
<td>0.55</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>996.60</td>
<td>0.20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>994.50</td>
<td>0.05</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**NOTE:** kmr or kilometeraai means kilometer range line, by which distances along the rivers are measured.

(a) Calculated by RWS' IMPLIC model for mean tidal conditions (unpublished information from the RWS (PAWN file DW-346)).

(b) The salt concentrations shown are due only to the effect of seawater. The so-called background salt concentration (from the Rijn and Maas and other inland sources) is subtracted.
• With the in situ measurements, only a limited number of cross sections were measured for each day; but, with the tests, more cross-sectional measurements were available for each day and each branch (Nieuwe Waterweg, Oude Maas, and Nieuwe Maas).
• The measurement accuracy in the model is greater than with the in situ measurements because of the better measuring and processing environment of the model. For example, many small boats were used to take measurements under adverse circumstances in the in situ measurements.

The data obtained through the above measurements are shown in Table 3.2.

3.1.3. Measurements in the Tidal Salinity Model Rijnmond

In the study of the effect on salt intrusion of the closing of the Oude Maas, two model experiments were conducted with an open Oude Maas. Our purpose was to investigate, given constant boundary conditions (tide at sea, river discharges, and withdrawals), the differences in salt intrusion between the existing situation (open Oude Maas) and a closed Oude Maas. The experiments suggested that both tests could be used to calibrate the modified Van der Burgh model to fit the existing infrastructure. The boundary conditions and the measured salt concentrations from these tests are shown in Table 3.3.

3.2. SITUATION WHEN OUDE MAAS IS CLOSED

A study was carried out using the tidal salinity model Rijnmond at the Delft Hydraulics Laboratory (DHL) to collect information about the change in salt intrusion into the Rotterdamsche Waterweg when the Oude Maas is closed. The study was designed to answer PAWN study needs, as well as questions pertaining to the closing raised by the RWS, Directie Benedenrivieren. In addition, DHL results were planned to be used in developing and verifying mathematical models describing the salt movement in this estuary. A major limitation of the study, however, was that the present boundaries of the tidal salinity model Rijnmond made it impossible to carry out the study at low river discharges. Table 3.4 displays a survey of the study plan. The study results are published in Ref. 4.

To calibrate the modified Van der Burgh model for PAWN, seven tidal model experiments were carried out. There were two tests with an open Oude Maas (see Table 3.4, experiment numbers T0 and T11) and five with the Oude Maas closed (T2, T3, T4, T5, T6). Of these, three (T2, T5, T6) were carried out at essentially average tidal conditions, but with river discharges through the Nieuwe Waterweg and the Nieuwe Maas having values of 630, 935, and 1267 m³/s as an average over one tidal period of about 25 hours. Furthermore, three experiments (T2, T3, T4) provided information on the change in salt intrusion as tidal conditions vary (normal tide, neap tide, and spring tide). The experimental data and the measurement results are shown in Table 3.5.
Table 3.2

IN SITU MEASUREMENTS REPRODUCED IN TIDAL SALINITY MODEL RIJNMOND

<table>
<thead>
<tr>
<th>Date of measurement</th>
<th>June 16, 1973</th>
<th>June 17, 1973</th>
<th>June 22, 1974</th>
<th>June 23, 1974</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>River discharges (m³/s)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nieuwe Waterweg</td>
<td>1650</td>
<td>1325</td>
<td>935</td>
<td>1055</td>
</tr>
<tr>
<td>Nieuwe Maas</td>
<td>735</td>
<td>595</td>
<td>415</td>
<td>460</td>
</tr>
<tr>
<td>Oude Maas</td>
<td>915</td>
<td>730</td>
<td>520</td>
<td>600</td>
</tr>
<tr>
<td><strong>Tidal conditions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tidal difference (m)</td>
<td>1.75</td>
<td>1.71</td>
<td>1.98</td>
<td>1.96</td>
</tr>
<tr>
<td><strong>Flood volume (10⁶m³)(a)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nieuwe Waterweg (kmr 1030.10)</td>
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<tr>
<td>Nieuwe Maas (kmr 1012.90)</td>
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</tr>
<tr>
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<td>17.5</td>
<td>22.7</td>
<td>22.4</td>
</tr>
<tr>
<td><strong>Chloride concentration (kg Cl⁻/m³)(b)</strong></td>
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<td></td>
</tr>
<tr>
<td>Nieuwe Waterweg kmr 1029.00</td>
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<td>10.48</td>
<td>11.97</td>
<td>11.86</td>
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<tr>
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<td>6.13</td>
<td>7.85</td>
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<td>4.95</td>
<td>4.40</td>
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<tr>
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<td>3.77</td>
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<td>1002.125</td>
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<td>0.07</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Oude Maas kmr 1005.50</td>
<td>0.43</td>
<td>1.20</td>
<td>2.36</td>
<td>1.98</td>
</tr>
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<td>0.44</td>
<td>1.22</td>
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<tr>
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<td>0.56</td>
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</tr>
<tr>
<td>996.70</td>
<td>0</td>
<td>0.04</td>
<td>0.22</td>
<td>0.15</td>
</tr>
</tbody>
</table>

(a) Based on calculations by the RWS analog computer model DELTAR. Tidal period is approximately 12.5 hours.
(b) Increase of chloride concentration caused by the effect of the seawater. The background chloride concentration is subtracted (0.200 kg Cl⁻/m³).
Table 3.3
RIJNMOND TIDAL MODEL MEASUREMENTS WITH OUDE MAAS OPEN

<table>
<thead>
<tr>
<th>Experiment number (a)</th>
<th>T0</th>
<th>T11</th>
</tr>
</thead>
<tbody>
<tr>
<td>River discharges (m³/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nieuwe Waterweg</td>
<td>1359</td>
<td>1014</td>
</tr>
<tr>
<td>Nieuwe Maas</td>
<td>499</td>
<td>342</td>
</tr>
<tr>
<td>Oude Maas</td>
<td>860</td>
<td>672</td>
</tr>
<tr>
<td>Tidal conditions (b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tidal difference (m)</td>
<td>1.75</td>
<td>1.75</td>
</tr>
<tr>
<td>Flood volume (10⁶ m³)(c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nieuwe Waterweg</td>
<td>70.3</td>
<td>70.8</td>
</tr>
<tr>
<td>Nieuwe Maas</td>
<td>44.8</td>
<td>47.2</td>
</tr>
<tr>
<td>Oude Maas</td>
<td>15.8</td>
<td>19.1</td>
</tr>
<tr>
<td>Chloride concentration (kg Cl⁻/m³)(d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nieuwe Waterweg kmr 1029.00</td>
<td>11.65</td>
<td>12.79</td>
</tr>
<tr>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
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<td>0</td>
</tr>
</tbody>
</table>

(a) The survey of the study plan is given in Table 3.4.
(b) The tide of June 16, 1973, is used for these experiments.
(c) Based on IMPLIC calculations for the physical model experiments.
(d) The increase of the chloride concentration caused by the effect of the seawater. The background chloride concentration is subtracted.
### Table 3.4

**SURVEY OF THE EXPERIMENTS IN THE TIDAL SALINITY MODEL RIJNMOND ON THE CLOSURE OF THE OUDE MAAS**

<table>
<thead>
<tr>
<th>Number of experiment</th>
<th>T0</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
<th>T8</th>
<th>T9</th>
<th>T10</th>
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<tr>
<td><strong>Closure, Oude Maas</strong></td>
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<tr>
<td>Closure; flushing rate: 0 m³/s</td>
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<tr>
<td>(Hoek van Holland)</td>
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<td></td>
<td></td>
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<td>Neap tide: August 28, 1974 (1.35 m)(a)</td>
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<td>Normal tide (+): June 16, 1973 (1.75 m)</td>
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<td>X</td>
<td>X</td>
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<tr>
<td>Spring tide: June 22, 1974 (1.98 m)</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Tide of 12.5 hours: 1971-0 (1.65 m)</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
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</tr>
<tr>
<td><strong>Discharges (m³/s)</strong></td>
<td></td>
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<tr>
<td>Bovenrijn (Lobith)</td>
<td>1400</td>
<td>1400</td>
<td>1025</td>
<td>1025</td>
<td>1025</td>
<td>1400</td>
<td>650</td>
<td>1025</td>
<td>1400</td>
<td>1400</td>
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<td>1025</td>
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<tr>
<td>Maas (Lith)</td>
<td>145</td>
<td>145</td>
<td>95</td>
<td>95</td>
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<td>95</td>
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<tr>
<td>Nieuwe Waterweg</td>
<td>1359</td>
<td>1359</td>
<td>935</td>
<td>1114</td>
<td>1114</td>
<td>803</td>
<td>1267</td>
<td>630</td>
<td>942</td>
<td>1201</td>
<td>1183</td>
<td>934</td>
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<tr>
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<td>543</td>
<td>935</td>
<td>1114</td>
<td>1114</td>
<td>803</td>
<td>1267</td>
<td>630</td>
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<td>437</td>
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<td>764</td>
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<td>0</td>
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<td>Extraction Gouda</td>
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<td>45</td>
<td>45</td>
<td>45</td>
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<td>45</td>
<td>45</td>
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</tr>
</tbody>
</table>

**Geometry**

| Existing situation | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  |
| Enlarging Noord     | X  |    |    |    |    |    |    |    |    |    |    |    |

*SOURCE: Delft Hydraulics Laboratory, Afsluiten Oude Maas; verkennend onderzoek t.b.v. gebruik rekenmodellen (Closing Oude Maas: Preliminary Research on Behalf of Use of Computer Models), M-1552-1, December 1979 (in Dutch only). (Ref. 4)*

(a) Tidal difference.

(b) Tide at Hoek van Holland corrected for the influence of closing the Oude Maas.
Table 3.5

PHYSICAL MODEL EXPERIMENTS WITH OUDE MAAS CLOSED

<table>
<thead>
<tr>
<th>Experiment number (a)</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
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</thead>
<tbody>
<tr>
<td>River discharges (m³/s)</td>
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<tr>
<td>Nieuwe Waterweg</td>
<td>935</td>
<td>1114</td>
<td>803</td>
<td>1267</td>
<td>630</td>
</tr>
<tr>
<td>Nieuwe Maas</td>
<td>935</td>
<td>1114</td>
<td>803</td>
<td>1267</td>
<td>630</td>
</tr>
<tr>
<td>Oude Maas</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Tidal conditions</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal difference (m)</td>
<td>1.75</td>
<td>1.35</td>
<td>1.98</td>
<td>1.75</td>
<td>1.75</td>
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<table>
<thead>
<tr>
<th>Flood volume (10⁶ m³) (b)</th>
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<th></th>
<th></th>
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<td>Nieuwe Waterweg</td>
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<td>40.9</td>
<td>63.1</td>
<td>56.9</td>
<td>65.0</td>
</tr>
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<td>Nieuwe Maas</td>
<td>41.4</td>
<td>26.7</td>
<td>44.3</td>
<td>37.3</td>
<td>45.4</td>
</tr>
<tr>
<td>Oude Maas</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</table>

<table>
<thead>
<tr>
<th>Chloride concentration (kg Cl⁻/m³) (c)</th>
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</thead>
<tbody>
<tr>
<td>Nieuwe Waterweg kmr</td>
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<td>12.23</td>
<td>13.05</td>
<td>11.64</td>
<td>13.98</td>
</tr>
<tr>
<td>1024.75</td>
<td>10.99</td>
<td>10.90</td>
<td>11.30</td>
<td>9.85</td>
<td>12.49</td>
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<tr>
<td>1020.50</td>
<td>9.12</td>
<td>9.39</td>
<td>9.14</td>
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<td>10.84</td>
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<td>1015.75</td>
<td>6.71</td>
<td>7.28</td>
<td>6.70</td>
<td>5.37</td>
<td>8.76</td>
</tr>
<tr>
<td>Nieuwe Maas kmr</td>
<td>5.22</td>
<td>5.76</td>
<td>5.42</td>
<td>3.74</td>
<td>7.78</td>
</tr>
<tr>
<td>1008.25</td>
<td>3.89</td>
<td>4.74</td>
<td>4.01</td>
<td>1.81</td>
<td>6.58</td>
</tr>
<tr>
<td>1002.125</td>
<td>0.87</td>
<td>1.21</td>
<td>1.22</td>
<td>0.29</td>
<td>2.89</td>
</tr>
<tr>
<td>998.00</td>
<td>0.11</td>
<td>0.07</td>
<td>0.37</td>
<td>0.03</td>
<td>1.31</td>
</tr>
<tr>
<td>994.10</td>
<td>0.07</td>
<td>0.06</td>
<td>0.12</td>
<td>0.07</td>
<td>0.48</td>
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<tr>
<td>991.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.03</td>
</tr>
</tbody>
</table>

(a) The survey of the experiments is given in Table 3.4.
(b) Based on IMPLIC calculations for these experiments.
(c) The increase in the chloride concentration caused by the effect of the seawater. The background chloride concentration is subtracted.
Chapter 4

DEVELOPMENT OF THE ROTTERDAM SALT WEDGE MODEL

4.1. DESCRIPTION OF THE ORIGINAL VAN DER BURGH MODEL

The mathematical model developed by Van der Burgh is based on the following one-dimensional salt balance equation, averaged over the tidal period:

\[
D(x) \frac{dc(x)}{dx} = -u_{riv}(x) \cdot c(x)
\]  

(4.1)

where \( x \) = coordinate in longitudinal direction,
\( D(x) \) = longitudinal dispersion coefficient as a function of \( x \),
\( c(x) \) = average salt concentration over tidal period and over the cross section as a function of \( x \),
\( u_{riv}(x) \) = velocity due to river discharge as a function of \( x \), averaged over tidal period.

On the basis of the many field measurements made in the estuaries in the Netherlands, Van der Burgh established the following empirical relation for the dispersion coefficient:

\[
D(x) = D_0 - k_1 D_1(x) = k_0 (\alpha g)^{\frac{5}{2}} d^{1.5} - k_1 \int_0^x u_{riv} \, dx
\]  

(4.2)

with

\[
\alpha = \frac{Q_{riv} \cdot T}{P(T)}
\]  

(4.3)

where \( x \) = distance from the mouth of the river,
\( D_0 \) = dispersion coefficient at the mouth of the tidal river
\( \alpha \) and \( d \) measured at the mouth of the river,
\( k_1 D_1(x) \) = reduction of dispersion coefficient with increasing \( x \)
(distance from the mouth),
\( k_0, k_1 \) = dimensionless parameters,
\( \alpha \) = flood number,
\( g \) = gravity acceleration; 9.81 m/s\(^2\),
\[ d = \text{depth at the mouth of the estuary}, \]
\[ Q_{riv} = \text{river discharge}, \]
\[ T = \text{tidal period}, \]
\[ P(T) = \text{flood volume}. \]

To compute the distribution of salt concentration, averaged over the tidal period, another boundary condition at the mouth must be measured. Van der Burgh established the following expression to define the relation between the concentration at the mouth and the concentration at sea:

\[ c(\text{mouth}) = c(\text{sea}) \ast e^{-k_2 \alpha} \quad (4.4) \]

On the basis of measurement data collected from the Rotterdamsche Waterweg, Van der Burgh used the following values for \( k_0 \), \( k_1 \), and \( k_2 \):

\[ k_0 = 26; \ k_1 = 0.9; \ \text{and} \ k_2 = 0.5 \quad (4.5) \]

A detailed description of the model and its background is included in Ref. 7. The method and its validation are dealt with in Refs. 8 and 9.

