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PHYSICAL MODELLING OF THE ROTTERDAMSE WATERWEG ESTUARY

by

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1. INTRODUCTION

Modelling estuaries, as characterized by the complex interaction of river discharge, tidal movement and density differences, is still a difficult operation. Exchange of information on the experience with hydraulic scale models of estuaries therefore seems necessary and useful.

The model of "Europoort" and the "Rotterdamse Waterweg" estuary has a long history and was therefore subjected to a far-reaching evolution in the philosophy of estuarine models. Improvement in knowledge of the hydrodynamic phenomena and technical possibilities has resulted in major changes in the model and its operation.

The present contribution describes both this evolution and the final state of the model, together with the related aspects of calibration, verification, operation and data processing.

The model was built and operated by the Delft Hydraulics Laboratory under contract by Rijkswaterstaat, Ministry of Public Works, which not only provided the necessary funds but also closely participated in the design and calibration of the model and provided field data and technical assistance.

2. PROBLEM STATEMENT, PURPOSE OF THE MODEL

Problem statement

The continuous extension of the Rotterdam harbour culminated in the construction of the Europoort harbour, situated at the seaboard end of the Rotterdamse Waterweg, one of the branches of the river Rhine. The increase in size of oil tankers and ore carriers called for the construction of a deep water port close to the sea. This was realized by building a harbour basin with a new inlet on the tidal flats south of the existing entrance of the Rotterdamse Waterweg (see Fig. 1).

As large tankers and ore carriers are greatly affected by cross currents during their stopping and entrance manoeuvres a careful study of the flow field was required. The first harbour basins had to be used in the early stages of the harbour construction with a temporary entrance. For that reason

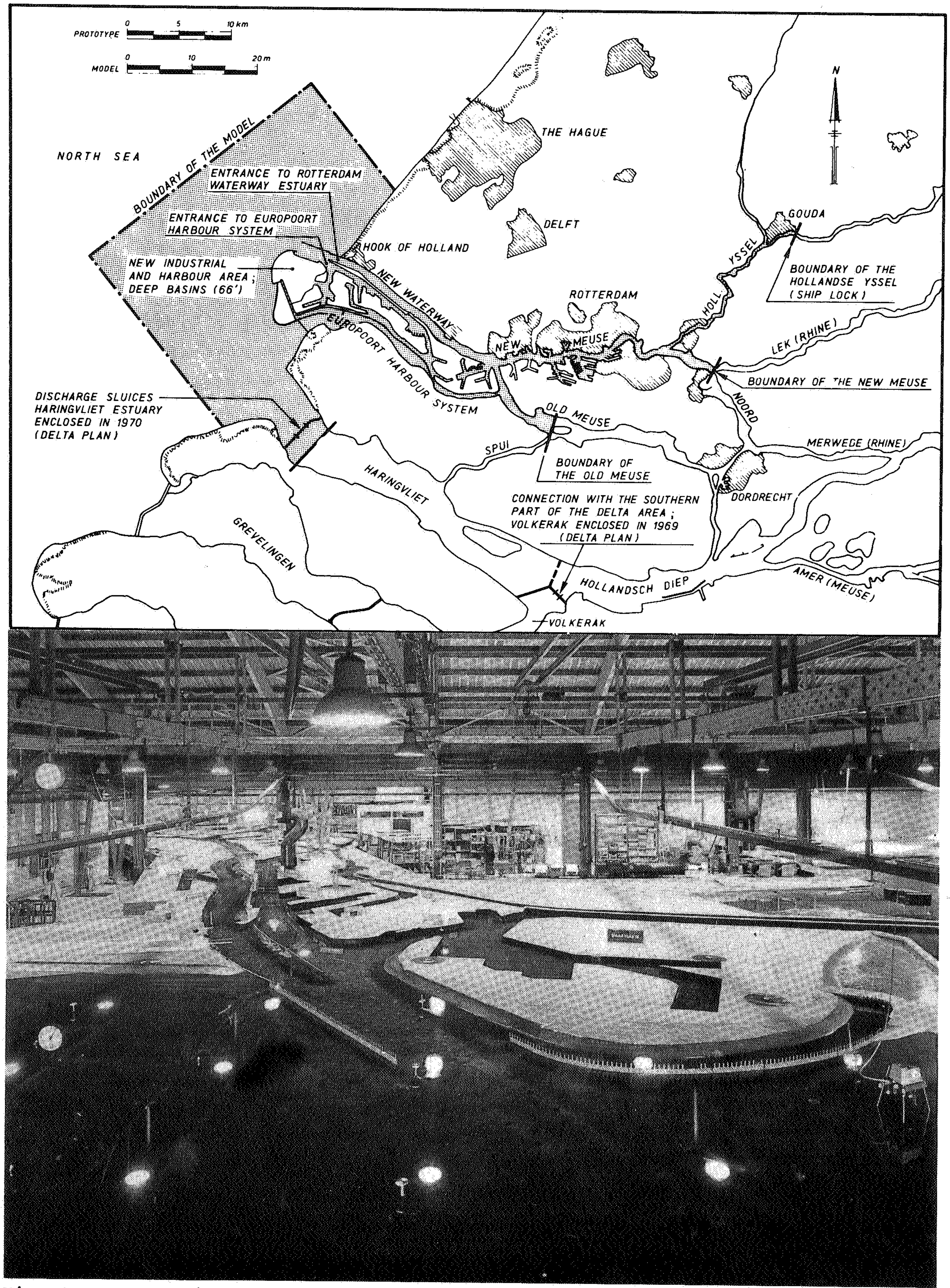


Fig. 1   General information

means had to be provided to evaluate the changes in the flow field due to the construction of the harbour moles and to prepare the harbour pilots for these changes. Also changes in the inner part of the harbour area had to be studied, with respect to their influence on navigation.

The increase in harbour area and the continuous deepening of the estuary to provide sufficient sailing depth was detrimental to the salinity intrusion. The river Rhine already carries large amounts of salt from the mines in France and Germany which cause high salinity levels during low river flows. Any additional increase in salinity due to intrusion from the sea is harmful to the existing water inlets in and east of Rotterdam. These inlets provide water for households, industry and agriculture (i.e. for flushing the polders in the western part of the Netherlands which lie below sea level (up to 6 m) and suffer from saline seepage).

Before the construction of Europoort harbour a critical situation was already extant so that further salinity intrusion had to be avoided and salinity intrusion had to be reduced, if possible. The increasing salinity intrusion and the extension of harbour facilities also caused an increase in siltation. Present dredging activities are in the order of 20 million m^3 annually. The dumping of the spoil causes problems because the spoil is strongly polluted by heavy metals, PCB, etc. due to the discharge of industrial effluents in the Rhine.

With reference to these problem areas the following aspects have to be covered by a model:

- navigational aspects: reproduction of the flow field, both depth averaged and vertical flow distribution;
- salinity intrusion: reproduction of salinity distribution under the influence of tides and river discharges; possibilities of reducing salinity intrusion;
- transport of pollutants and silt; possibilities of reducing siltation.

This requires the reproduction of the driving mechanisms:

- tidal movement;
- river discharge;
- density difference between sea and river water,

with the resulting flow phenomena such as:

- tidal elevation and currents, displacing and mixing water masses;
- estuarine circulations induced by density differences;

- mixing by turbulence generated by bed shear and wall roughness (groynes, harbour entrances) and mixing due to exchange currents between harbours and estuary and the confluence of tidal branches;
- erosion, transport and deposition of sediments.