### 4.2. THE MODIFIED MODEL

For PAWN, the basic form and parameter definitions of the Van der Burgh model described above have been retained. However, in order to best reproduce the available data (described in Chap. 3), we had to modify the model, changing both the equations and the values of the coefficients. To distinguish between the original Van der Burgh model and the model used in the PAWN study, we call the latter model the modified Van der Burgh model. The primary objective of this model is to reproduce, as closely as possible, the data collected through in situ and physical model measurements. We modified the model to reproduce these data without examining whether such modifications conform with the available information on the physical process of salt intrusion into estuaries. We may add, however, that the physical basis of the original Van der Burgh model is also uncertain (see Ref. 8). But as long as the available measurement data can be reproduced adequately, and the modified model is not used for situations that differ widely from the measurement situations, we can use the model for the purposes of the PAWN project. In describing how the model was changed, we discuss the following aspects in turn:
1. Premise
2. Boundary conditions near the sea
3. Relation for dispersion coefficient
4. Expression for flood volume
5. Required data (geometry, etc.)

4.2.1. Premise

The starting point for the modified model is the expression of the one-dimensional salt balance, averaged over one tidal period, as given above in Eq. 4.1:

\[ D(x) \ast \frac{dc(x)}{dx} = -u_{riv}(x) \ast c(x) \]

4.2.2. Boundary Condition near the Sea

Van der Burgh's model relates the concentration in the river mouth to the concentration in the seawater through Eq. 4.4:

\[ c(\text{mouth}) = c(\text{sea}) \ast e^{-k_2 \alpha} \]

Distances along the rivers are measured in terms of kilometer range lines. In the original Van der Burgh model, kmr 1034 was selected as the location of the river mouth. In the modified model for PAWN, we took kmr 1029 as the location of the mouth, because this was the range line nearest to the sea for which the salt concentration values were available for all measurements. We also chose kmr 1029 because it is located upstream of the connection between the Nieuwe Waterweg and the Europoort Harbor area. This location is more representative of the branch of the Nieuwe Waterweg. Figure 4.1a shows the variation in salt concentration at kmr 1029, c(1029), for all measurements, with flood number volume. The data used to compute \( \alpha \) (see Eq. 4.3) and the flood volumes for c(1029) were taken from Tables 3.1, 3.2, 3.3, and 3.5 and are summarized in Table 4.1. Figure 4.1a further shows the curves from Eq. 4.4 for \( k_2 = 0.5, 0.6, \) and 0.7, with c(sea) equal to 19 kg Cl\(^-\)/m\(^3\). The spread of the measurement data shows that Eq. 4.4 is not a suitable expression to determine the boundary condition, that is, the chloride concentration at kmr 1029. The standard deviation of the measurement data from the curve for \( k_2 = 0.6 \) is 0.84 kg Cl\(^-\)/m\(^3\).

In Fig. 4.1b, the chloride concentration at kmr 1029 is plotted against the average river discharge through the Nieuwe Waterweg, Q(NWW). The figure shows that the measurement results for c(1029) in kg/m\(^3\) obtained in both cases (Oude Maas branch open and closed) can be fairly well represented by
Fig 41 - Chloride concentration at kmr 1029, $c(1029)$, versus
(a) flood number $\alpha$ and (b) discharge at Nieuwe Waterweg $Q(NWW)$
Table 4.1
SUMMARY OF DATA FOR FIG. 4.1

<table>
<thead>
<tr>
<th>Measurement/Experiment</th>
<th>Chloride Concentration, kmr 1029, c(1029) (kg Cl⁻/m³)</th>
<th>River Discharge, N. Waterweg, Q(NNW) (m³/s)</th>
<th>Flood Volume, Mouth of N. Waterweg, P(T) (10⁶m³)</th>
<th>Flood Number, α</th>
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</thead>
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<tr>
<td>Oude Maas open</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>600 m³/s</td>
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<td>~600</td>
<td>71.3 (c)</td>
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<tr>
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<td>13.0</td>
<td>~1000</td>
<td>64.7 (c)</td>
<td>0.70</td>
</tr>
<tr>
<td>1600 m³/s</td>
<td>10.3</td>
<td>~1600</td>
<td>54.6 (c)</td>
<td>1.32</td>
</tr>
<tr>
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<td>9.45</td>
<td>1650</td>
<td>64.2</td>
<td>1.16</td>
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<tr>
<td>17/6/73</td>
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<td>0.85</td>
</tr>
<tr>
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<td>77.1</td>
<td>0.54</td>
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<td>77.8</td>
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<td>11.65</td>
<td>1359</td>
<td>70.3</td>
<td>0.87</td>
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<td>T11</td>
<td>12.79</td>
<td>1014</td>
<td>70.8</td>
<td>0.64</td>
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<td>61.2</td>
<td>0.69</td>
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<td>40.9</td>
<td>1.23</td>
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<td>803</td>
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<td>0.57</td>
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<td>1267</td>
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<td>1.00</td>
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<td>T6</td>
<td>13.98</td>
<td>630</td>
<td>65.0</td>
<td>0.44</td>
</tr>
</tbody>
</table>

(a) Based on IMPLIC calculations for these experiments.
(b) α = Q(NNW) * T/P(T); T = 12.5 hours.
(c) Calculated with IMPLIC for mean tidal conditions.

\[ c(1029) = 18.10 \exp[-0.0003608 \times Q(NNW)] \quad (4.6) \]

when Q(NNW), in m³/s, is given. The power of e is not dimensionless here, unless it is assumed that the dimension of coefficient 0.0003608 makes the entire power dimensionless, or that Q(NNW) was made dimensionless due to one or several parameters. This suggests that the physical basis of Eq. 4.6 is not correct. On the other hand, Fig. 4.1b shows that Eq. 4.6 is a better fit to the c(1029) data than Eq. 4.4. Although the dimensions of Eq. 4.4 are correct, its physical basis is uncertain, as shown by the poor fit to the data in Fig. 4.1a.

The modified Van der Burgh model uses Eq. 4.6 for the boundary condition near the sea (c(1029)) since the available data are reproduced well (see Fig. 4.1b), in spite of the physical inadequacies referred to above. The standard deviation of the measurement results from Eq. 4.6 is 0.20 kg Cl⁻/m³.
4.2.3. Relation for the Dispersion Coefficient

The original Van der Burgh model uses the following empirical relation from Eq. 4.2 for the dispersion coefficient:

\[
D(x) = k_0 (ag)^{0.5} d^{1.5} - k_1 \int_0^x u_{riv} \, dx
\]

The values for \( \alpha \) and \( d \) relate to the situation at the mouth of the Nieuwe Waterweg. The values for \( k_0 \) and \( k_1 \) that have been empirically determined apply to the situation in the Nieuwe Waterweg, as well as to the Oude Maas and Nieuwe Maas.

In the modified model, we took a different approach. We assumed that dispersion may be different for each of the river branches (Nieuwe Waterweg, Oude Maas, Nieuwe Maas). We modified Eq. 4.2 slightly for each branch, but we used the values for the flood number \( \alpha \) and the water depth \( d \) as they exist at the mouth of each branch involved. Then, on the basis of the available measurement results, the values for \( k_0 \) and \( k_1 \) were determined for each individual branch, resulting in a different set of values for each branch.

We selected this modification of the Van der Burgh model for both physical and practical reasons. The dispersion of salt in tidal rivers is determined to a substantial extent by geometric factors, such as water depth and width/depth ratio; by roughness; and by the flow conditions, such as the mean velocity due to the river discharge \( u_{riv} \) and the ratio between the velocity due to tidal motion and \( u_{riv} \). This latter ratio is represented by the flood number \( \alpha \). The majority of the above parameters occur in one form or another in the dispersion coefficient, Eq. 4.2; but a discussion of to what extent Eq. 4.2 adequately reflects the physical mechanisms exceeds the scope of this study.

Significant differences exist in the geometry and flow conditions in the three river branches (Nieuwe Waterweg, Oude Maas, Nieuwe Maas). Therefore, it is improbable that the same equation--based on the conditions for \( \alpha \) and \( d \) at the mouth of the Nieuwe Waterweg and using the same constants \( k_0 \) and \( k_1 \)--would estimate correctly the dispersion in all three river branches. This was confirmed during the calibration of the modified Van der Burgh model when we found that the measurements could be reproduced better by using different values for \( \alpha \), \( d \), \( k_0 \), and \( k_1 \) in the dispersion coefficient equation for each river branch.
During the calibration of the modified model, it also became obvious that proper reproduction of the measurements required a change in the power of \( a \) in the dispersion coefficient equation. Without such modification, correct reproduction at all river discharges could not be accomplished. Consequently, the modified model uses the following dispersion coefficient:

\[
D(x) = k_0 \ast a^{k_1} \ast g^{0.5} \ast d^{1.5} - k_1 \int_{0}^{x} u_{riv} \, dx
\]  

(4.7)

4.2.4. Expression for the Flood Volume, \( P \)

The flood number \( a \) was defined previously in Eq. 4.3. To compute \( a \), we need to know the value of the flood volume \( P \) as a function of the river discharge \( Q_{riv} \) and the tidal conditions. For the case with the Oude Maas open, a general expression for \( P \) was determined using IMPLIC, which is a mathematical model for computing the one-dimensional water movement within a river/canal system. With this model the RWS, Directie Waterhuishouding en Waterbeweging, District Zuidwest, made nine computations for three different tidal conditions (mean tide, spring tide, and neap tide) and three different river discharges through the Nieuwe Waterweg (600, 1000, and 1600 m³/s).

In order to run IMPLIC, it is necessary to make a number of specific assumptions regarding inputs, which are of secondary importance for the flood volume calculations made here. Thus, in these runs, the Rotterdamsche Waterweg infrastructure for the model experiments is characterized as Delta Project, stage I, phase I; that is, the situation as it prevailed in the course of the 1973-1974 period: bottom elevation in Nieuwe Maas and Nieuwe Waterweg trapjeslijn completed; Dordtse Kil not widened except near Dordrecht where the Mallegat branch is closed and the Krabbe branch is widened; Hartelkanaal closed; and Spui open. The tidal curves used at Hoek van Holland were the so-called 1971-0 tides. These tidal curves were created by taking the average of measured levels at mean tide, spring tide, and neap tide. These tidal curves are cyclical.

Some of the results of these nine computations are summarized in Table 4.2. (Additional data are included in unpublished information from RWS (PAWN file DW-346).) From the data in Table 4.2, we derived the following equations for mean tidal conditions (nos. 2, 5, and 8 in Table 4.2):

\[
P(NWW) = 81.3 \ast 10^6 - 16,700 \ast Q(NWW)
\]  

(4.8)

\[
P(NM) = [0.00005 \ast Q(NWW) + 0.58] \ast P(NWW)
\]  

(4.9)

\[
P(OM) = [-0.00008 \ast Q(NWW) + 0.34] \ast P(NWW)
\]  

(4.10)
Table 4.2
FLOOD VOLUME FOR DIFFERENT RIVER BRANCHES OF THE ROTTERDAMSCHIE WATERWEG

<table>
<thead>
<tr>
<th>IMPLIC Calculation</th>
<th>Tidal Difference, (2a_0) (m)</th>
<th>Discharge, (Q(\text{NWW})) (m³/s)</th>
<th>Flood Volume at Mouth of: (P(\text{NWW})) (10⁶ m³/s)</th>
<th>(P(\text{NM})) (10⁶ m³/s)</th>
<th>(P(\text{OM})) (10⁶ m³/s)</th>
<th>(P(\text{NWW}))</th>
<th>(P(\text{NM}))</th>
<th>(P(\text{OM}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.34</td>
<td>600</td>
<td>55.6</td>
<td>34.7</td>
<td>16.3</td>
<td>0.62</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.65</td>
<td>600</td>
<td>71.3</td>
<td>43.1</td>
<td>20.8</td>
<td>0.60</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.84</td>
<td>600</td>
<td>76.5</td>
<td>45.8</td>
<td>22.5</td>
<td>0.60</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.34</td>
<td>1000</td>
<td>48.7</td>
<td>32.1</td>
<td>12.0</td>
<td>0.66</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.65</td>
<td>1000</td>
<td>64.7</td>
<td>40.8</td>
<td>16.5</td>
<td>0.63</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.84</td>
<td>1000</td>
<td>70.4</td>
<td>43.5</td>
<td>18.5</td>
<td>0.62</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.34</td>
<td>1600</td>
<td>38.1</td>
<td>26.3</td>
<td>7.1</td>
<td>0.69</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.65</td>
<td>1600</td>
<td>54.6</td>
<td>35.4</td>
<td>11.6</td>
<td>0.65</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1.84</td>
<td>1600</td>
<td>60.7</td>
<td>38.3</td>
<td>13.8</td>
<td>0.63</td>
<td>0.23</td>
<td></td>
</tr>
</tbody>
</table>

where \(P(\text{NWW})\) = flood volume at the mouth of the Nieuwe Waterweg (m³), \(Q(\text{NWW})\) = mean river discharge through the Nieuwe Waterweg (m³/s), \(P(\text{NM})\) = flood volume at the mouth of the Nieuwe Maas (m³), \(P(\text{OM})\) = flood volume at the mouth of the Oude Maas (m³).

The expression below was derived to apply to all tidal conditions (see Fig. 4.1a):

\[
P(\text{NWW}) = [6.57 - .0160 \, Q(\text{NWW}) + 44.3 \, (2a_0)] \times 10^6
\]  
(4.11)

where \(2a_0\) = tidal range at the Hoek van Holland (m).

Equations 4.8 and 4.11 are very crude tools for estimating the value of the flood volume. But it is not necessary to predict this value exactly, because the results of the modified Van der Burgh model are not very sensitive to changes in the flood volume. To calibrate the modified model to the available data, Eq. 4.11 was used. But we used Eq. 4.8 in the PAWN analysis, because our study is based on mean tidal conditions (see Chap. 7). For the tidal salinity model experiments, the flood volume was computed using IMPLIC.

Somewhat different assumptions were used for these IMPLIC runs than were used in determining Eq. 4.11; the resulting flood volumes were found to be +10 percent higher than those given by Eq. 4.11. Because of the insensitivity of the Van der Burgh model to minor uncertainties in flood volume, this difference is not important for our purposes, and we have used Eq. 4.11 to determine the calibration constants in the modified Van der Burgh model. The fact that we were able to fit all three sets of data with a single set of calibration constants is evidence that this discrepancy is not important.
For the case with the Oude Maas closed, the expression for the flood volume, \( P \), was determined as follows: The flood volumes for the five Rijnmond model experiments were determined using IMPLIC (see Table 3.5). For three experiments (T2, T5, and T6) at virtually identical tidal conditions, the flood volume was correlated with the discharge in the Nieuwe Waterweg (see Fig. 4.2b), and the resulting expression for the flood volume \( P \) for mean tidal conditions is

\[
P(NW) = 72.9 \times 10^6 - 12,500 \times Q(NW)
\]  

(4.12)

It was not possible to develop a formula for other tidal conditions on the basis of these five experiments.

Using the results of all five model experiments for the calibration of the modified model, we took the flood volume values of Eq. 4.7, computed with IMPLIC (see Table 3.5). However, in the PAWN analysis, we used Eq. 4.12 because the study is based on mean tidal conditions. We assumed that the flood volume at the mouth of the Nieuwe Maas was the same as that at the mouth of the Nieuwe Waterweg. Thus, the decrease of the flood volume between the mouth of the Nieuwe Waterweg and that of the Nieuwe Maas was accounted for in the value of \( k_0 \) of the Nieuwe Maas branch.

4.2.5. Required Data (Geometry, etc.)

Computations with the modified model require certain geometric data and other constants. These data are summarized in Table 4.3.

For the dispersion coefficient \( D_x \) (see Eq. 4.7), we need the depth values \( d \) for the river branches at the mouth. These values were derived from IMPLIC input data. For depth \( d \), the value chosen was the hydraulic radius\(^1\) of the profile relative to NAP\(^2\). When the ratio between the width and depth of a cross section of a river is large, and the cross section is almost rectangular, the hydraulic radius is about equal to the mean depth. For the cross section of the branches considered, these conditions are fairly well met. Moreover, if a different value for depth \( d \) had been chosen, this would not have affected the modified model, except that the calibration of the model would have produced a different value for \( k_0 \) in Eq. 4.7. When applying the modified model for some of the river branches in PAWN, \( d \) cannot be varied to investigate the effect of depth variations on salt intrusion, because it is uncertain whether the model can forecast the effect on salt intrusion of changes in the geometry when these changes occur in the area of the salt wedge (see Ref. 8 and also Chap. 6).

The mean velocity over one tidal period, due to the river discharge \( Q_{riv} \), is
Fig 4.2 - Flood volume $P_{(NWW)}$ versus discharge at Nieuwe Waterweg $Q_{(NWW)}$ with (a) Oude Maas open and (b) Oude Maas closed.
Table 4.3
DATA FOR THE MODIFIED VAN DER BURGH MODEL

<table>
<thead>
<tr>
<th>Water depth at mouth: d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nieuwe Waterweg : 13.59 m (kmr 1029.000)</td>
</tr>
<tr>
<td>Nieuwe Maas : 11.70 m (kmr 1012.700)</td>
</tr>
<tr>
<td>Oude Maas : 9.06 m (kmr 1006.500)</td>
</tr>
</tbody>
</table>

Mean current-carrying profile per segment: \( A(x) \)

<table>
<thead>
<tr>
<th>River branch</th>
<th>( x ) (km)</th>
<th>Mean current-carrying profile of preceding segment, ( \int_0^x \frac{1}{A(x)} , dx ), (m(^{-1}))</th>
<th>Boundary of segment to beginning of river branch, (km)</th>
<th>( A(x) ) (m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nieuwe Waterweg</td>
<td>1029.00</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1027.37</td>
<td>1.63</td>
<td>6876</td>
<td>0.232</td>
</tr>
<tr>
<td></td>
<td>1020.53</td>
<td>8.47</td>
<td>6150</td>
<td>1.342</td>
</tr>
<tr>
<td></td>
<td>1016.60</td>
<td>12.40</td>
<td>5506</td>
<td>2.057</td>
</tr>
<tr>
<td></td>
<td>1012.70</td>
<td>16.30</td>
<td>6410</td>
<td>2.639</td>
</tr>
<tr>
<td>Nieuwe Maas</td>
<td>1012.70</td>
<td>0</td>
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<td>-</td>
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<tr>
<td></td>
<td>1008.57</td>
<td>4.13</td>
<td>5756</td>
<td>0.715</td>
</tr>
<tr>
<td></td>
<td>1003.22</td>
<td>9.48</td>
<td>5063</td>
<td>1.773</td>
</tr>
<tr>
<td></td>
<td>999.16</td>
<td>13.54</td>
<td>4055</td>
<td>2.773</td>
</tr>
<tr>
<td></td>
<td>994.24</td>
<td>18.46</td>
<td>2818</td>
<td>4.518</td>
</tr>
<tr>
<td></td>
<td>989.01</td>
<td>23.69</td>
<td>2816</td>
<td>6.338</td>
</tr>
<tr>
<td>Oude Maas</td>
<td>1006.50</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1003.58</td>
<td>2.92</td>
<td>2655</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>1002.68</td>
<td>3.82</td>
<td>2990</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td>995.36</td>
<td>11.14</td>
<td>2361</td>
<td>4.50</td>
</tr>
</tbody>
</table>

Tidal period: \( T = 12.5 \) hours = 45,000 s
Gravity acceleration: \( g = 9.81 \) m/s\(^2\)
\[ u_{riv} = \frac{Q_{riv}}{A} \]  

(4.13)

where \( A \) = the area of the river cross section, assuming the water level is at NAP, \( Q_{riv} \) = mean river discharge over tidal period in \( m^3/s \).

For each river branch, the discharge is determined using the Water Distribution Model. We have subdivided the various river branches into several segments. For each segment, the mean cross section \( A \) was obtained from IMPLIC input data, as shown in Table 4.3, along with the value for the integral \( I(x) \). The value for \( I(x) \) was derived from Eq. 4.7 as follows:

\[ k_1 \star \int_0^X u_{riv} \, dx = k_1 \star \int_0^X \frac{Q_{riv}}{A(x)} \, dx = k_1 \star Q_{riv} \star \int_0^X \frac{1}{A(x)} \, dx \]

(4.14)

Equation 4.14 applies to each river branch, because \( Q_{riv} \) is constant there.

In determining \( \alpha \) for use in Eq. 4.7, the tidal period is fixed at 12.5 hours (\( \alpha \) is defined in Eq. 4.3).

4.3. CALIBRATION OF THE MODIFIED MODEL

The modified model described in Sec. 4.2 is summarized in Table 4.4. Using the available measurement results (see Chap. 3) and the data contained in Sec. 4.2.3, we estimated the values for constants \( k_0 \), \( k_1 \), and \( k_3 \) for the different branches. Our procedure was to assume a set of values for the coefficients, calculate the variation of salt concentration with distance from the mouth of the Nieuwe Waterweg, and then compare the results with the measured data. The values used for the coefficients were then adjusted, and the procedure was repeated until satisfactory fits were obtained. The coefficients are shown below:

<table>
<thead>
<tr>
<th>River Branch</th>
<th>Oude Maas Open</th>
<th>Oude Maas Closed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( k_0 )</td>
<td>( k_1 )</td>
</tr>
<tr>
<td>Nieuwe Waterweg</td>
<td>29.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Nieuwe Maas</td>
<td>6.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Oude Maas</td>
<td>7.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Table 4.4
SUMMARY OF MODIFIED VAN DER BURGH MODEL

Modified model

Starting point

\[ D(x) * \frac{dc(x)}{dx} = -u_{riv}(x) * c(x) \]  \hspace{1cm} (4.1)

Boundary condition at sea

\[ c(1029) = c(\text{sea}) * \exp[-0.0003608 * Q(\text{NWW})] \]
\[ c(\text{sea}) = 19 \text{ kg } \text{Cl}^-/\text{m}^3 \]  \hspace{1cm} (4.6)

Dispersion coefficient

\[ D(x) = k_0 * \alpha^{k_1} * g^{0.5} * d^{1.5} - k_1 \int_0^x u_{riv} \, dx \]  \hspace{1cm} (4.7)
\[ \alpha = \frac{P(T)}{Q_{riv}} \]  \hspace{1cm} (4.3)
\[ u_{riv} = \frac{Q_{riv}}{A} \]  \hspace{1cm} (4.13)

Oude Maas open

\[ P(\text{NWW}) = 81.3 * 10^6 - 16,700 * Q(\text{NWW}) \]  \hspace{1cm} (4.8)
\[ P(\text{NM}) = [0.00005 * Q(\text{NWW}) + 0.58] * P(\text{NWW}) \]  \hspace{1cm} (4.9)
\[ P(\text{OM}) = [-0.00008 * Q(\text{NWW}) + 0.34] * P(\text{NWW}) \]  \hspace{1cm} (4.10)

Oude Maas closed

\[ P(\text{NWW}) = 72.9 * 10^6 - 12,500 * Q(\text{NWW}) \]  \hspace{1cm} (4.12)
\[ P(\text{NM}) = P(\text{NWW}) \]

NOTE: The coefficients are given in the text.
Comparisons of the measurements and the modified model results after calibration are shown in Figs. 4.3 through 4.11 for the Oude Maas open case and in Figs. 4.12 through 4.14 for the Oude Maas closed case. The computer program for the Oude Maas open case is listed in App. A, and that for the Oude Maas closed case in App. B. The computer language used is JOSS, an interactive language developed by The Rand Corporation for use with the IBM 370 computer.


We made computations with the modified Van der Burgh model for a large number of discharge combinations through the Nieuwe Waterweg, Oude Maas, and Nieuwe Maas for the Oude Maas open case. In addition, we made computations for various discharges through the Nieuwe Maas and Nieuwe Waterweg for the Oude Maas closed case. These computations yield the salt concentrations of the water at the mouths of the Hollandsche IJssel and the Spui and at the junction of the Oude and Nieuwe Maas. (These concentrations are averaged over the tidal period and over the cross section.) The results were fitted with the equations given below.

4.4.1. Oude Maas Open Case

The salinity at the mouth of the Hollandsche IJssel with the Oude Maas open, as it is at present, is given by

\[
c_{(m\cdot H\cdot IJ.)} = \exp[.318 - .00106 \times Q(\text{NWW})] \\
* \exp[2.14 - .0111 \times Q(\text{NM})]
\]

for \(300 \leq Q(\text{NWW}) \leq 800\) and \(80 \leq Q(\text{NM}) \leq 290\) \hspace{1cm} (4.15)

where \(c_{(m\cdot H\cdot IJ.)}\) = mean chloride concentration at the mouth of the Hollandsche IJssel (kg Cl\(^-\)/m\(^3\)),

\(Q(\text{NWW})\) = mean river discharge through the Nieuwe Waterweg (m\(^3\)/s),

\(Q(\text{NM})\) = mean river discharge through the Nieuwe Maas (m\(^3\)/s).

The difference between the results from Eq. 4.15 and those computed by the modified model (Table 4.5) is less than 0.050 kg Cl\(^-\)/m\(^3\).

The salinity at the junction of the Oude Maas and Nieuwe Maas when the Oude Maas is open is given by
Fig. 4.3 - Results of calibration of modified model with Oude Maas open: $Q(NWW) = 600\ m^3/s$
Fig. 4.4 - Results of calibration of modified model with Oude Maas open: $Q(\text{NWW}) = 1000 \text{ m}^3/\text{s}$
Fig. 4.5 - Results of calibration of modified model with
Oude Maas open: Q(NWW) = 1500 m³/s
Fig 4.6 - Results of calibration of modified model with Oude Maas open: June 16, 1973, data
Fig. 4.7 - Results of calibration of modified model with Oude Maas open: June 17, 1973, data
Fig. 4.8 - Results of calibration of modified model with Dordt Maas open: June 22, 1974, data
Fig. 4.9 - Results of calibration of modified model with Oude Maas open: June 23, 1974, data
Fig. 4.10 - Results of calibration of modified model with Oude Maas open: Test TO data
Fig. 4.11 - Results of calibration of modified model with Oude Maas open: Test T11 data
Fig. 4.12 - Results of calibration of modified model with Oude Maas closed: (a) Test T2 data and (b) Test T5 data
Fig. 4.13 – Results of calibration of modified model with Oude Maas closed: Test T6 data
Fig. 4.14 - Results of calibration of modified model with Oude Maas closed: (a) Test T3 data and (b) Test T4 data
Table 4.5
RESULTS WITH THE MODIFIED VAN DER BURGH MODEL: OEUDE MAAS OPEN

<table>
<thead>
<tr>
<th>Discharge, Nieuwe Waterweg, Q(NWW) (m³/s)</th>
<th>Discharge, Nieuwe Maas, Q(NM) (m³/s)</th>
<th>Chloride Concentration at Mouth of Hollandsche IJssel (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modified Model</td>
<td>Equation 4.15</td>
</tr>
<tr>
<td>300</td>
<td>95</td>
<td>2.913</td>
</tr>
<tr>
<td>350</td>
<td>95</td>
<td>2.757</td>
</tr>
<tr>
<td>400</td>
<td>95</td>
<td>2.610</td>
</tr>
<tr>
<td>350</td>
<td>125</td>
<td>1.984</td>
</tr>
<tr>
<td>400</td>
<td>125</td>
<td>1.879</td>
</tr>
<tr>
<td>450</td>
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<td>450</td>
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<td>1.289</td>
</tr>
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<td>500</td>
<td>155</td>
<td>1.221</td>
</tr>
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<td>550</td>
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<td>550</td>
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<tr>
<td>600</td>
<td>185</td>
<td>0.795</td>
</tr>
<tr>
<td>650</td>
<td>185</td>
<td>0.753</td>
</tr>
<tr>
<td>650</td>
<td>215</td>
<td>0.545</td>
</tr>
<tr>
<td>700</td>
<td>215</td>
<td>0.516</td>
</tr>
<tr>
<td>750</td>
<td>215</td>
<td>0.489</td>
</tr>
<tr>
<td>700</td>
<td>245</td>
<td>0.373</td>
</tr>
<tr>
<td>750</td>
<td>245</td>
<td>0.353</td>
</tr>
<tr>
<td>800</td>
<td>245</td>
<td>0.334</td>
</tr>
</tbody>
</table>
\[ c(j) = 15.8(1 - 0.323 \times 10^{-6}[Q(NWW) - 700]^2) \times \exp[-1.172 \times 10^3 Q(NWW)] \]

for 700 \(< Q(NWW) \]

and

\[ c(j) = 15.8 \exp[-1.172 \times 10^3 Q(NWW)] \]

for \( Q(NWW) > 700 \) \hspace{1cm} (4.16)

where \( c(j) \) = salinity at the junction of the Oude and Nieuwe Maas (kg Cl\(^{-}\)/m\(^3\)).