It will be clear that no model provides an exact reproduction of all relevant phenomena. A discussion of reproductive capabilities and possible scale effects will therefore be necessary.

The required accuracy of a model in the reproduction of natural phenomena will depend on the type of investigation:

- comparative tests, in which various alternatives are compared mutually or with the original situation; the required accuracy will be determined by the detectability of changes in practice. Moreover, this type of test requires a very easy and stable model control.
- absolute tests, in which velocity and salinity have to be predicted for a certain condition (tide, river discharge) at a certain location; here the accuracy of the model results will depend also on the "measurability" of the present situation in nature, because this determines the accuracy of the model calibration.
- fundamental research, giving information to improve the understanding of physical phenomena, which is necessary to develop both hydraulic (scale) models and mathematical models. The accuracy of the results must be sufficient to detect the effect of the various parameters during this type of research.

3. RELATION TO OTHER SOLUTION METHODS

In general, the following methods are available:

- field studies;
- physical (scale) models;
- mathematical (analytical and numerical) models.

For all methods information on accuracy, possibilities and limitations is required. Each method has to start with a definition and schematization of the problem area, and boundary conditions have to be defined.

Salinity intrusion in estuaries is the result of a complicated interaction between several mechanisms. Both mathematical and scale models have to be validated by field data. However, each method is limited, so that in general only a combination of all methods will lead to results.

Field data can be obtained only for the existing situation. Systematic changes in the variables (depth etc.) are not possible. Sufficiently complete sets of field data are essential for obtaining physical insight.

Mathematical models are based on the knowledge of the physical processes involved such as turbulent mixing, boundary resistance, etc. Their predictive ability depends on the degree of schematization of the physical processes. The ideal model is a three-dimensional one with a good turbulence modelling, representing the influence of density differences on the turbulence structure as well. This type of model has not yet left the research stage and is presented only for ideal situations, for example with a simple representation of the eddy viscosity (5, 9).

Two-dimensional models (two horizontal space dimensions) cannot be used here, because the estuary is partly mixed and an accurate representation of the salinity and velocity distribution is required. Moreover, these models are limited in reproducing areas with recirculation flows and, in general, turbulence generated by shear stress in a vertical plane. These models are useful, however, in providing boundary conditions for scale models.

Two dimensional models (one horizontal, one vertical space dimension) are being developed with reasonable success (4, 10) for estuaries in which lateral variations are insignificant. In these models an empirical correction for the influence of stratification on the mixing length or eddy viscosity is used; their predictive ability is therefore limited. Application for the present estuary is questionable, due to the effects of groynes, harbours and a confluence of two branches which can be introduced only as lumped parameters. The model therefore cannot predict effects of changes in wall roughness, harbour configuration etc. but can be useful to obtain more insight into the physical phenomena.

In one-dimensional models, the effect of velocity and density distribution is very crudely reproduced by a dispersion coefficient. This means that the effect of highly two- or three-dimensional mechanisms (e.g. gravitational circulation, exchange with harbours or lateral irregularities) has to be schematised by a gradient-type dispersion modelling. Tuning of the model constants on a range of prototype measurements is therefore essential. Even then the predictive capacity of this kind of models is very limited (6). These models can be used, however, to obtain boundary conditions for the inland boundaries of the model, if the scale model does not cover the whole area with tidal influences.

Summarizing it can be said that mathematical models do not yet yield the possibilities to predict the flow velocity and salinity field in sufficient detail. Therefore the main tool for estuarine problems at present is the physical (scale) model, although this type of model also has certain limitations (effects of distortion and Reynolds number).

For the study of transport of pollutants and sediments the situation is different. The initial stages (near field) of pollution dispersion generally cannot be modeled properly in a distorted physical model, while sediment transport characteristics like flocculation, erosion etc., are difficult to model physically. However, if the three-dimensional velocity field is known, a fair prediction of pollutant concentration is possible if a reasonable value of the diffusion coefficient can be given, because the influence of advection is predominant in many cases.

The knowledge of the physical processes of sediment transport is so limited that reproduction, both in mathematical and scale models, is based on empirical knowledge only so that no preference can be expressed for any of these methods.

4. MODEL DESIGN AND CONSTRUCTION

4.1 Introduction

In discussing the present Europoort model it must be realized that the first design was made in 1965, when the available knowledge (physical processes and field data) and the technical tools (instrumentation and mathematical models) were far less than at present. In 1974 it was decided to construct a new seaboundary control system and to adapt the model to new requirements expecially related to the study of salinity intrusion. This new model "sea" was completed in 1976. Recently (early in 1979) it was decided to extend the model in landward direction with a threefold aim:

- to extend the range of fresh water flows where the model can be used (especially low fresh water discharge giving a high salinity intrusion)

- to extend the area of possible research in inland direction
- to reproduce the tide-affected part of the estuary.

This extension of the model will be combined with the reconstruction of the existing model which was greatly damaged by a fire.

The model had to serve several purposes each of which makes special demands on the selection of the model boundaries and scales:

- studies for the influence of the harbour extension on the flow field near the entrance of the Rotterdamse Waterweg and the consequences with respect to navigation
- studies on the salinity intrusion in the estuary, as a result of changes in the geometry of the Rotterdamse Waterweg and Oude Maas
- studies on dispersion of sediment, heat and pollutants.

The emphasis of the model studies gradually shifted from the first to the second aspect, with occasional studies on the third aspect. At the start of the model study most attention was paid to the reproduction of the flow field around the entrance. Parallel to the Europoort model also a schematised estuary model was built: the "tidal salinity flume" which is extensively used to obtain basic knowledge on the physical processes related to salinity intrusion and to the reproduction of these processes in a distorted scale model (see for example (12)).

4.2 Definition of the model area

The choice of the model boundaries depends on the physical phenomena to be reproduced. The sea boundaries have to be chosen in such a way that the conditions at these boundaries are not affected by changes in the problem area and that the fresh water discharge of the river leaves the model in a correct way. The salinity distribution in the estuary and near the harbour mouth should not be affected by the conditions at the boundaries (11).

Flow conditions near the harbour mouth are governed by tidal and density currents. The tidal range is from 1.35 (neap tide) to 1.75 m (spring tide). The fresh water discharge through the Rotterdamse Waterweg ranges from 400 to 4000 m^3/s (average 1000 m^3/s). The salinity of the North Sea is about 33 ppt. The tidal flow pattern at sea is nearly parallel to the coast with high-water slack at sea at 3.5 hours after H.W. at Hook of Holland. In view of this tidal flow pattern it was decided to take a closed western model boundary (see Fig. 1) parallel to the dominant flow direction and to have two control boundaries (north and south) at some 10 to 15 km from the entrance, perpendicular to the main flow direction. The distance of the western boundary to the coast

was roughly estimated from a potential flow computation on the influence of the proposed harbour extension. This estimate was verified later with two-dimensional tidal flow calculations which showed that the influence of the closed western boundary was within the experimental accuracy limits.
The initial choice of the river boundaries was a compromise between cost and accuracy. Since attention was concentrated on the harbour entrance, only the salinity-affected part of the estuary was reproduced.
This means, however, that tidal discharges and fresh water discharges have to be known at the river boundaries. This is a weak point because the scale model becomes dependent on a mathematical model. The other possibility, viz. extension of the model up to the limits of tidal influence, is costly but makes the model self-supporting. In both cases, however, calibration is necessary to obtain accurate values for the discharges.

4.3 Selection of model scales

Selection of model scales, defined here as the ratio of quantities in nature and model, is finding a compromise between cost and accuracy. This holds also for mathematical models. Several aspects are of importance (see also ref. (7)):

- length and depth scales should be large to reduce model dimensions, discharges and use of salt. In the present case tidal discharges up to 250,000 m^3/s have to be simulated which certainly presents a lower limit to the scales,
- reproduction of tidal flow phenomena requires Froude scaling (velocity scale = length scale $^{\frac{1}{2}}$),
- reproduction of density-influenced flow and mixing requires at least reproduction of the internal Froude number which means, in combination with the previous requirement, a one-to-one scaling of densities,
- the distortion of the model (ratio of length to depth scale) has to be limited for several reasons:
  - slopes are exaggerated in a distorted model but should remain below a certain value to avoid flow separation,
  - the correct reproduction of vertical mixing becomes increasingly difficult with augmenting distortion,
  - distortion means an increase in roughness. The Darcy-Weisbach friction factor in the model has to be increased in the same ratio as the distortion. Bed roughness (cubes, strips) is preferred in the present model, which gives an upper limit to the model friction factor,
  - dimensions of instruments require a minimum water depth.

- accuracy of the model and the instrumentation give maximum values for the model scales. The required accuracy for water levels and flow velocities presented no special problems here, but the salinity intrusion had to be reproduced in such an accurate way that special measures were necessary (see the chapter on model verification).

Consideration of all aspects and previous experience with tidal models has led to the following scales:

length scale	640	depth scale 64	(distortion 10)
velocity scale	8	(discharge scale 327, 680)	

Several aspects were not considered or reproduced:

- waves: the effects of waves on vertical mixing can be neglected in general,
- wind: wind can change the tide-averaged circulation (drift) in the North Sea which is in the order of 5 cm/s to the north under normal conditions. If necessary, storm effects can be reproduced by changing the boundary conditions of the model,
- Coriolis acceleration: neglecting the effects of the wrong representation of the Coriolis acceleration in models causes deviations in water levels and flow direction in general. Simulation of these effects requires rotation of the model or the use of rotating cylinders, where the lift force (Magnus effect) can simulate the Coriolis acceleration effects (13). Tidal computations have shown that in the present case Coriolis acceleration only affected water levels but not the flow velocity and direction. Only correction of water levels is therefore necessary in comparing water levels in model and nature,
- reproduction of sediment transport was not considered at the start of the model. Preliminary tests have shown that the model can be of some use for studying sediment transport but not all aspects are reproduced correctly.

4.4 Model boundary control systems

For the river boundaries a discharge control was chosen. The fresh-water discharge was regulated independently to obtain sufficient accuracy. The tidal flow was generated with a constant supply and a controllable underflow. The resulting tidal discharge was measured with a propellor current meter some distance from the inlet. When calibrating the model the underflow gate is controlled in such a way that the flow velocity is in accordance with the prototype data. Once the movement of the gate is known only this movement is reproduced. This system is stable but it is very time-consuming to find a new calibration. This was not a problem for the Europoort harbour studies, but the system was not flexible enough for salinity intrusion studies. Therefore it was decided to switch to a volumetric discharge control, where the tidal discharge is stored in a large tank and the water level in the tank is used as control variable (see Fig. 2). These tidal discharges on the river boundary are calculated with a one-dimensional mathematical model of the whole estuary.

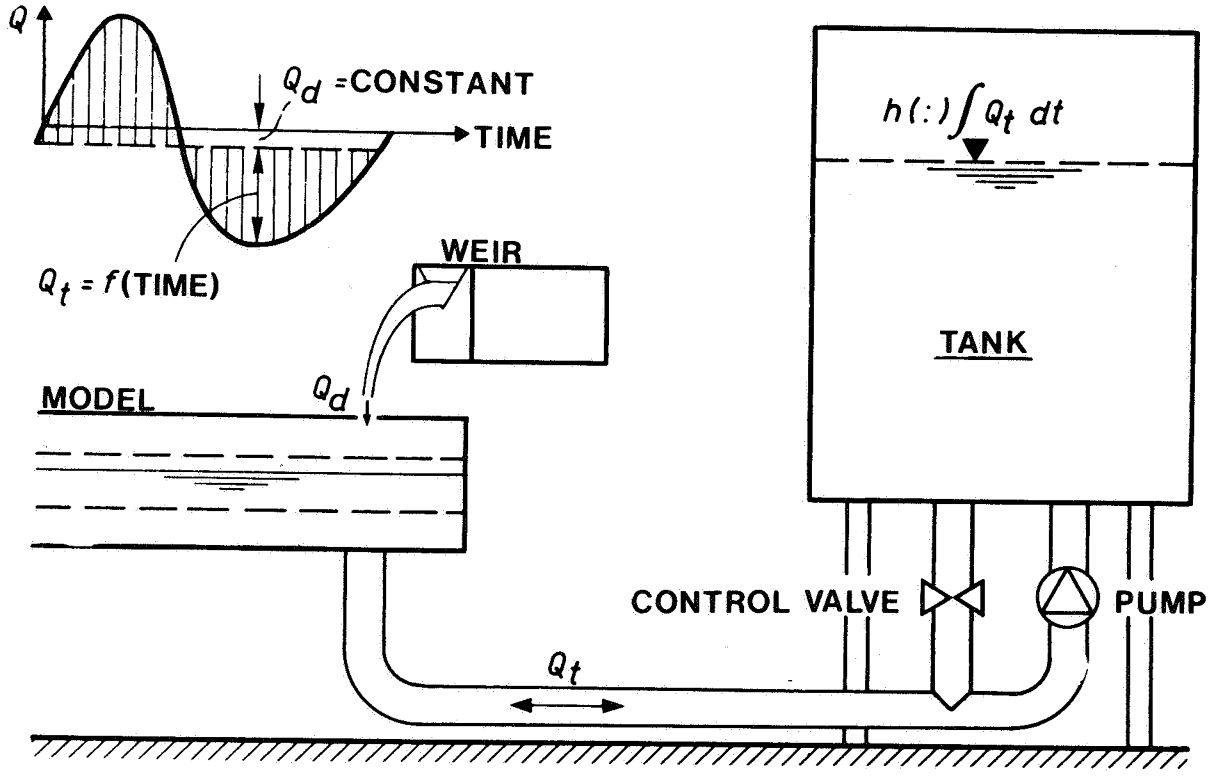


Fig. 2 River boundary control

For the sea boundaries a discharge control was chosen in 1965 because experience had shown that for a relatively small "sea" a water level control on all boundaries gives an unstable and inaccurate control of velocities in the sea area. This is especially true if the effects of resistance and the phase differences between the boundaries are small. (See Ref. 6).

The north boundary was divided in 5 sections and the south boundary in 7 sections each with an overflow gate. The tidal discharge was roughly produced with a central pumping station and by-pass channels whereas the fine control was done with the overflow gates. The resulting tidal discharges were measured with a large propellor current meter close to the model boundary. This system will not give a good water level reproduction in view of inaccuracies in prototype data and the model. Therefore one of the gates of the North boundary (the farthest away from the shore) was used to control the water level at Hook of Holland which was used as the reference level for the model. Although this system was able to reproduce the tidal movements (discharges and levels) to the required accuracy, it lacked flexibility because introducing a new tide was very time-consuming and reproduction of time series was impossible. Since flexibility was required for the water management studies, it was decided in 1974 to reconstruct the model sea boundary control system, thereby creating the possibility to reproduce longer series (up to 30 days).