The salinity at the mouth of the Spui when the Oude Maas is open is given by

\[ c(sp) = 0 \hspace{1cm} \text{for } Q(NWW) \geq 600 \]

\[ c(sp) = C_1 - (C_1 - C_2)[Q(NWW) - 400]/400 \hspace{1cm} \text{for } Q(NWW) < 600 \]

\[ C_1 = 6137 - 49.6 Q(OM) + 0.1564 Q(OM)^2 \]

\[ - 2.238 \times 10^{-6} Q(OM)^3 + 1.208 \times 10^{-7} Q(OM)^4 \]

\[ C_2 = 4037 - 31.8 Q(OM) + 0.0999 Q(OM)^2 \]

\[ - 1.444 \times 10^{-4} Q(OM)^3 + 7.917 \times 10^{-8} Q(OM)^4 \] \hspace{1cm} (4.17)

where \( c(sp) \) = salinity at the mouth of the Spui (kg Cl\(^{-}\)/m\(^3\)),

\( Q(NWW) \) = mean river discharge through the Nieuwe Waterweg (m\(^3\)/s),

\( Q(OM) \) = mean river discharge through the Oude Maas (m\(^3\)/s).

Results obtained from Eqs. 4.15, 4.16, and 4.17 for the salt concentrations at the mouths of the Hollandsche IJssel and Spui and the junction of the Oude and Nieuwe Maas are shown graphically in Figs. 4.15, 4.16, and 4.17.
Fig. 4.15 - Salinity at the mouth of the Hollandsche IJssel, as estimated by the modified Van der Burgh model, with Oude Maas open: Equation 4.15
Fig. 4.16: Salinity at the junction of the Oude Maas and Nieuwe Maas, as estimated by the modified Van der Burgh model, with Oude Maas open: Equation 4.16.

SALINITY AT THE JUNCTION OF OUDE AND NIEUWE MAAS (kg Cl⁻/m³)
Fig. 4.17—Salinity at the mouth of the Spui, as estimated by the modified Van der Burgh model, with Oude Maas open: Equation 4.17
4.4.2. Oude Maas Closed Case

The salinity at the mouth of the Hollandsche IJssel when the Oude Maas is closed is given by

\[ c(\text{m.H.IJ.}) = \sum_{i=0}^{5} a_i \times Q(\text{NWW})^i \quad \text{but} \quad c(\text{m.H.IJ.}) = 0 \]  

(4.18)

if this result is negative, where

\[ c(\text{m.H.IJ.}) = \text{mean chloride concentration at the mouth of the Hollandsche IJssel (kg} \ \text{Cl}^-/\text{m}^3), \]

\[ Q(\text{NWW}) = \text{mean river discharge through the Nieuwe Waterweg} \ (\text{m}^3/\text{s}), \]

\[ a_0 = +15.97, \]
\[ a_1 = -0.07826, \]
\[ a_2 = +0.1827 \times 10^{-3}, \]
\[ a_3 = -0.2725 \times 10^{-6}, \]
\[ a_4 = +0.2489 \times 10^{-9}, \]
\[ a_5 = -0.1005 \times 10^{-12}. \]

The maximum difference between the results from Eq. 4.18 and those computed by the modified model is less than 0.010 kg Cl\(^-\)/m\(^3\), as shown in Table 4.6.

Salt concentrations at the mouth of the Hollandsche IJssel with the Oude Maas closed have been calculated from Eq. 4.18 and are shown graphically in Fig. 4.18.

In Figs. 4.15 through 4.18, we have used our equations to extrapolate well beyond the region in which measured data exist. We have done so because PAWN investigates some extreme situations in which river flows are outside the ranges that have actually been experienced. To give some idea of the extent of this extrapolation, we have indicated the regions in which the actual measured data lie on Figs. 4.15 through 4.18. When the equations give results outside this range, they should be viewed with caution.
Fig. 4.18 - Salinity at the mouth of the Hollandsche IJssel, as estimated by the modified Van der Burgh model, with Oude Maas closed: Equation 4.18
Table 4.6
RESULTS WITH THE MODIFIED VAN DER BURGH MODEL: OUDE MAAS CLOSED

<table>
<thead>
<tr>
<th>Discharge, Nieuwe Waterweg, Q(NWW) (m³/s)</th>
<th>Chloride Concentration at Mouth of Hollandsche IJssel (kg/m³)</th>
<th>Modified Model</th>
<th>Equation 4.16</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>4.446</td>
<td>4.440</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>300</td>
<td>3.348</td>
<td>3.349</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>350</td>
<td>2.478</td>
<td>2.484</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>400</td>
<td>1.797</td>
<td>1.801</td>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>450</td>
<td>1.272</td>
<td>1.270</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>500</td>
<td>0.874</td>
<td>0.868</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>550</td>
<td>0.580</td>
<td>0.574</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>600</td>
<td>0.368</td>
<td>0.369</td>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>650</td>
<td>0.220</td>
<td>0.226</td>
<td>0.2</td>
<td>2.6</td>
</tr>
<tr>
<td>700</td>
<td>0.121</td>
<td>0.113</td>
<td>0.2</td>
<td>5.3</td>
</tr>
</tbody>
</table>

NOTES
1. The hydraulic radius is the flow area of a cross section divided by the perimeter in contact with the bottom or banks.
2. Normaal Amsterdams Peil is the reference level for measuring elevations in the Netherlands.
Chapter 5
DEVELOPMENT OF THE GOUDA INLET SALINITY MODEL

5.1. ANALYSIS WITH CONSTANT RIVER DISCHARGES

The model described in Chap. 4 provides an estimate of the mean salt concentrations of the water of the Nieuwe Waterweg, Nieuwe Maas, and Oude Maas as a function of the discharge through the various river branches. Thus, the model also computes the mean salt concentration at the mouth of the Hollandsche IJssel at Kralingse Veer. Further upstream on the Hollandsche IJssel at Gouda is located the water extraction point for the water boards of Rijnland, Delfland, and Schieland. The mean capacity of the extraction point is currently 35 m³/s. The water that is taken is used for controlling the water level in the boezems and polders, for flushing to control the internal pollution, as well as for limiting salt intrusion at locks and outlet sluices where the area borders on saline or brackish water. For horticulture in the region, it is important to know the salt concentration of the water that is taken in at Gouda, especially when salt intrusion from the sea occurs. For this purpose, we have developed the Gouda Inlet Salinity Model that relates the salt concentration at the Gouda inlet to that at the mouth of the Hollandsche IJssel.

Since the Haringvliet and Volkerak branches were closed (about 1970), salt intrusion into the water of the Hollandsche IJssel at Gouda has occurred several times—in 1971, 1972, and in 1976. However, the data available on these occurrences are so limited that they could not serve as the basis for estimating the relationship between the mean salt concentrations at the mouth of the Hollandsche IJssel and at the extraction point at Gouda. (Report on an investigation of this problem by the RWS has been published in Refs. 10 and 11.)

For purposes of the PAWN study, we selected the following approach. We used a mathematical model to describe the water movement and the salt concentration of the water in the Hollandsche IJssel. The model computed, as a function of time, the velocity (flow rates) and salt concentration in one dimension along the Hollandsche IJssel. We simplified the water movement in the model (by neglecting inertia effects) by using a so-called tidal fill computation, which implies that water level values as a function of time are the same at each point along the river branch. The salt movement reflects both the advective and the dispersive transport. The advective transport causes a change in the salt concentration because the salt is carried off by the mean water movement. The dispersive transport causes an additional longitudinal dispersion in the river branch because of differences between the local velocity and salt concentration on one hand and the mean velocity and concentration over the cross section on the other hand. These differences are due to density effects and the effect of the bottom and banks on the velocity distribution.
In the Hollandsche IJssel, however, the mixing in the cross section is such that density effects are not expected to be significant. The dispersive transport is accounted for in the model through a dispersion coefficient. We varied the value of the coefficient to investigate the sensitivity of the results to that coefficient. The dispersion coefficient is expressed as:

\[ D(x, t) = k \times u_s \times h_s \]  \hspace{1cm} (5.1)

where \( D(x, t) \) = dispersion coefficient as a function of the longitudinal direction \( x \) and of time \( t \),
\( k \) = dispersion constant,
\( u_s \) = mean velocity in the transporting water,
\( h_s \) = mean water depth of the transporting water.

The water level and the salt concentration, as a function of time, at the mouth of the Hollandsche IJssel are inputs to the model. For the Oude Maas open case, these data are derived from in situ measurements (water levels at the weir at Krimpen and the salt concentration of the water at the Van Brienenoord Bridge) and from physical model measurements [4]. Some of the computations examined the effect on the salt concentration at Gouda of a phase displacement of the water level curve compared with the salt concentration curve. As a result of these computations, the phase displacement was set at 30 minutes, which is expected to be an upper bound for the phase displacement.

At the extraction point at Gouda, we specified a withdrawal rate of either 20 or 40 m\(^3\)/s, with the majority of the computations carried out with the lower rate.

The input data and the results of the computations are summarized in Table 5.1 and are plotted in Fig. 5.1. This part of the study is described in detail in Ref. 5. Here we summarize several of its important conclusions:

- The computer program we developed can be used to describe adequately the mechanism of the salt intrusion into the Hollandsche IJssel and to carry out comparative studies.
- The results of the computations are essentially insensitive to the estimated values of the dispersion coefficients (calculations 8 and 9 in Table 5.1).
- The change in the salt concentration at Gouda when the withdrawal rate is varied between 20 and 40 m\(^3\)/s is small (calculations 5 and 8, 17 and 18, or 19 and 20). The withdrawal rate does affect the time that elapses before salt


<table>
<thead>
<tr>
<th>Origin of data (water level, chloride concentration)</th>
<th>Mean Chloride Concentration</th>
<th>Mean Chloride Concentration at Mouth, Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cal- Hollandsche IJssel: M = Model Experiment, Phase</td>
<td>Withdrawal</td>
<td>at Dispersal Gouda c(m.H.IJ.) c(Gouda)</td>
</tr>
<tr>
<td>cu- N = In Situ Measurement Difference (m³/s) Constant (kg/m³)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Oude Maas closed**

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M: experiment T6(a)</td>
<td>-</td>
<td>20</td>
<td>20</td>
<td>0.430</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>M: experiment T6</td>
<td>-</td>
<td>40</td>
<td>20</td>
<td>1.265</td>
<td>0.012</td>
</tr>
<tr>
<td>3</td>
<td>M: experiment T6</td>
<td>-</td>
<td>20</td>
<td>20</td>
<td>1.265</td>
<td>0.007</td>
</tr>
<tr>
<td>4</td>
<td>M: experiment T6</td>
<td>1/2 hour</td>
<td>20</td>
<td>20</td>
<td>1.265</td>
<td>0.003</td>
</tr>
<tr>
<td>5</td>
<td>M: experiment T6</td>
<td>-</td>
<td>20</td>
<td>20</td>
<td>3.000</td>
<td>0.660</td>
</tr>
<tr>
<td>6</td>
<td>M: experiment T6</td>
<td>1/2 hour</td>
<td>20</td>
<td>20</td>
<td>3.000</td>
<td>0.970</td>
</tr>
<tr>
<td>7</td>
<td>M: experiment T6</td>
<td>-</td>
<td>40</td>
<td>20</td>
<td>3.000</td>
<td>0.780</td>
</tr>
<tr>
<td>8</td>
<td>M: experiment T6</td>
<td>-</td>
<td>40</td>
<td>5</td>
<td>3.000</td>
<td>0.737</td>
</tr>
<tr>
<td>9</td>
<td>M: experiment T6</td>
<td>-</td>
<td>20</td>
<td>20</td>
<td>4.320</td>
<td>3.580</td>
</tr>
<tr>
<td>10</td>
<td>M: experiment T6</td>
<td>-</td>
<td>20</td>
<td>20</td>
<td>4.320</td>
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</tr>
<tr>
<td>11</td>
<td>M: experiment T6(a)</td>
<td>-</td>
<td>20</td>
<td>20</td>
<td>0.910</td>
<td>0.008</td>
</tr>
<tr>
<td>12</td>
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<td>-</td>
<td>20</td>
<td>20</td>
<td>1.050</td>
<td>0.025</td>
</tr>
<tr>
<td>13</td>
<td>M: experiment T11</td>
<td>-</td>
<td>20</td>
<td>20</td>
<td>0.850</td>
<td>0.030</td>
</tr>
<tr>
<td>14</td>
<td>M: experiment T11</td>
<td>-</td>
<td>40</td>
<td>20</td>
<td>0.850</td>
<td>0.035</td>
</tr>
<tr>
<td>15</td>
<td>M: experiment T11</td>
<td>-</td>
<td>20</td>
<td>20</td>
<td>2.800</td>
<td>1.000</td>
</tr>
<tr>
<td>16</td>
<td>M: experiment T11</td>
<td>-</td>
<td>40</td>
<td>20</td>
<td>2.800</td>
<td>1.050</td>
</tr>
</tbody>
</table>

(a) See Table 3.4.
Fig. 5.1—Chloride concentration at the mouth of the Hollandsche IJssel versus Chloride concentration at Gouda
intrusion can be observed at Gouda. At a rate of 20 m³/s, that time is well in excess of three days, whereas it is only about two days at a rate of 40 m³/s. After six days an equilibrium is achieved; that is, the salt concentration at the extraction point is almost constant.

- The sensitivity of the salt concentration at Gouda to the correct phase difference between the water level and salt curve is considerable (calculation 5 compared with 7).
- The model provides a reasonably accurate forecast of the salt concentration at Gouda as a function of the mean salt concentration at the mouth of the Hollandsche IJssel.
- As shown in Fig. 5.1, salt intrusion occurs more readily at Gouda if the Oude Maas is open than if it is closed. But it is hard to say whether this result is significant, because confidence intervals cannot be determined on the basis of this limited study.
- Under normal conditions, the peak of the curve of the salt concentration at the mouth does not affect the salt concentration at the withdrawal point, because the water with high salt concentration flows in with the flood tide and out again at ebb tide. Salt intrusion into the Hollandsche IJssel is determined by the lower part of the descending slope of the salt concentration curve and by the bottom of that curve at low tide (see Fig. 5.6 below).

The results shown in Table 5.1 were fitted with the following equations for the Oude Maas closed case (chloride concentration in kg/m³) (see also Fig. 5.1):

\[
\text{If } c(\text{m.H.IJ.}) \leq 1.270, \quad \text{then } c(\text{Gouda}) = 0, \quad (5.2)
\]

\[
\text{if } 1.270 < c(\text{m.H.IJ.}) \leq 3.000, \quad \text{then } c(\text{Gouda}) = 0.46 \times c(\text{m.H.IJ.}) - 0.580, \quad (5.3)
\]

\[
\text{if } 3.000 < c(\text{m.H.IJ.}) \leq 5.675, \quad \text{then } c(\text{Gouda}) = 1.83 \times c(\text{m.H.IJ.}) - 4.710, \quad (5.4)
\]

\[
\text{if } c(\text{m.H.IJ.}) > 5.675, \quad \text{then } c(\text{Gouda}) = c(\text{m.H.IJ.}). \quad (5.5)
\]

For the Oude Maas open case, the following equations were found:

\[
\text{If } c(\text{m.H.IJ.}) \leq 0.915, \quad \text{then } c(\text{Gouda}) = 0, \quad (5.6)
\]
if $0.915 < c(\text{m.H.IJ.}) \leq 2.800$,  
then $c(\text{Gouda}) = 0.53 \, c(\text{m.H.IJ.}) - 0.460$. \hfill (5.7)

Data are unavailable for salt concentrations higher than 2.80 at the mouth of the Hollandsche IJssel. No problems are expected to arise, however, because higher salt concentrations are very unlikely to occur. If it should appear necessary to consider higher values, the same slope is assumed to apply as in the Oude Maas closed case. This results in

If $2.800 < c(\text{m.H.IJ.}) \leq 4.940$,  
then $c(\text{Gouda}) = 1.83 \, c(\text{m.H.IJ.}) - 4.100$, \hfill (5.8)

if $c(\text{m.H.IJ.}) > 4.940$, then $c(\text{Gouda}) = c(\text{m.H.IJ.})$. \hfill (5.9)

where $c(\text{m.H.IJ.}) =$ mean chloride concentration at the mouth of the Hollandsche IJssel (kg/m³),  
c(\text{Gouda}) =$ mean chloride concentration at the withdrawal point at Gouda (kg/m³).

The results shown above apply to the situation where the discharges through the Nieuwe Waterweg, Oude Maas, and Nieuwe Maas are assumed to be constant over a long period of time.

5.2. ANALYSIS WITH VARYING RIVER DISCHARGES

Section 5.1 discussed the relationship between the salt concentration at Gouda and that at the mouth of the Hollandsche IJssel, but only during a specific period of time (e.g., the 10-day period used in the PAWN study) in which the discharges through the Rotterdamsche Waterweg did not vary. However, river discharges do vary over such a time period in the real world. These variations are caused mainly by two phenomena: tidal oscillations at sea and the variations of the discharges through the Rijn and Maas [6].

Tidal oscillation at sea, resulting from the gravitational interaction between the water of the world's seas and the sun and moon, manifests itself as a variation in the tidal difference at the Hoek van Holland. From neap tide, with a mean tidal difference of 1.34 m, the tidal difference increases to an average 1.84 m at spring tide, then drops again to neap tide. This variation covers a period of approximately 14 days. (It is possible that, in addition to the variation in the tidal difference, there is a variation in the mean water level at the Hoek van Holland—a topic that needs further study.) Tidal oscillation at sea causes variation in the water level in the Haringvliet and the Hollandsch Diep.
Because of the vast storage area of both of these waters (Haringvliet, Hollandsch Diep), discharge from the Rijn (through the Waal and Lek) and the Maas is stored in the area when the water levels rise. This storage reduces the mean river discharge through the Oude Maas, Nieuwe Maas, and Nieuwe Waterweg. When the water levels fall, the reverse effect occurs. This phenomenon is sometimes referred to as the Haringvliet effect. However, because it has not as yet been adequately studied, data are unavailable on these interactions. The effects of variation in river discharges due to this Haringvliet effect on the relative salt concentrations is another uncertain factor.

On the basis of computations with tidal sequences for the Oude Maas closed study in the tidal salinity model, it was established that the Haringvliet effect may cause a variation in the discharge through the Nieuwe Waterweg of approximately \( \pm 250 \text{ m}^3/\text{s} \) with respect to the equilibrium (e.g., NLP - 70) with the Oude Maas open. For the Oude Maas closed, the variation is apparently reduced by approximately 40 percent to \( \pm 150 \text{ m}^3/\text{s} \). Although sufficient information is lacking on the Haringvliet effect, we made the following assumptions in the PAWN study:

- The Haringvliet effect causes a sinusoidal variation in the discharge through the Nieuwe Waterweg for a 14-day period. For the open Oude Maas, we assumed a relationship of the following form: \( 250 \times \sin \left( \frac{x}{14} \times 360 \text{ deg} \right) \). For the closed Oude Maas, we assumed a relationship of \( 150 \times \sin \left( \frac{x}{14} \times 360 \text{ deg} \right) \), where \( x \) represents the number of days.
- For the open Oude Maas, the discharge distribution over the Oude Maas and Nieuwe Maas is not affected by the Haringvliet effect.

The discharges of the Rijn and Maas rivers vary continuously, but the PAWN study uses constant values for a 10-day period. The relationships between the discharges and the salt concentration at the mouth of the Hollandsche IJssel, and the relations between that salt concentration and the salt concentration at the extraction point at Gouda, are not linear (see Eqs. 4.15 and 4.16 and Fig. 5.1). Consequently, using only mean values over a 10-day period and ignoring discharge variations, we can produce an inaccurate estimate of the mean salt concentration at Gouda.

We determined the discharge variation over a 10-day period as follows: Considering the observed difference between the 10-day period mean of the Rijn and Maas discharges at low discharges through the Rijn (less than 900 m\(^3\)/s), we found that a difference of 200 m\(^3\)/s or more occurs with a probability of about 20 percent. We therefore considered this value to be a practical upper bound. It was derived as follows:
- Discharge variations in the Rijn and Maas cause a linear variation of the discharges through the Nieuwe Waterweg, Oude Maas, and Nieuwe Maas around the 10-day period mean: The variation is ± 100 m³/s at the start of a 10-day period and ± 100 m³/s at the end of that period. The total difference between the start and end values, therefore, is 200 m³/s. This applies to both open and closed Oude Maas.

- The discharge distribution over the Oude Maas and Nieuwe Maas for the Oude Maas open case is not affected by this variation.

We considered three cases in examining the effects of the two phenomena--river discharges and tidal oscillations.

5.2.1. Unfavorable Case

Here we assumed that both phenomena occur during the 10-day period so that, in terms of salt intrusion into the Hollandsche IJssel, the most adverse situation arises. In this case, shown in Fig. 5.2a, the lowest discharge values of the sine curve and of the linear variation coincide. The result is superposed on the 10-day period mean discharge through the Nieuwe Waterweg. Then the discharges through the Oude Maas and Nieuwe Maas are found, assuming they maintain their original ratio (from NLP - 70).

5.2.2. Favorable Case

Here the two phenomena are assumed to occur so that, in terms of salt intrusion into the Hollandsche IJssel, the most favorable situation arises. In this case, shown in Fig. 5.2b, the lowest (negative) discharge values of the sine are omitted, and the remaining lowest discharges are offset, as much as practical, by discharge values of the linear variation. This result is superposed on the 10-day period mean discharge through the Nieuwe Waterweg.

5.2.3. Average Case

In this case, we omit the linear variation. The sinusoidal variation throughout the 14-day period is superposed on the mean discharge situation, according to NLP - 70.

In each of these three cases, we computed the mean discharge for each day of the period (10 days for the unfavorable and favorable cases and 14 days for the average case) for the Nieuwe Waterweg, Nieuwe Maas, and Oude Maas. Next, we used these discharges in Eqs. 4.15 and 4.16 and Eqs. 5.2 through 5.9 to compute the mean chloride concentration at the Gouda extraction point for each day. Then, we derived the
Fig. 5.2 - Cases for varying discharges via Nieuwe Waterweg:
(a) unfavorable case and (b) favorable case
arithmetic mean of these values for the 10 or 14 days. The results of this procedure for several discharges through the Rotterdamsche Waterweg are shown in Table 5.2, and Figs. 5.3 and 5.4. Figure 5.5 gives the chloride concentration as a function of the Nieuwe Waterweg discharge with the Oude Maas closed. This type of figure cannot be presented with the Oude Maas open because the ratio between the discharge of the Oude and Nieuwe Maas is not constant.

The computed results for the average case, given in Table 5.2, were fitted by the following equations to be used in the Water Distribution Model:

**Oude Maas Open**

\[
c(\text{Gouda}) = -0.07432 + 0.2417 \times c(\text{m.H.IJ.}) - 0.07388 \times c(\text{m.H.IJ.})^2 \\
+ 0.2902 \times c(\text{m.H.IJ.})^3
\]

for \(0.310 < c(\text{m.H.IJ.}) < 1.530\),  \hspace{1cm} (5.10)

\[
c(\text{Gouda}) = 0 \quad \text{for } c(\text{m.H.IJ.}) < 0.310,
\]

(5.11)

where \(c(\text{Gouda}) = \) chloride concentration at the Gouda extraction point (kg Cl\(^{-}/\)m\(^3\)),

\(c(\text{m.H.IJ.}) = \) chloride concentration at the mouth of the Hollandsche IJssel (kg Cl\(^{-}/\)m\(^3\)).

The difference between the results of Table 5.2 and Eq. 5.10 is less than 0.025 kg/m\(^3\).

**Oude Maas Closed**

The computed results for the average case, given in Table 5.2, were fitted by the following equations:

\[
c(\text{Gouda}) = 0.1235 - 0.5408 \times c(\text{m.H.IJ.}) + 0.6949 \times c(\text{m.H.IJ.})^2 \\
- 0.0861 \times c(\text{m.H.IJ.})^3
\]

for \(0.370 < c(\text{m.H.IJ.}) < 3.350 \text{ kg/m}^3\),  \hspace{1cm} (5.12)

\[
c(\text{Gouda}) = 0 \quad \text{for } c(\text{m.H.IJ.}) < 0.370 \text{ kg/m}^3.
\]

(5.13)

The difference between the results of Table 5.2 and Eq. 5.12 is less than 0.025 kg/m\(^3\).
Table 5.2

CHLORIDE CONCENTRATION AT GOUDA WITH VARYING RIVER DISCHARGES

<table>
<thead>
<tr>
<th>Discharge, N. Waterweg/ N. Maas (m³/s)</th>
<th>Chloride Concentration at Mouth H. IJssel Discharges (kg/m³)</th>
<th>Chloride Concentration at Gouda with Constant Discharges (kg/m³)</th>
<th>Chloride Concentration at Gouda (kg/m³) with Varying Discharges</th>
<th>Unfavorable Case</th>
<th>Favorable Case</th>
<th>Average Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oude Maas open</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>800/245</td>
<td>0.330</td>
<td>0</td>
<td>0.059</td>
<td>0</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>700/215</td>
<td>0.511</td>
<td>0</td>
<td>0.186</td>
<td>0</td>
<td>0.073</td>
<td></td>
</tr>
<tr>
<td>625/194</td>
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<td>0.167</td>
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<tr>
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<td>2.121</td>
<td>0.284</td>
<td>1.164</td>
<td></td>
</tr>
<tr>
<td>Oude Maas closed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>0.368</td>
<td>0</td>
<td>0.091</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>0.580</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0.041</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>0.874</td>
<td>0</td>
<td>0.568</td>
<td>0.039</td>
<td>0.134</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>1.797</td>
<td>0.247</td>
<td>2.082</td>
<td>0.313</td>
<td>0.869</td>
<td></td>
</tr>
<tr>
<td>350</td>
<td>2.478</td>
<td>0.560</td>
<td>2.968</td>
<td>0.677</td>
<td>1.750</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>3.348</td>
<td>1.417</td>
<td>4.098</td>
<td>1.301</td>
<td>2.848</td>
<td></td>
</tr>
</tbody>
</table>
CHLORIDE CONCENTRATION AT MOUTH OF H. IJSSEL (kg/m³)

RELATION WITH CONSTANT DISCHARGES
RELATION WITH VARYING DISCHARGES

NOTE: THE CHLORIDE CONCENTRATION AT THE MOUTH OF THE HOLLANDSCHE IJSSEL WITH CONSTANT DISCHARGES (EQUATION 4.15)

Fig. 5.3 - Chloride concentration at Gouda with Oude Maas open
Fig. 5.4 – Chloride concentration at Gouda with Oude Maas closed

CHLORIDE CONCENTRATION AT MOUTH OF H. IJSSEL (kg/m³)

CHLORIDE CONCENTRATION AT GOUDA (kg/m³)

---

AND

RELATION WITH

CONSTANT DISCHARGES

RELATION WITH

VARYING DISCHARGES

NOTE: THE CHLORIDE CONCENTRATION AT THE MOUTH OF THE HOLLANDSCHE IJSSEL WITH CONSTANT DISCHARGE (EQUATION 4.16)
Fig. 5.5 - Chloride concentration at mouth of Hollandsche IJssel and at Gouda versus discharge at the Nieuwe Waterweg with Oude Maas closed.
With the Oude Maas closed, the chloride concentration at Gouda can also be given as a function of the discharge through the Nieuwe Waterweg (or Nieuwe Maas: \( Q(\text{NWW}) = Q(\text{NM}) \)) as follows:

\[
c(\text{Gouda}) = 21.22 - 0.1032 \times Q(\text{NWW}) + 0.1669 \times 10^{-3} \times Q(\text{NWW})^2 \\
- 0.08978 \times 10^{-6} \times Q(\text{NWW})^3
\]

for \( 300 \leq Q(\text{NWW}) \leq 560 \text{ m}^3/\text{s} \) \hspace{1cm} (5.14)

This relationship is based on the following two assumptions:

1. The salt concentration at the mouth of the Hollandsche IJssel adapts rapidly (i.e., daily) to the discharge variations.
2. Although equilibrium conditions are assumed (constant flow rate, water level and salt concentration), we estimate that
   the relationship also holds for day-to-day variations.