For the choice of boundary control type and to obtain control procedures an extensive programme was executed, including one- and two-dimensional analytical and numerical tidal calculations (8).

From the computations the following conclusions were drawn:

- effects of friction in the model sea are not important for the choice of the control type,
- the advective acceleration terms have almost no effect on the flow field. The model behaves therefore as a linear system which is of great importance for the control system,
- closing of the western boundary has only a minor effect on the velocities near the entrance of the estuary if the discharge through the western boundary is correctly compensated on the north and south boundaries. Because more field data were available in 1975 it was found that a slight rotation of the western boundary gave better results that the existing boundary,
- omission of the Coriolis acceleration does not affect the flow field but only the water levels,
- water level control for both boundaries (north and south) gives unacceptable inaccuracies because of the small phase difference between the two boundaries. Tide-averaged discharges cannot be generated with a water level control system and have to be independently generated,
- the most stable solution is a water-level control at one side and a discharge control at the other boundary. Possible errors in one of the boundary conditions do not influence the other boundary.

A review of existing tidal models in other laboratories showed that for long (relative to the length of the tidal wave) estuaries a water level control at the mouth of the estuary gives good results. For short sections of estuaries generally one discharge and one water level control is applied.

Although a discharge control for both boundaries requires a very great accuracy to obtain a reasonable water balance and water level control it was decided to use this type of control also because it can be used to simulate tide-averaged discharges. (drift in northerly or southerly direction). The tidal discharges at the sea boundary are obtained as follows: the out-going discharge is pumped from the model into a reservoir under the model; the flow into the model is supplied by the existing by-pass circuit (see Fig. 3).

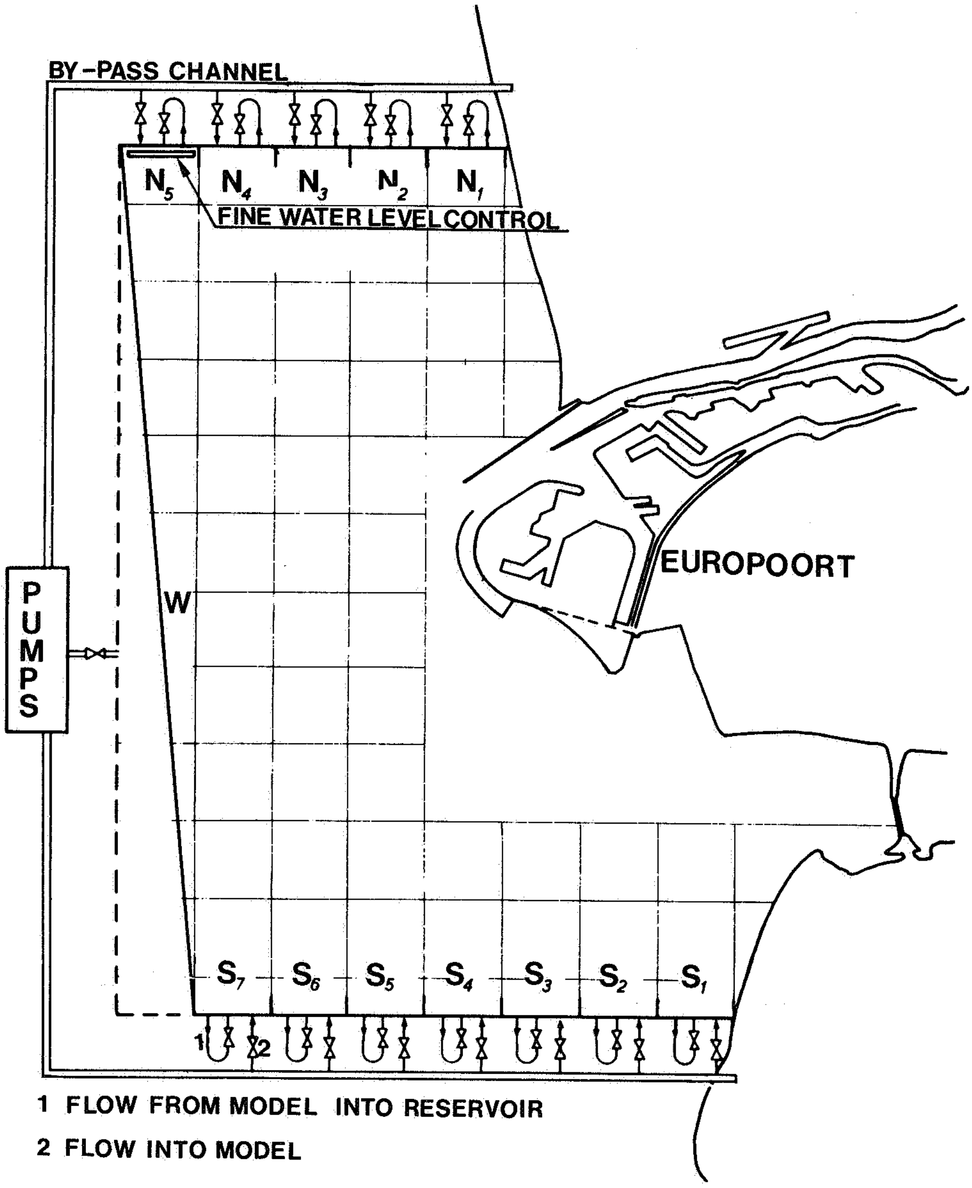


Fig. 3 Sea boundary control

Discharges are measured with electro-magnetic flowmeters which have a very high accuracy. This fact and the large number of control sections give a very good overall water balance. The remaining error in the water level at Hook of Holland is very small and can be easily compensated with a "fine water-level control" of limited capacity. This "fine water-level control" is a feed-back system where the difference between desired and realised water level at Hook of Holland is translated in a correction of the discharges at Section N5.

Special attention had to be given to the influence of the salinity distribution along the model boundaries. Field data show density gradients both in vertical direction as well as perpendicular to the coast. An exact reproduction of this distribution is almost impossible. It was therefore decided to generate a well mixed outflow (with water jets) and a uniform density of the incoming water and to study the effect of this change in boundary condition on the salinity distribution in the estuary itself.

In one test a temporary, closed boundary parallel to the western boundary, halfway the model sea, was constructed leaving all other conditions the same. In another test additional fresh water was introduced near the model boundaries (in the same order as the river discharge). Both changes did not affect the salinity distribution in the Rotterdamse Waterweg to a measurable extent, so that it was decided that the proposed salinity control at the model boundary was sufficiently accurate.

4.5 Roughness and mixing

The distortion of estuary models necessitates the adjustment of roughness and mixing. The roughness can be separated in wall and bed roughness. Wall roughness effect due to groynes, harbour entrances and other protrusions is reproduced correctly, because their shape is reproduced geometrically similar. The distortion does not have a significant influence here because these protrusions are already sharp (in the sense that the flow will separate from the protrusion) in nature. The friction factor for the bed roughness has to be increased with the distortion factor, to obtain the correct water level shapes.

Means to provide the required model roughness are cubes, strips and vertical bars. In the present case, where a reasonable reproduction of velocity and salinity profiles is required, bed roughness (cubes or strips) is preferred. The effective roughness of these elements can be measured separately so that *if* the prototype roughness is known, the model roughness can be determined also. In general, a calibration of the roughness is necessary, however, because the prototype roughness is not known sufficiently accurate. The optimum model roughness is determined by comparing water levels and gradients in model and nature.