On the basis of the results of a study of salt intrusion into the Rotterdamsche Waterweg area carried out by the RWS and the DHL, the first assumption does not appear unreasonable. Moreover, this assumption was already made with the selection of the calibration procedure for the modified Van der Burgh model. This point is discussed in detail in Ref. 12.

As to the second assumption, we observed that the salt concentration at Gouda was determined by the salt concentration of the water at the mouth of the Hollandsche IJssel at low tide [5]. Fig. 5.6 shows how the water level and salt concentration at the mouth of the Hollandsche IJssel vary throughout a typical cycle. The figure suggests that most of the salt that flows into the mouth of the IJssel at high tide flows out again as the tide drops and, thus, does not reach the inlet at Gouda, some 15 km upstream from the IJssel mouth. However, more detailed analysis shows that the salt that affects the concentration at the Gouda inlet comes into the IJssel during the period immediately after low tide when water flow is into the IJssel and salt concentration from the previous high tide has not decreased fully. Withdrawal at Gouda causes an upstream flow of water in the Hollandsche IJssel. Thus, the net volume of water flowing up the Hollandsche IJssel per tidal period has the salt concentration of the mouth at low tide. The volume of water is determined by the withdrawal rate at Gouda. During a following tidal period when a different salt concentration curve prevails at the mouth of the Hollandsche IJssel, because of a change in river discharges, the net volume of inflowing water has a different salt concentration. Now, if the withdrawal rate at Gouda is constant over a 10-day period, the second assumption may be taken as a starting point. Then, the daily volumes are constant, and only the mean salt concentration for each day or tidal period will vary. However, because the net volume of
Fig. 56 - Water level (a) and chloride concentration (b) at mouth of the Hollandsche IJssel (Oct 22, 1972, data)

THE CHLORIDE CONCENTRATION AT GOUDA WILL BE DETERMINED MAINLY BY THE CHLORIDE CONCENTRATION DURING THIS PERIOD.
water flowing upstream in the Hollandsche IJssel takes days to arrive at the extraction point at Gouda, there is a phase difference in salt concentration at the mouth and at the withdrawal point at Gouda. This phase difference is not important in the PAWN study, because it does not affect the total damage caused by salt penetration into the agricultural area. For this reason, the phase difference was neglected in the study. In reality, the water boards might use this difference to their advantage by varying the extraction rate during a 10-day period, if water demand allows it. Because the discharges through the Nieuwe Maas and Nieuwe Waterweg vary with the discharges of the Rijn and also because of the Haringvliet effect, the mean salt concentration of the water at the mouth of the Hollandsche IJssel will also vary. The water boards could then adjust the extraction rate accordingly. However, before this can be done in practice, more research is needed on the Haringvliet effect and on the mechanism of salt intrusion into the Hollandsche IJssel.

5.3. VERIFICATION WITH IN SITU MEASUREMENTS

In Sec. 5.1 we noted that since the Haringvliet and Volkerak branches were closed about 1970, salt intrusion into the Hollandsche IJssel at Gouda has occurred in 1971, 1972, and 1976, and the limited data on these occurrences are insufficient to derive a relationship between the mean salt concentration at the extraction point at Gouda and the mean salt concentration at the mouth of the Hollandsche IJssel. The data of 1976, however, can be used to verify some of the results of the approach given in Sec. 5.1. The data used in this section are taken from Ref. 11 and are shown in Tables 5.3 and 5.4.

We used these data in the following way. The maximum concentrations (more than 3.000 kg/m³) at Van Brieneenoordbrug in July (see Table 5.3) occurred between July 8 (second tide) and July 13 (first tide). This is a period of 10 tidal cycles. At Gouda, the maximum concentrations occurred between July 13 and July 17. The time lapse between the maxima at the Van Brieneenoordbrug and at Gouda was four and five days. The mean chloride concentrations at the mouth of the Hollandsche IJssel and at the extraction point at Gouda for this period were 0.800 and 0.150 kg/m³. This is deduced from the data of Table 5.3 as described below:

- The background chloride concentration of the Rijn and Maas for this period is subtracted (about 0.300 kg Cl⁻/m³; see Table 5.3, under Van Brieneenoordbrug, LSW).
- The mean of the HSW values at Van Brieneenoordbrug less the background concentration for this period was 3.200 - 0.300 = 2.900 kg/m³.
- The RWS developed a relationship between the HSW chloride concentration at Van Brieneenoordbrug and the tidal mean concentration at that location. This relationship, given in Ref. 11 as a figure in App. 11, shows that the mean
Table 5.3

CHLORIDE CONCENTRATION IN KG/M$^3$ AT VAN BRIENENOORDBRUG, STORMVLOEDKERING (STORM-SURGE BARRIER), AND GOUDA STATIONS, JULY 7 TO JULY 19

<table>
<thead>
<tr>
<th>Date</th>
<th>Van Brienenoordbrug</th>
<th>Stormvloedkering</th>
<th>Gouda</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HSW(a)</td>
<td>LSW(b)</td>
<td>HSW</td>
</tr>
<tr>
<td>July  7</td>
<td>2.120</td>
<td>0.230</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2.610</td>
<td>0.255</td>
<td>0.295</td>
</tr>
<tr>
<td>July  8</td>
<td>2.570</td>
<td>0.255</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3.070</td>
<td>(0.315)</td>
<td>(0.455)</td>
</tr>
<tr>
<td>July  9</td>
<td>3.100</td>
<td>(0.315)</td>
<td>0.229</td>
</tr>
<tr>
<td></td>
<td>3.090</td>
<td>-</td>
<td>(0.600)</td>
</tr>
<tr>
<td>July 10</td>
<td>3.190</td>
<td>0.290</td>
<td>(0.500)</td>
</tr>
<tr>
<td></td>
<td>3.410</td>
<td>(0.345)</td>
<td>(0.730)</td>
</tr>
<tr>
<td>July 11</td>
<td>3.300</td>
<td>(0.375)</td>
<td>(0.740)</td>
</tr>
<tr>
<td></td>
<td>2.950</td>
<td>(0.420)</td>
<td>(0.690)</td>
</tr>
<tr>
<td>July 12</td>
<td>3.320</td>
<td>0.290</td>
<td>(0.580)</td>
</tr>
<tr>
<td></td>
<td>3.000</td>
<td>(0.385)</td>
<td>(0.760)</td>
</tr>
<tr>
<td>July 13</td>
<td>3.400</td>
<td>0.315</td>
<td>(0.460)</td>
</tr>
<tr>
<td></td>
<td>2.670</td>
<td>(0.435)</td>
<td>(2.000)</td>
</tr>
<tr>
<td>July 14</td>
<td>2.790</td>
<td>0.330</td>
<td>(0.590)</td>
</tr>
<tr>
<td></td>
<td>2.400</td>
<td>(0.395)</td>
<td>(0.500)</td>
</tr>
<tr>
<td>July 15</td>
<td>2.520</td>
<td>0.330</td>
<td>(0.405)</td>
</tr>
<tr>
<td></td>
<td>2.040</td>
<td>(0.385)</td>
<td>(0.475)</td>
</tr>
<tr>
<td>July 16</td>
<td>2.090</td>
<td>0.305</td>
<td>0.350</td>
</tr>
<tr>
<td></td>
<td>2.320</td>
<td>(0.335)</td>
<td>(0.495)</td>
</tr>
<tr>
<td>July 17</td>
<td>2.450</td>
<td>0.335</td>
<td>(0.430)</td>
</tr>
<tr>
<td></td>
<td>2.130</td>
<td>(0.420)</td>
<td>(0.475)</td>
</tr>
<tr>
<td>July 18</td>
<td>2.180</td>
<td>0.285</td>
<td>0.360</td>
</tr>
<tr>
<td></td>
<td>1.960</td>
<td>0.295</td>
<td></td>
</tr>
<tr>
<td>July 19</td>
<td>1.870</td>
<td>0.265</td>
<td>0.345</td>
</tr>
<tr>
<td></td>
<td>1.900</td>
<td>0.280</td>
<td>0.295</td>
</tr>
</tbody>
</table>

(a) HSW = high slack water.
(b) LSW = low slack water.
(c) (———) : chloride concentration higher than the background chloride concentration of the Rijn and Maas.
Table 5.4

CHLORIDE CONCENTRATION IN KG/M³ AT VAN BRIENENOORDBRUG, STORMVLOEDKERING (STORM-SURGE BARRIER), AND GOUDA STATIONS, AUG. 24 TO SEPT. 2

<table>
<thead>
<tr>
<th>Date</th>
<th>Van Brienenoordbrug</th>
<th>Stormvloedkering</th>
<th>Gouda</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HSW</td>
<td>LSW</td>
<td>HSW</td>
<td>LSW</td>
<td></td>
</tr>
<tr>
<td>Aug. 24</td>
<td>2.460</td>
<td>0.240</td>
<td>0.245</td>
<td>0.215</td>
<td>0.230</td>
</tr>
<tr>
<td></td>
<td>2.450</td>
<td>-</td>
<td>(0.345)</td>
<td>(a) 0.235</td>
<td></td>
</tr>
<tr>
<td>Aug. 25</td>
<td>2.990</td>
<td>0.230</td>
<td>(0.305)</td>
<td>0.240</td>
<td>0.250</td>
</tr>
<tr>
<td></td>
<td>2.830</td>
<td>0.255</td>
<td>(0.420)</td>
<td>0.260</td>
<td></td>
</tr>
<tr>
<td>Aug. 26</td>
<td>3.210</td>
<td>0.250</td>
<td>(0.350)</td>
<td>0.255</td>
<td>0.265</td>
</tr>
<tr>
<td></td>
<td>2.880</td>
<td>(0.340)</td>
<td>(0.510)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Aug. 27</td>
<td>3.060</td>
<td>(0.275)</td>
<td>(0.430)</td>
<td>(0.295)</td>
<td>0.285</td>
</tr>
<tr>
<td></td>
<td>2.690</td>
<td>(0.390)</td>
<td>(0.560)</td>
<td>(0.285)</td>
<td></td>
</tr>
<tr>
<td>Aug. 28</td>
<td>2.450</td>
<td>0.235</td>
<td>(0.330)</td>
<td>0.240</td>
<td>(0.305)</td>
</tr>
<tr>
<td></td>
<td>1.970</td>
<td>0.225</td>
<td>(0.315)</td>
<td>0.235</td>
<td></td>
</tr>
<tr>
<td>Aug. 29</td>
<td>2.050</td>
<td>0.205</td>
<td>0.240</td>
<td>0.205</td>
<td>(0.355)</td>
</tr>
<tr>
<td></td>
<td>1.760</td>
<td>0.220</td>
<td>0.280</td>
<td>0.215</td>
<td></td>
</tr>
<tr>
<td>Aug. 30</td>
<td>1.890</td>
<td>0.225</td>
<td>0.265</td>
<td>0.225</td>
<td>(0.375)</td>
</tr>
<tr>
<td></td>
<td>1.750</td>
<td>0.280</td>
<td>0.335</td>
<td>0.225</td>
<td></td>
</tr>
<tr>
<td>Aug. 31</td>
<td>1.770</td>
<td>0.265</td>
<td>0.360</td>
<td>0.245</td>
<td>(0.375)</td>
</tr>
<tr>
<td></td>
<td>1.540</td>
<td>0.275</td>
<td>0.330</td>
<td>0.265</td>
<td></td>
</tr>
<tr>
<td>Sept. 1</td>
<td>1.490</td>
<td>0.255</td>
<td>0.280</td>
<td>0.250</td>
<td>(0.355)</td>
</tr>
<tr>
<td></td>
<td>2.160</td>
<td>0.265</td>
<td>(0.365)</td>
<td>0.260</td>
<td></td>
</tr>
<tr>
<td>Sept. 2</td>
<td>-</td>
<td>-</td>
<td>(0.850)</td>
<td>(0.330)</td>
<td>(0.350)</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>(0.370)</td>
<td>(0.735)</td>
<td>(0.410)</td>
</tr>
</tbody>
</table>

(a) (-----): chloride concentration higher than the background chloride concentration of the Rijn and Maas.
concentration at Van Brienenoordbrug is 1.000 kg/m³ when the HSW concentration is 2.900 kg/m³.

- The distance between the Van Brienenoordbrug and the mouth of the Hollandsche IJssel is about 1 km. From Figs. 4.3 and 4.4, we can deduce that the decrease in the mean chloride concentration near the tip of the salt wedge at low discharges is about 0.200 kg/m³ per kilometer. This yields a mean chloride concentration at the mouth of the Hollandsche IJssel of about 0.800 kg/m³.

- The mean chloride concentration at the extraction point at Gouda is taken as the mean of the HSW concentrations from July 13 through July 17 less the background concentration: 0.450 - 0.300 = 0.150 kg/m³. We use the HSW concentrations because the withdrawal at Gouda occurs mainly during high-water hours, taking advantage of gravity flow.

Employing the same approach for August 1976 (August 25 through 27 at Van Brienenoordbrug; August 29 through September 1 at Gouda) results in a mean chloride concentration at the mouth of the Hollandsche IJssel of about 0.700 kg/m³ and a chloride concentration at the Gouda extraction point of about 0.120 kg/m³.

These results from in situ measurements of July and August 1976 agree fairly closely with the results obtained from the approach described in Sec. 5.1. However, there are no in situ measurements available for comparison at higher concentrations.
Chapter 6
APPLICABILITY TO PAWN OF THE MODIFIED VAN DER BURGH MODEL

6.1. TACTICS AFFECTING SALT INTRUSION

All water management tactics that affect salt intrusion in the Rotterdamsche Waterweg area can be classified in one of three ways: (a) tactics implemented outside the Rotterdamsche Waterweg area, but having consequences (particularly on the discharge distribution) that affect salt intrusion in the area; (b) tactics implemented in the Rotterdamsche Waterweg area; (c) tactics that do not directly affect salt intrusion, but rather ensure that salt intrusion into the major withdrawal point is prevented (e.g., by relocating the extraction point or by constructing an alternative supply route). In what follows, we categorize a number of such tactics that might be considered.

a. Changing the discharge or the discharge distribution through the Rotterdamsche Waterweg

a.1. Changing how the weir at Driel is used.
a.2. Canalization of the IJssel River, in conjunction with tactic a.1.
a.3. Creating a North-South connection to transport water from the IJsselmeer to the Lek River.
a.4. Increasing the discharge from the Lek River by transporting water from the Waal River through the Amsterdam-Rijnkanaal.
a.5. Increasing the discharge from the Lek River by transporting water through the MerwedeKanaal.

b. Changing the infrastructure of the Rotterdamsche Waterweg area

b.1. Closing the Oude Maas branch.
b.2. Closing the Nieuwe Maas branch.
b.3. Closing the Spui branch.
b.4. Changing the dimensions (depth, width) of the cross sections of the various branches of the Rotterdamsche Waterweg.
b.5. Introducing mixing devices, such as air bubble screens and groins.

c. Changing the extraction configuration

c.1. Substituting the supply through the Hollandsche IJssel with supply from the Amsterdam-Rijnkanaal to Bodegraven through a new canal.
c.2. Substituting the supply through the Hollandsche IJssel with supply from the Lek River to the Gouda area by a canal through the Krimpenerwaard polder.
c.3. Substituting the supply through the Hollandsche IJssel with supply from the Lek River and the Amsterdam-Rijnkanaal through improved emergency supply facilities.
c.4. Using the storm-surge barrier at Krimpen for longer periods of time (one week or more) at low discharges to control salt intrusion into the Hollandsche IJssel.

c.5. Using the storm-surge barrier for shorter periods of time (one or two days) during a storm.