If all mixing in an estuary is thought to be caused by bed-shear generated turbulence it can be shown that the vertical mixing in a distorted model is too small (2). So the vertical mixing has to be increased. On the other hand,

mixing due to wall-roughness generated turbulence (groynes, harbour inlets, confluence) is correctly reproduced in a distorted model. This was proven in the systematical salt intrusion research in the tidal salinity flume. It depends therefore on the relative importance of wall and bed roughness whether the mixing in the model is to scale. Tests in the Europoort model and in the tidal salinity flume have shown that the vertical mixing can be influenced by the choice of type of roughness elements, used for the additional roughness (1). With the same total roughness, generated with different means (strips on the side walls, vertical bars and cubes or small plates on the bed) different values for the vertical mixing and the salinity intrusion were found. Wall strips produced the maximum mixing.
The conclusion is therefore that in reproducing the roughness, lack of knowledge of the prototype roughness is the weak point, but that calibration of the model will provide a sufficient solution. For the turbulent mixing, the model acts more or less as a "black box" and has to be calibrated also. The choice of the type of roughness element is here a calibration parameter. In the present model additional mixing can be provided by air-bubble screens, giving almost no effect on the roughness. The influence of vertical mixing on the reproduction of the salinity distribution will be discussed in the chapter on model calibration and verification.

4.6 Model construction

The model was constructed in a traditional way. The sea bottom was constructed by pre-stressed concrete plates following the sea bed contours, leaving a reservoir under the floor for water storage. The river sections were constructed with sand and mortar using wooden profiles for the cross section. To keep the model sea at constant density, brine is injected in the by-pass circuit. The brine is produced with a special installation with a maximum capacity of 4000 kg NaCl/hour.

5. MODEL OPERATION AND CONTROL. INSTRUMENTATION AND DATA PROCESSING

Operation and control

In the original conception of the model, the sea boundaries were controlled by overflow weirs with feedback control on the velocity along the boundary or, if the reproduction of the tide was completed, by control on the position of the weirs. The desired programs were created on special analog programmers and the model was trimmed by trial and error.

In 1977, a new, computer-based, Rijnmond Model Control System (RMCS) was developed, in combination with a data-acquisition system, by PANDATA for use on a PDP computer (for a detailed description see ref. (3)).

Discharges for the model boundaries are computed from simultaneous 13-hours prototype measurements along the model boundaries. These raw data need correction to obtain a water balance and to compensate for the closing of the Western model boundary. The corrected data are used to compute the model discharges for the 12 control sections. For time series, discharges are predicted with the aid of continuous records in a few points in nature. River boundary discharges are computed with a one-dimensional mathematical model (IMPLIC) of the estuary.

The purpose of the Model Control is to accurately generate tides in the model to enable the execution of experiments under strictly defined conditions. Taking into account the deficiencies of the original model control, five areas of improvement were identified:

- faster adjustments, preferably automated as much as possible;
- better operational control, ease of use and flexibility;
- reproducibility of tides without a need to readjust;
- a library of tides, to be able to do tests under different tidal conditions;
- improvement of accuracy.

The adjustment process should be no longer a trial-and-error method but flexible methods should enable the operator to perform adjustments of new tides.

The model is controlled by a PDP 11/40 running under the RSX-11D operating system. The total hardware configuration is shown in Fig. 4. The model computer is connected to a central computer facility of the Laboratory. In this remote facility data analysis and data plotting take place after experiments have been run. Communication between the process control and data collection equipment of the model is performed by "UDC" hardware (standard process control hardware for PDP's) and a separate analog/digital controller. The analog/digital channels are mainly used for the data acquisition system although five analog channels are used by RMCS for sensing water-levels and salinity.

Operator control of the model takes place by means of push-buttons and a control terminal in the control room.

A specific situation in the model is generated by four different control mechanisms:

a. direct flow control along the sea boundaries;
b. direct flow control at the up-river control sections;
c. supervisory control of the water-level at a central location in the model;

d. density difference control between fresh and salt water.

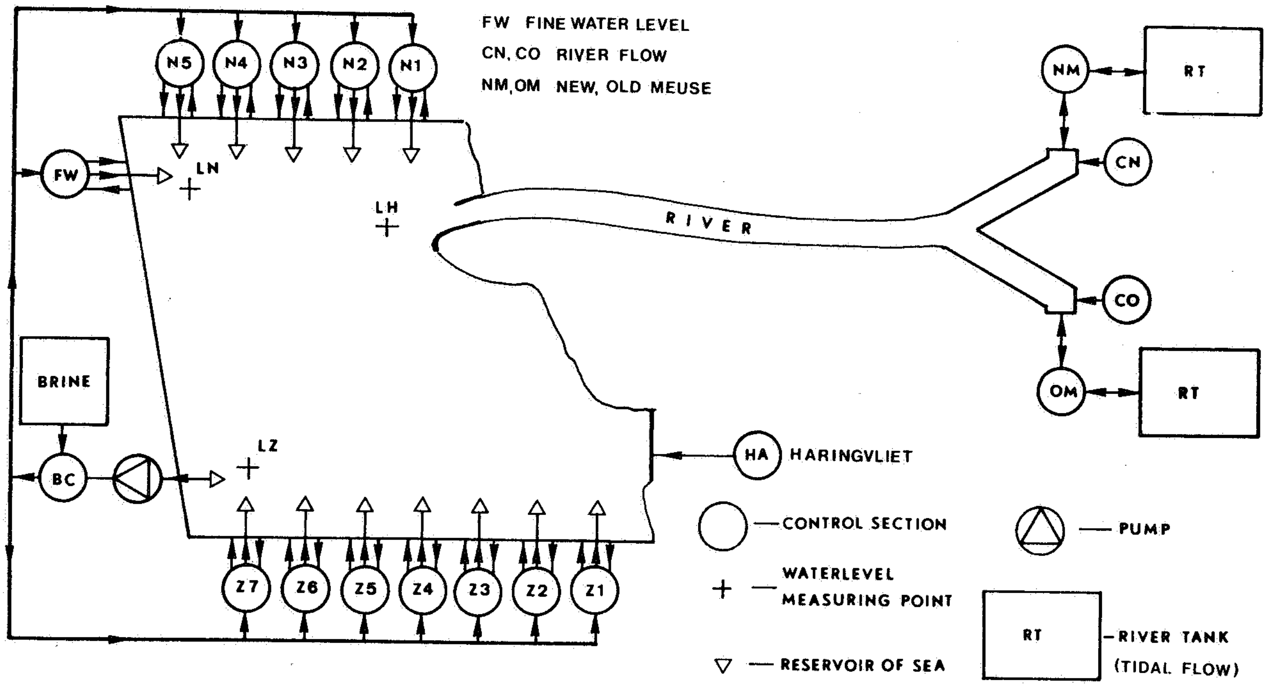


Fig. 4 Computer system

The set-up is shown schematically in Fig. 5.