6.2. APPLICABILITY OF THE MODIFIED VAN DER BURGH MODEL TO THE VARIOUS TACTICS

We modified and calibrated the Van der Burgh model for application in the PAWN study, using all available data describing the current infrastructure and with the Oude Maas branch closed. The equations used in both the original and the modified Van der Burgh model, particularly the dispersion coefficient (Eqs. 4.2 and 4.7) suggest that changes in specific physical quantities, such as the flood volume P, the cross section A, and the water depth d, can be accounted for in the model. It has been demonstrated, however (see Ref. 8), that this is not true. For each situation where significant changes occur in the relevant physical parameters for tidal fluctuation and salt intrusion, the modified Van der Burgh model must be calibrated again using field measurements or using models that are indeed capable of representing the effect of such changes on salt intrusion. (An example of the latter is the tidal salinity model Rijmond.) Consequently, those tactics shown above that affect the relevant physical parameters cannot be analyzed using the modified Van der Burgh model. The tactics that can be analyzed with the model are discussed below. Section 6.2.2 describes the tactics considered in PAWN that cannot be analyzed with the model.

6.2.1. Tactics That Can Be Analyzed with the Modified Van der Burgh Model

All tactics listed in Sec. 6.1.a can be analyzed with the modified Van der Burgh model because their implementation (technical or managerial) occurs outside the Rotterdamsche Waterweg area. Thus, there is little or no change in tidal fluctuation. The effects on salt intrusion of the river discharge rate or of the discharge distribution over the Oude Maas and the Nieuwe Maas branches are measured in a sufficiently reliable way in the model. (It is assumed that the changes in the mean river discharge are computed in the Water Distribution and the Managerial Strategy Design models.)

Those tactics listed in Sec. 6.1.c that involve selecting an alternative supply route for the extraction point at Gouda (c.1, c.2, c.3) can also be analyzed with the model. The model's primary purpose is to forecast the salt concentration at the extraction point at Gouda. But these tactics obviate the need for the model, as the salt concentration of the extraction water is then determined by the salt concentration of the Lek River water, the Amsterdam-Rijnkanaal water, or both. However, if the supplied water is first transported to the Hollandsche IJssel at Gouda and is then withdrawn into the Gouwe River
(by means of the current construction), salt intrusion from the Nieuwe Maas branch is possible. Salt intrusion here can be controlled by supplying (through the new supply route) more water than is needed for water supply to the midwest region of Holland. Then the additional quantity of water results in a tide-averaged river discharge through the Hollandsche IJssel from Gouda to the Nieuwe Maas. The volume of that discharge would be adjusted to prevent salt intrusion from the Nieuwe Maas.

Using the modeling techniques described in this volume, we determined when salt intrusion at Gouda may occur with the above tactics. The Water Distribution Model incorporates the capabilities to ensure the supply of additional water quantities via the alternative routes to control salt intrusion into the Hollandsche IJssel at Gouda.

The closing of the Oude Maas branch (b.1) can also be analyzed with the modified Van der Burgh model, because investigation with the tidal salinity model Rijmond [14] defined the model coefficients, as we noted previously.

The closing of the Spui (b.3) can also be analyzed with the modified Van der Burgh model. We conducted a preliminary rough analysis of the effect of the closing of the Spui on the tidal fluctuation in the Nieuwe Waterweg, Oude Maas, and Nieuwe Maas branches. The RWS, District Zuidwest, carried out two different computations using IMPLICIT, one for the open Spui and one for the closed Spui. The table below shows the results. (The data were taken from Ref. 14.)

<table>
<thead>
<tr>
<th>Results</th>
<th>Spui Open</th>
<th>Spui Closed</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water Motion</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flood volume ($10^6$ m$^3$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mouth Oude Maas</td>
<td>27.2</td>
<td>23.8</td>
<td>-13</td>
</tr>
<tr>
<td>Mouth Nieuwe Maas</td>
<td>41.5</td>
<td>42.7</td>
<td>+3</td>
</tr>
<tr>
<td>Nieuwe Waterweg, at Oude/Nieuwe Maas bifurcation</td>
<td>68.7</td>
<td>66.5</td>
<td>-3</td>
</tr>
<tr>
<td><strong>River discharge ($m^3/s$)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nieuwe Waterweg</td>
<td>505</td>
<td>505</td>
<td>-</td>
</tr>
<tr>
<td>Oude Maas</td>
<td>315</td>
<td>295</td>
<td>-6</td>
</tr>
<tr>
<td>Nieuwe Maas</td>
<td>190</td>
<td>210</td>
<td>-11</td>
</tr>
</tbody>
</table>

From this table we can conclude the following:

- The change in tidal fluctuation on the Nieuwe Waterweg and Nieuwe Maas is very slight (3 percent). Therefore, with
regard to these river branches we may assume that the salt intrusion estimates, with the same coefficients in the modified Van der Burgh model, are sufficiently accurate.

- The change in tidal fluctuation on the Oude Maas is approximately 13 percent. This may cause the mean salt concentration to increase slightly because reduced flood volume means reduced mixing. But, at the same time, the flood current path will be reduced in length so it is possible that the maximum salt concentration will change very little. For purposes of PAWN, a more uncertain forecast of the salt intrusion into the Oude Maas matters little as there are no major extraction points on the Oude Maas branch.

- The effect on the discharge distribution is that an additional 20 m³/s will be carried through the Nieuwe Maas instead of through the Oude Maas. This effect has been incorporated into the Water Distribution Model and the effect on salt intrusion, particularly of the water of the Nieuwe Maas, has been included in the modified Van der Burgh model.

Changes in the dimensions (depth, width) of the cross sections of the various river branches of the Rotterdamsche Waterweg (b.4) can be analyzed, in part, with the modified Van der Burgh model. Changes in dimensions outside of the area of salt intrusion (i.e., the Nieuwe Waterweg, Nieuwe Maas, and Oude Maas areas) can be dealt with in a manner analogous to the closing of the Spui. Possible tactics are to widen the Noord or the Dordtsche Kil. But these dimensional changes will have a negligible effect on the tidal fluctuation in the river branch in which salt intrusion occurs. If the effect on tidal fluctuation is not negligible, or if the tactics are implemented in the salt intrusion area, no reliable salt intrusion forecast can be made with the modified Van der Burgh model. Currently, the effect of these tactics on salt intrusion can be analyzed only with a physical scale model such as the tidal salinity model Rijnmond.

6.2.2. Tactics That Cannot Be Analyzed with the Modified Van der Burgh Model

The closing of the Nieuwe Maas (b.2) is a tactic that is comparable to the closing of the Oude Maas insofar as the effect on tidal fluctuation and salt intrusion are concerned. But a reliable picture of the change in the salt intrusion process can be obtained with the tidal salinity model Rijnmond. The necessary coefficients to be entered in the modified Van der Burgh model, or in other mathematical models, would be determined in the course of such an investigation.

Changes in the dimensions of the cross section of the various river branches of the Rotterdamsche Waterweg (b.4) cannot be analyzed if their effects on tidal fluctuation are nonnegligible or if the tactics are implemented in the salt intrusion area.
Mixing devices (b.5), such as air bubble screens or groins, affect salt intrusion by increasing the mixing rate in that area of the Rotterdamsche Waterweg basin where stratified flows of saltwater and freshwater normally occur (salty bottom layer and brackish or fresh upper layer). In 1975, an investigation was conducted to determine the effect of air bubble screens on salt intrusion using the tidal salinity model Rijnmond [15]. This investigation found that

- As the total volume of insufflated air increases, the effect on salt intrusion also grows.
- The maximum displacement of lines connecting points of equal density during the time of salt intrusion into the Nieuwe Waterweg (at km 1013 to 1018) is about 1.5 km; and on the Oude and Nieuwe Maas, near the tip of the salt wedge (at kmr 1002 to 1005 (Oude Maas) and kmr 1006 to 1012 (Nieuwe Maas)), it is about 3 km. The total volume of air to be insufflated to achieve the maximum reduction of salt intrusion is 175 m³/s, distributed over two screens at kmr 1024 and 1020. For the purpose of converting the air yield from the model to the prototype, the upper limit allowed within the scaling rules has been applied.
- This investigation was carried out at the following river discharges: 1.500 m³/s through the Nieuwe Waterweg; 650 m³/s through the Nieuwe Maas; and 850 m³/s through the Oude Maas.

Within the framework of the tidal salinity model Rijnmond investigation into the effect on salt intrusion of the deepening of the shipping route to the Maasvlakte area (the so-called 72- to 75-foot channel), a detailed study was planned to estimate the effects of mixing devices such as air bubble screens and groins, to compensate for a possible increase in salt intrusion when the channel is deepened. Due to a fire that broke out in the tidal salinity model Rijnmond, the study was carried out only partially. But on the basis of the partial results, we concluded that by constructing groins near the mouth of the Nieuwe Waterweg, salt intrusion could be pushed back by at least 1 km at the Nieuwe Waterweg branch. This result holds for river discharges of 1250 m³/s (Nieuwe Waterweg), 460 m³/s (Nieuwe Maas), and 790 m³/s (Oude Maas). The results of this study are published in Ref. 16.

On the basis of the foregoing discussion, we conclude that there is still a lack of quantitative data needed to establish a relationship between the mixing device characteristics (number and location of air bubble screens and groins, groin design, air rate and energy consumption of air bubble screens, construction and maintenance costs, etc.) and their effect on salt intrusion as a function of the river discharges through the Nieuwe Waterweg, Nieuwe Maas, and Oude Maas. Some information on the costs of air bubble screens in the Nieuwe Waterweg can be found in Ref. 18. Consequently, the effect of such mixing devices on salt intrusion cannot yet be simulated by adapting
the coefficients of the modified Van der Burgh model. For purposes of the PAWN study, we assumed that application of such mixing devices will permit pushing back the intrusion of salt water by one or several kilometers. This is based on Refs. 15 and 16. Restraining salt intrusion by applying such mixing devices was translated into a reduction in the mean river discharge needed to control salt intrusion into the Hollandsche IJssel in particular. We derived an approximate relationship between these variables as follows: For the Oude Maas open case, and with tests T0 and T11 (see Table 4.1 and Figs. 4.10 and 4.11), we determined the effects of differences in the river discharge through the Nieuwe Waterweg (1359 - 1014 = 345 m$^3$/s) on maximum salt intrusion (krm 1001 and 994). The results show that an increase in the river discharge of about 50 m$^3$/s produces a reduction of saltwater intrusion into the Nieuwe Maas by 1 km. The same approach, with the Oude Maas closed case, with tests T5 and T6 (see Table 4.1 and Figs. 4.12b and 4.13) produces a reduction of the saltwater intrusion into the Nieuwe Maas of 1 km, for an increase in the river discharge of about 70 m$^3$/s.

Tactics c.4 and c.5 use the storm-surge barrier at Krimpen to control salt intrusion into the Hollandsche IJssel in two different situations—when low river discharges occur for longer periods of time (one week or longer) and during storm conditions. For the latter, the storm-surge barrier may be instrumental in preventing salt intrusion into the Hollandsche IJssel, provided that the following conditions are satisfied:

- The storm-surge barrier must be lowered at a water level comparable to the normal high tide level, without an increase of the mean water level due to the storm.
- The barrier must be lowered before the tip of the salt wedge has reached it.
- During the barrier closing time, little water must be taken in from the Hollandsche IJssel, so as not to drop the water level significantly.
- After the storm, the barrier must be lifted at a specific time to produce a strong ebb current from the Hollandsche IJssel that will carry the salt water that has accumulated (in particular near the bottom at the mouth of the Hollandsche IJssel—the Kralingse Veer-Krimpen stretch) back to the Nieuwe Maas.

These conditions were derived from tests with the tidal salinity model (see Ref. 17) and from information in Ref. 5. (See Sec. 5.1 and Fig. 5.6.) We conclude, therefore, that salt intrusion problems during storm surges may be neglected in PAWN, assuming use of mean tidal conditions.

The investigations in Refs. 4 and 17 also lead us to conclude that use of the storm-surge barrier will not prevent or effectively control saltwater intrusion into the Hollandsche IJssel if it is in danger of
salt intrusion at low river discharges over longer periods of time (c.4). This applies particularly in cases where, during such periods, water is still being withdrawn from the Hollandsche IJssel to supply water to the Rijnland, Delfland, and Schieland regions. Consequently, the storm-surge barrier was eliminated in the PAWN evaluations.
Chapter 7

LIMITATIONS AND SENSITIVITY OF THE MODELS

7.1. LIMITATIONS OF THE APPROACH

The following observations on the limitations of our modeling should be noted:

- The models were developed for use in the PAWN study. They were not developed by the rigorous application of physical principals; rather, they are empirical in nature. The results (particularly the modified Van der Burgh model) are models that, while not directly derivable from the laws of physics, reproduce the available measured data obtained in nature and from the tidal salinity model Rijnmond.
- The modeling applies to mean tidal conditions. It does not permit forecasting daily mean values by translating the tidal fluctuations at sea (spring tide or neap tide) into a fluctuation of the flood number (with Eq. 4.11) and using this flood number in Eq. 4.7. It is intended to provide a mean value of salt concentration over a period of a week to 10 days. The fluctuations due to the tide at sea and the so-called Haringvliet effect (see Sec. 5.2) are included in this mean value.
- Care and a knowledge of physical reality must be used in interpreting PAWN results, which depend critically on our estimates of salt intrusion. A rough estimation of the inaccuracy in our salt intrusion calculations is given in the next section. PAWN results should be examined in the light of this inaccuracy before they are accepted.
- Storm conditions may strongly affect the tidal fluctuation in the Rotterdamsche Waterweg, and, consequently, the salt intrusion. The lowering of the storm gate at Krimpen may prevent salt intrusion into the Hollandsche IJssel under storm conditions. Salt intrusion into the Haringvliet and the Hollandsche Diep--due to a storm raising the water level in the Noord, the Dordtsche Kil, or the Spui--cannot be analyzed using the models described in this volume.

7.2. MODELING INACCURACIES AND SENSITIVITIES

Although our models are not in obvious disagreement with the measured results, we must recognize that there are inaccuracies in our modeling that may affect the results. These inaccuracies spring from several sources:
The inaccuracy in the estimation of the total river discharge via the Rotterdamsche Waterweg and the distribution of this discharge between the Oude Maas and Nieuwe Maas. (PAWN used results of the IMPLIC model of the RWS.) The inaccuracy in the prediction of the discharge distribution is partially reflected in the calibration of the modified Van der Burgh model, because the discharge distribution used for the different salt measurements is also based on IMPLIC calculations (or on results of the analog computer model DELTAR).

The limitations of the modified Van der Burgh model and its calibration using the available measurements in nature and in the tidal salinity model Rijnmond.

The inaccuracies in the relationship between the salt concentration at the mouth of the Hollandsche IJssel and the extraction point at Gouda, which could not be verified by measurements in nature (see Sec. 5.2).

The inaccuracy introduced by our approximate treatment of the Haringvliet effect.

The inaccuracies introduced by extrapolating beyond the range of the available data. Low discharge situations are important in the PAWN study, but available data are scant.

Our models indicate that salt concentrations under conditions of low river flows are particularly sensitive to uncertainties in river flows. This follows from the nonlinear nature of the relations between river flows and the salt concentration at the mouth of the Hollandsche IJssel (Figs. 4.15 and 4.18), and between the salt concentration at the mouth of the Hollandsche IJssel and at the inlet at Gouda (Figs. 5.3 and 5.4).

A sensitivity investigation showed that a 1-percent change in river flow can cause almost ten times the change in salt concentration at the Gouda inlet when the flow in the Nieuwe Maas is low than when it is high. On a percentage basis, however, the sensitivity is nearly independent of river flows, that is, a 1-percent change in river flow results in about a 10-percent change in salt concentration at Gouda regardless of the river flow.

If we assume that the prediction of the flows in the river branches is correct, there are still errors in the predicted salt concentrations arising from the several sources mentioned above. An estimate of these errors, provided by experts at the RWS and the DHL, is as follows:

- With river discharges leading to low salt intrusion at the extraction point at Gouda, the inaccuracies in the chloride concentration at the mouth of the Hollandsche IJssel are approximately 0.150 kg Cl\(^{-}/m^{3}\) (Oude Maas open) and
approximately 0.200 kg Cl⁻/m³ (Oude Maas closed), and at the extraction point at Gouda for both situations approximately 0.050 kg Cl⁻/m³.

- With lower river discharges in the Nieuwe Waterweg, the inaccuracies in the chloride concentrations at the mouth of the Hollandsche IJssel and at the extraction point at Gouda are significantly higher: For the Oude Maas open case in both locations, from 0.500 kg Cl⁻/m³ with Q(NWW) approximately equal to 400 m³/s; for the Oude Maas closed case, from 0.300 to 0.800 kg Cl⁻/m³ for the same river discharges as above.
Appendix A

COMPUTER PROGRAM FOR THE OUEDE MAAS OPEN CASE

1.5 To step 1.6.
1.6 Do part 2.
1.7 Do part 3 for i=1(1)Z.
1.705 Do part 10.
1.706 Set C(10)=C(Z).
1.8 Do part 4.
1.81 Do part 3 for i=1(1)Z.
1.815 Do part 10.
1.82 Do part 5.
1.83 Do part 3 for i=1(1)Z.
1.835 Do part 10.
1.836 Set F(2)=P.
1.837 Set C(11)=C(Z).
1.838 To step 14.2 if Y=1.
1.839 To step 14.4 if Y=2.
1.8391 To step 14.5 if Y=3.
1.83915 To step 15.11 if Y=4.
1.83916 To step 15.21 if Y=10.
1.8392 Type "N,L determined" if Y=11.

2.11 Set x(0)=0.
2.12 Set x(1)=1.625.
2.13 Set x(2)=8.465.
2.14 Set x(3)=12.395.
2.15 Set x(4)=16.30.
2.21 Set A(1)=6876.
2.22 Set A(2)=6150.
2.23 Set A(3)=5506.
2.24 Set A(4)=6410.
2.31 Set I(0)=0.
2.32 Set I(1)=.232.
2.33 Set I(2)=1.342.
2.34 Set I(3)=2.057.
2.35 Set I(4)=2.639.
2.5 Set k(0)=29.5.
2.51 Set k(1)=1.0.
2.52 Set b=13.59.
2.53 Set P=(6.57-.0160*Q(1)+44.3*T)*10^6.
2.535 Set p(1)=P.
2.54 Set c(0)=19000*exp(-.0003608*Q(1)).
2.55 Set q=Q(1).
2.56 Set Z=4.
2.57 Set M=1029.
2.58 Set s=.5.
2.6 Set y=.3.
3.1 Set \( D(0) = 9.81**.5*45000**y*k(0)*(h**1.5)*(q**y)/(P**y) \).
3.2 Set \( D(1) = D(0) - .50*k(1)*(I(i)+I(i-1))\).
3.3 Set \( J(i) = 1000*[x(i) - x(i-1)]/A(1)*D(1) \).

4.11 Set \( x(0) = 0 \).
4.12 Set \( x(1) = 4.13 \).
4.13 Set \( x(2) = 9.48 \).
4.14 Set \( x(3) = 13.54 \).
4.15 Set \( x(4) = 18.46 \).
4.16 Set \( x(5) = 23.69 \).
4.21 Set \( A(1) = 5756 \).
4.22 Set \( A(2) = 5063 \).
4.23 Set \( A(3) = 4055 \).
4.24 Set \( A(4) = 2818 \).
4.25 Set \( A(5) = 2816 \).
4.31 Set \( I(0) = 0 \).
4.32 Set \( I(1) = .715 \).
4.33 Set \( I(2) = 1.773 \).
4.34 Set \( I(3) = 2.773 \).
4.35 Set \( I(4) = 4.518 \).
4.36 Set \( I(5) = 6.338 \).
4.5 Set \( k(0) = 6 \).
4.51 Set \( k(1) = .2 \).
4.52 Set \( h = 11.70 \).
4.53 Set \( P = p(1)*(.00005*Q(1) + .58) \).
4.54 Set \( q = Q(2) \).
4.55 Set \( c(0) = C(4) \).
4.56 Set \( Z = 5 \).
4.57 Set \( M = 1012.7 \).
4.58 Set \( s = .15 \).
4.6 Set \( y = .3 \).
4.61 Set \( k(1) = .4 \).

5.11 Set \( x(0) = 0 \).
5.12 Set \( x(1) = 2.92 \).
5.13 Set \( x(2) = 3.82 \).
5.14 Set \( x(3) = 11.14 \).
5.21 Set \( A(1) = 2655 \).
5.22 Set \( A(2) = 2990 \).
5.23 Set \( A(3) = 2361 \).
5.31 Set \( I(0) = 0 \).
5.32 Set \( I(1) = 1.10 \).
5.33 Set \( I(2) = 1.40 \).
5.34 Set \( I(3) = 4.50 \).
5.5 Set \( k(0) = 7 \).
5.51 Set \( k(1) = .2 \).
5.52 Set \( h = 9.06 \).
5.53 Set \( P = p(1)*(-.00008*Q(1) + .34) \).
5.54 Set \( q = Q(3) \).
5.55 Set \( c(0) = C(10) \).
5.56 Set \( Z = 3 \).
5.57 Set \( M = 1012.7 \).
5.58 Set \( M = 1007 \).
10.1 Set i=0.
10.2 Set w=0.
10.25 Set J(0)=0.
10.3 Set w=w+J(i).
10.35 To step 10.45 if D(i)≤0.
10.4 Set C(i)=c(0)*exp(-q*w).
10.45 Set C(i)=0 if D(i)≤0.
10.46 Set B=n+1 if i=0.
10.47 Set n=B+i.
10.5 Set L(n)=M-x(i).
10.51 Set L(n)=L(n)-500 if M=1007.
10.55 Set N(n)=C(i).
10.6 Set i=i+1.
10.7 To step 10.3 if i≤7.

13.05 Set G=1.
13.06 Set Y=0.
13.07 Set T=1.65.
13.08 Set n=0.
13.1 Set Q(1)=600.
13.2 Set Q(2)=165.
13.3 Set Q(3)=435.
13.4 Set Q(4)=50.
13.5 Set Q(5)=385.
13.6 To step 1.5.
13.7 Line.
13.71 Line.
13.72 Line.
13.725 Set G=2.
13.73 Set Q(1)=1000.
13.74 Set Q(2)=300.
13.75 Set Q(3)=700.
13.76 Set Q(4)=50.
13.77 Set Q(5)=650.
13.78 To step 1.5.
13.79 Line.
13.791 Set G=3.
13.8 Line.
13.81 Line.
13.82 Set Q(1)=1600.
13.83 Set Q(2)=625.
13.84 Set Q(3)=975.
13.85 Set Q(4)=50.
13.86 Set Q(5)=925.
13.87 To step 1.5.
13.88 Do part 14.

14.05 Set G=0.
14.06 Set n=0.
14.1 Set T=1.75.
14.11 Set Q(1)=1650.
14.12 Set Q(2)=735.
14.13 Set Q(3) = 915.
14.15 To step 1.5.
14.2 Set T = 1.98.
14.205 Set Y = 2.
14.21 Set Q(1) = 935.
14.22 Set Q(2) = 415.
14.23 Set Q(3) = 520.
14.24 To step 1.5.
14.3 Set T = 1.54.
14.4 Set Y = 3.
14.41 Set T = 1.71.
14.42 Set Q(1) = 1325.
14.43 Set Q(2) = 595.
14.44 Set Q(3) = 730.
14.45 To step 1.5.
14.5 Set Y = 4.
14.51 Set T = 1.96.
14.52 Set Q(1) = 1055.
14.53 Set Q(2) = 460.
14.54 Set Q(3) = 595.
14.55 To step 1.5.
15.11 Set Y = 10.
15.12 Set T = 1.75.
15.13 Set Q(1) = 1359.
15.14 Set Q(2) = 499.
15.15 Set Q(3) = 860.
15.16 To step 1.5.
15.21 Set Y = 11.
15.22 Set T = 1.75.
15.23 Set Q(1) = 1014.
15.24 Set Q(2) = 342.
15.25 Set Q(3) = 672.
15.35 To step 1.5.
Appendix B

COMPUTER PROGRAM FOR THE OUDE MAAS CLOSED CASE

1.1 Set Q(2)=Q(1).
1.2 Set G=0.
1.5 Type form 1.
1.6 Do part 2.
1.7 Do part 3 for i=1(1)Z.
1.705 Do part 10.
1.706 Set C(10)=C(Z).
1.8 Do part 4.
1.81 Do part 3 for i=1(1)Z.
1.815 Do part 10.

2.11 Set x(0)=0.
2.12 Set x(1)=1.625.
2.13 Set x(2)=8.465.
2.14 Set x(3)=12.395.
2.15 Set x(4)=16.300.
2.21 Set A(1)=6876.
2.22 Set A(2)=6150.
2.23 Set A(3)=5506.
2.24 Set A(4)=6410.
2.31 Set I(0)=0.
2.32 Set I(1)=.232.
2.33 Set I(2)=1.342.
2.34 Set I(3)=2.057.
2.35 Set I(4)=2.639.
2.4 Type "Rotterdam Waterway".
2.5 Set k(0)=32.
2.51 Set k(1)=1.0.
2.52 Set h=13.59.
2.53 Set P=72.9*10**6-12500*Q(1).
2.54 Set c(0)=19000*exp(-0.0003608*Q(1)).
2.55 Set q=Q(1).
2.56 Set Z=4.
2.57 Set M=1029.
2.6 Set y=.3.

3.1 Set D(0)=9.81***.5*45000**y*k(0)*(h**1.5)*q**y/(p**y).
3.2 Set D(i)=D(0)-.50*k(1)*I(i)+I(i-1)]*q.
3.3 Set J(i)=1000[x(i)-x(i-1)]/A(1)*D(i).

4.11 Set x(0)=0.
4.12 Set x(1)=4.13.
4.13 Set x(2)=9.48.
4.14 Set x(3)=13.54.
4.15 Set x(4)=18.46.
4.16 Set x(5)=23.69.
4.21 Set A(1)=5756.
4.22 Set $A(2)=5063.$
4.23 Set $A(3)=4055.$
4.24 Set $A(4)=2818.$
4.25 Set $A(5)=2816.$
4.31 Set $I(0)=0.$
4.32 Set $I(1)=.715.$
4.33 Set $I(2)=1.773.$
4.34 Set $I(3)=2.773.$
4.35 Set $I(4)=4.518.$
4.36 Set $I(5)=6.338.$
4.4 Type "New Maas".
4.5 Set $k(0)=13.1.$
4.51 Set $k(1)=.4.$
4.52 Set $h=11.7.$
4.55 Set $c(0)=C(4).$
4.56 Set $Z=5.$
4.57 Set $H=1012.7.$
4.6 Set $y=.075.$

10.1 Set $i=0.$
10.2 Set $w=0.$
10.25 Set $J(0)=0.$
10.3 Set $w=w+J(i).$
10.35 To step 10.45 if $D(i)\leq 0.$
10.4 Set $C(i)=c(0)\exp(-q^kw).$
10.45 Set $C(i)=0$ if $D(i)\leq 0.$
10.46 Set $s(i)=.5*P/A(i)/1000$ if $i>0.$
10.461 Set $s(i)=0$ if $i=0.$
10.47 Set $S(i)=.5*P/A(i+1)/1000$ if $(i+1)\leq Z.$
10.471 Set $S(i)=0$ if $i=Z.$
10.5 Type $x(i), [M-x(i)], D(i), P_i, C(i)$ in form 2.
10.6 Set $i=i+1.$
10.7 To step 10.3 if $i\leq Z.$

100.1 Do part 1 for $Q(1)=935, 1114, 803, 1267, 630.$

Form 1:
\[
\begin{array}{cccccc}
  x & (km) & L(km) & D & P(cum) & c(ppm) \\
\end{array}
\]

Form 2:
\[
\begin{array}{cccccc}
  \_ & \_ & \_ & \_ & \_ & \_ \\
\end{array}
\]
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