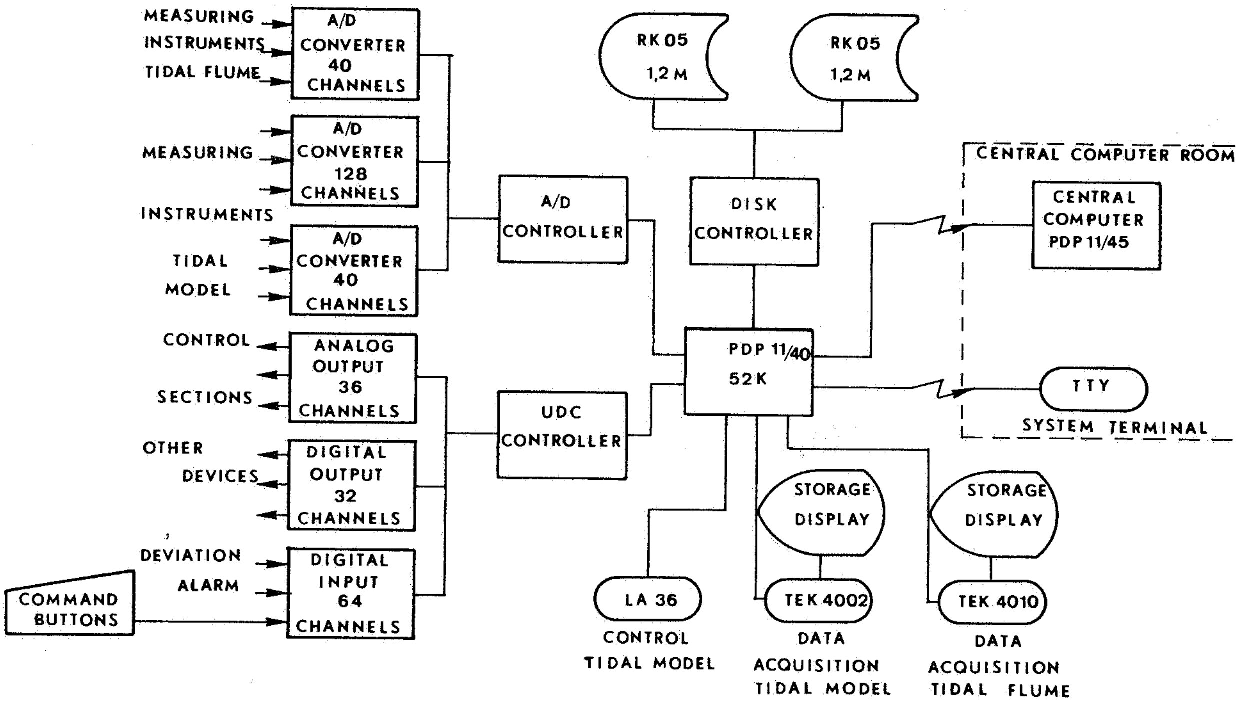


Fig. 5 Tidal model control

Flow into the model is supplied with a large constant-pressure by-pass and a pumping station. The density control maintains the incoming flow at a constant relative density, in comparison with the fresh water that comes from the river ends. Injection of brine takes place on the suction side of the pumping station. The outgoing flow controls have their own pumps which return the water to a large sump beneath the model which is also connected to the pumping station mentioned above. The flow control sections vary in size; the sections nearest to the coast-line have a capacity of about 80 litres per second, while further away from the coast, sizes of about 260 litres per second exist. The flows are measured by electro-magnetic flow meters and finally controlled by means of control valves.

The flow control of the river ends, Nieuwe Maas and Oude Maas, is divided into two different functions. One control is used for simulating the tidal movement by setpoint control of the level in a storage tank. The other one, the upper river discharge, is mostly a constant value during one experiment and is set by hand.

The RMCS also takes care of the start-up of the model and the adjustment of the discharges to obtain the required vertical tide at Hook of Holland. Several adjustment procedures are available. In one of these procedures the difference between the actual and required water level is measured continuously and used to compute a (small) correction in the discharges of all control sections. Another procedure ensures a constant mean sea level during the experiments. Set-points for the control section are computed every 7.5 real-time (model) seconds with linear interpolation to obtain set-points each 0.1 real time second. Water levels are also measured every 7.5 real-time seconds and if necessary used for the adjustment procedures by the operator.

The task of the operator is of a supervisory nature. He must ensure that the tide is generated as required for the experiment. His actions are limited and include: checking that the model is functioning properly, sequence control of the phases of model operation, setting up equipment such as cameras and water level recorders, and acting in exceptional situations. The most essential part of the operator task is during the adjustment of a new tide. Tides which have been satisfactorily adjusted can be stored by the user in the model library.

The RMCS software was developed under the Digital Equipment RSX-11D operating system which has many features for real-time system development. In total the system is composed of over 100 Fortran programs (7500 executable statements in all) and three programs written in PDP 11 - Assembler.

Experience has shown that the system permits fast and flexible adjustments.

Usually a new tide can be adjusted within one or two days. The reproducibility of the water levels is accurate within 0.1 mm (for comparable times in different tidal cycles). Difference between desired and realized water level is generally less than 0.2 mm at any time.

Instrumentation and data processing

The standard instrumentation of the model comprises:

- water level followers (vibrating-needle principle) with an error < 1 cm prototype
- propellor current meters, fixed or rotating with a vane to measure flow direction (error < 2 cm/s prototype or 3^o)
- conductivity and temperature probes to measure density (total error < 0.25 kg/m^3 for measurements at different days); for measurements at the same day a greater accuracy is possible.

Besides there is the possibility of special measurements:

- overall stream patterns are recorded by photographing floats (5 m, 10 m and 15 m length)
- to measure lateral forces and moments on a ship, due to currents along a certain sailing line, a towed plate is used. For tanker simulation a plate of 300 x 15 m is used and smaller plates are used for coasters, etc. Although these plates give only a crude simulation to the actual ships, the instrument is very useful in comparing various situations or sailing lines.

The accuracy of water level and velocity measurements is sufficient for all practical purposes but the measurement of density deserves special attention. The accuracy required by the contractor for the determination of the salinity intrusion ($\pm$ 100 m prototype) corresponds to an accuracy in the density measurements of 0.1 kg/m^3. Therefore special methods are necessary here.
Data processing started with line-following of paper records with computations and plotting by computer but since 1974 a computer-based data acquisition system (up to 168 channels) is used. Computational and plotting programs are available to produce vertical and longitudinal profiles, vertical and profile-averaged values, discharges, dispersion coefficients etc.

6. MODEL CALIBRATION AND VERIFICATION

6.1 The model "sea"

Possibilities for calibration and verification of the model "sea" are limited. The information on tidal discharges at the sea boundaries and the water level at Hook of Holland are used to control the model. The only variables left are the roughness of the model and the way the discharges of the (closed) western boundary are compensated. Velocities in the inner part of the model sea are hardly affected by changes in the bed roughness. Only water level differences can be influenced, but the roughness cannot be checked accurately because measurements in the open sea are not reliable. It was therefore assumed that reproduction of a reasonable (estimated) value of the prototype roughness was sufficient. By applying several ways of compensating the discharges through the western boundary:

- either by a 40% - 60% distribution over the northern and southern boundary
- or a 100% compensation on the North-Western part of the boundary, as far away from the project area as possible (see fig. 3)

and a comparison of resulting velocities in the model and a few measuring points in nature it was concluded that preference had to be given to the second procedure. The first procedure proved to be wrong because it affected the two-dimensional flow pattern at sea. As a verification, float measurements near the entrance were used. Comparison of flow pattern obtained for floats with a length of 5 m for both neap, average and spring tides showed a good similarity. As an example, results for an average tide are given in Fig. 6, which shows that even the complicated, density influenced, flow pattern near the mouth of the estuary is correctly reproduced in the model.

6.2 The river system

The most important feature of the river is the salinity intrusion, but of course tidal propagation and velocities have to be similar as well.

Tidal propagation

For calibrating this aspect two parameters are of importance for the Europoort model:

- the model roughness,
- the river boundary conditions.

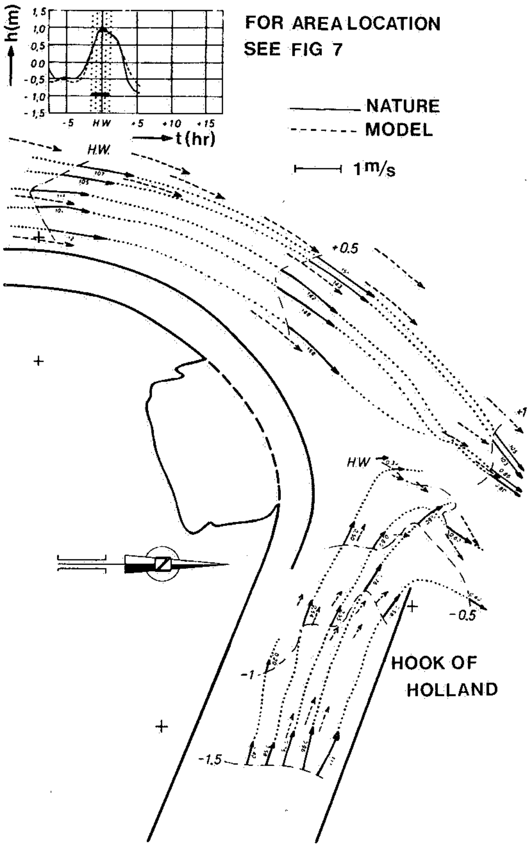


Fig. 6 Comparison of float patterns in model and prototype around Europoort.

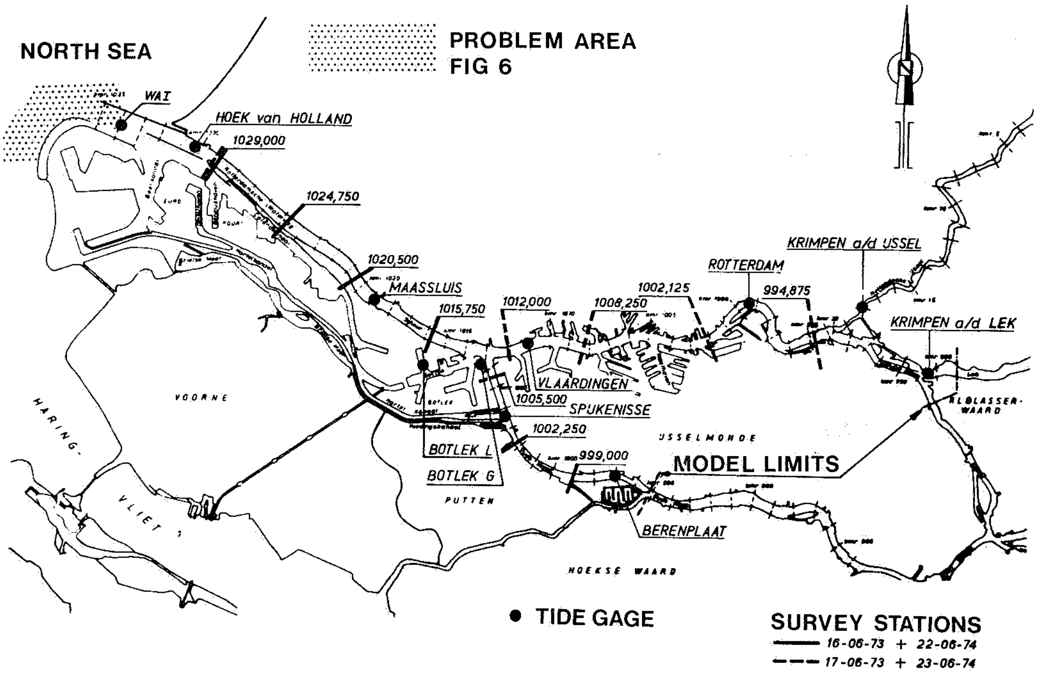


Fig. 7 Measuring points for verification tests

The longitudinal distributions of amplitude and phase of the M2 component of the water levels were used as parameters for calibration. From sensitivity tests with the model it was found that the change in amplitude and phase over a certain section was almost linearly related to the amount of additional roughness. The use of these parameters therefore provides a good means to obtain the optimum roughness in the model.

On the other hand it was found that relatively small changes in the boundary conditions had an influence of the same order as appreciable changes in the model roughness. The river boundary condition has a limited accuracy both for discharges measured in nature (limited number of measuring points and inaccuracy of instruments) and for the discharges computed with mathematical models (both the analog DELTAR and the numerical model IMPLIC do not account for density differences and have to be calibrated also with discharges and water levels in nature). Differences in the tidal discharge at the river boundary sections up to 20% and phase differences up to 30 minutes are possible. Calibration of the model is therefore always possible (but uncertain) by a combination of changes in the roughness and changes of the boundary conditions within the accuracy limits.

For the calibration two sets of measurements in nature were available: 16 and 17 June 1973 and 22 and 23 June, 1974. The measurement took two days because the number of measuring positions for velocity and salinity was too large for the available number of ships. Tidal amplitudes were measured continuously and at the mouth of the estuary (km 1029, see Fig. 7) measurements were done all four days.

The data for 16 June 1973 were used to obtain an optimum set of roughness and boundary conditions. The other days were used for verification. As an example Fig. 8 is given in which mean water level, amplitude and phase of the M2 component is presented. The prototype data show some differences depending on the agency which provided the data. Except for the stations close to the model boundary a good similarity is obvious.

Salinity intrusion, density and velocity distribution

The required capabilities of a model to simulate natural phenomena depends on the nature of the investigation (comparative or predictive, support of fundamental research).

The capability of the model depends on several factors:

- accuracy of boundary conditions,
- accuracy of the model boundary control,

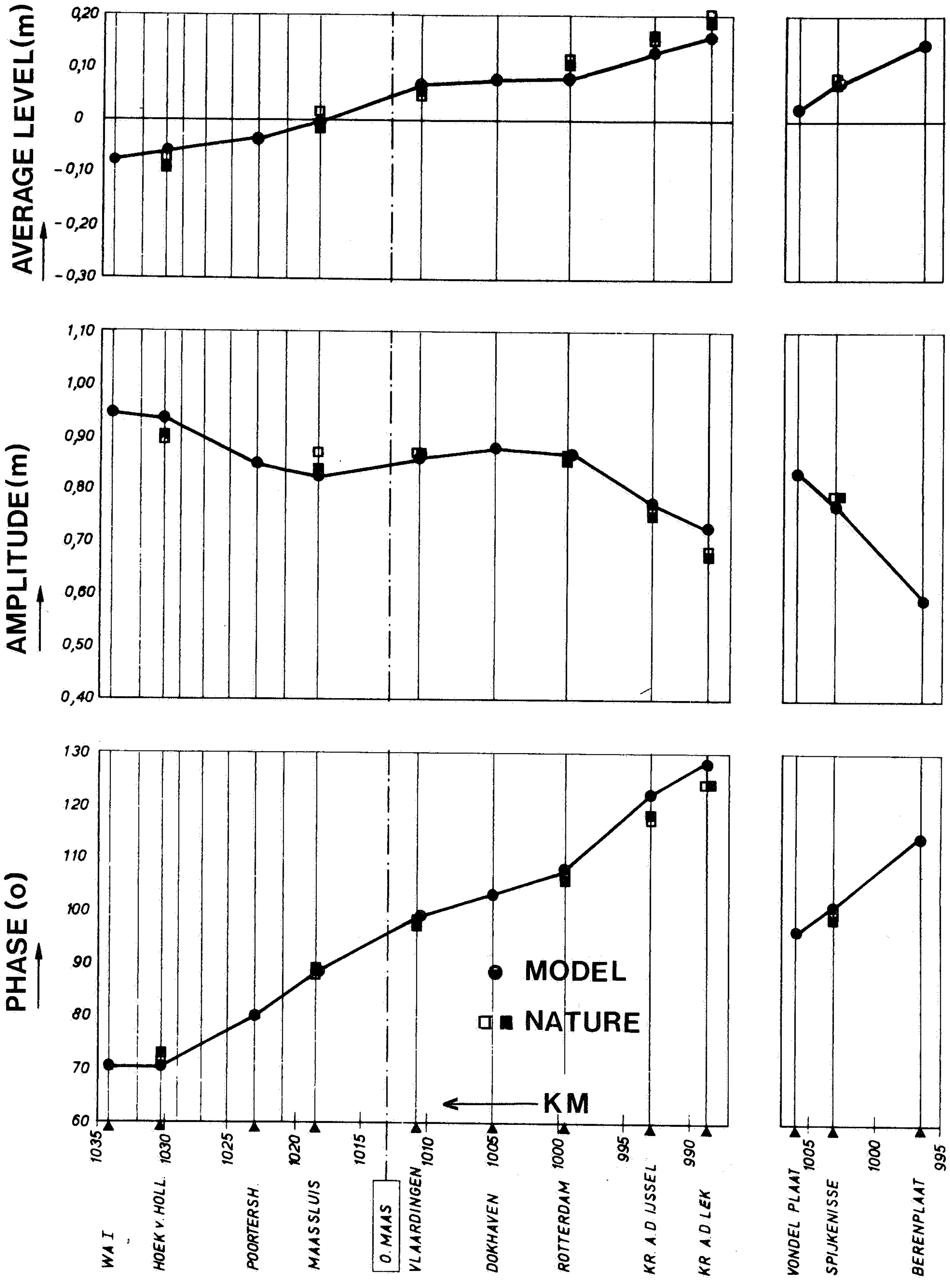


Fig. 8 Verification of tidal propagation on the river, 22-06-1974

- accuracy of instruments,
- drift of boundary control and instruments.

For the tests in which a comparison has to be made between two situations (for example deepening of part of the estuary) a high accuracy is required. These tests should preferably be carried out on the same day because incidental errors in model control and instrument calibration are avoided. From tests with constant control conditions it was found that drift and other errors were small (< 0.07 kg/m^3); density changes larger than this value can be detected.

This corresponds roughly to changes in salinity intrusion length of ± 75 m in nature. This seems to be sufficient for practical applications. For tests on different days, using the same boundary conditions, density variations up to 0.25 kg/m^3 occur in the upstream part of the salinity intrusion. This corresponds roughly to changes in salinity intrusion of ± 300 m. For a completely new situation the accuracy of salinity prediction is limited therefore but this will be sufficient in general, in view of the large variations in boundary conditions in nature (variations in tides and river discharges, wind effects).

A model like the Europoort model can provide useful information for fundamental research but only in the verification of theoretical restuls. Measuring techniques are generally not sufficiently accurate and detailed to obtain gradients and fluxes of mass and momentum. Efforts to improve this do not seem to be very promising up to now.

The salinity distribution and intrusion in the model can be influenced in several ways, assuming tidal propagation has already been adjusted:

- the type of roughness: from observations in the tidal flume and the present model it has been concluded that for the same total friction factor, the vertical mixing and salinity intrusion depends on the roughness type,
- additional mixing can be obtained by the injection of air. Experimentally it has been found that quantities up to 20 cm^3/m^2/s hardly affect the roughness but greatly enhance the vertical mixing and reduce the salinity intrusion,
- the "history" effects of the tidal movement: It cannot be assumed that the salinity intrusion during a certain tide is independent of the preceeding tides, for example a spring tide following a normal tide. In the model the tides have to be made cyclic. Comparisons, where the measurement period of 12.5 hours (one tide) was part of a cycle of 25 (one preceeding tide) or 75 hours (five preceeding tides) showed that for practical application,

(normal tidal variations) "history" effects can be neglected,

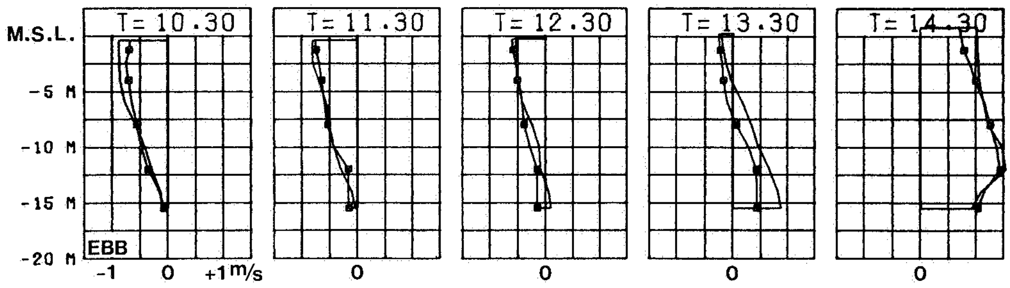
- the density difference between river and sea water. In principle this difference is kept at a constant value, obtained from prototype measurements, but slight deviations during a test are possible. However, if the interpretation of the results is on the basis of the relative density distribution, these deviations have no significant effect,
- river boundary conditions. The effect of this parameter was already obvious for the tidal propagation but the effects on the salinity distribution are dramatic.

  From sensitivity tests both with the tidal flume and the present model it appears that to obtain an accuracy of ± 100 m in the salinity intrusion (for instance defined as the position of a point near the bed with a salinity of 0.5 kg/m^3 at the time of maximum salinity intrusion) the following accuracy in the river boundary conditions is required:

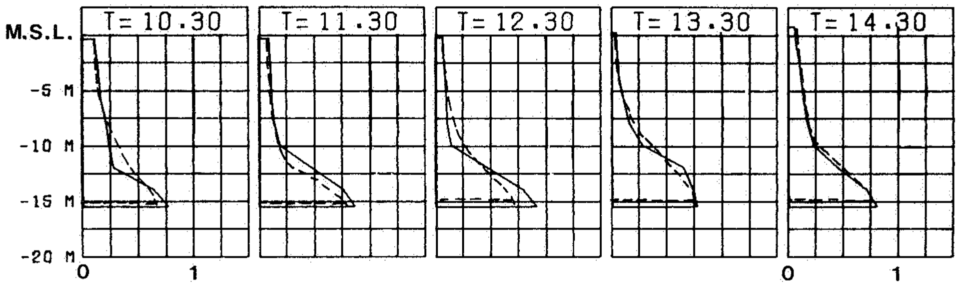
  for the average (river) discharge : ± 1%
  for the amplitude of the M2 component of the tidal discharge : ± 1%
  for the phase of the M2 component of the tidal discharge : ± 1 min (or 0.5°)

It will be clear that these accuracies are not obtainable from measurements in nature or from mathematical models. This means that for absolute predictions of the salinity a relatively large uncertainty margin is present. It also means that an absolute calibration of the model is impossible, because small changes, within the limits of uncertainty in the model boundary conditions, have such a dominating effect on the salinity intrusion. Extension of the model up to the tidal limit is only a partial solution because this extension also has to be calibrated with data from nature.

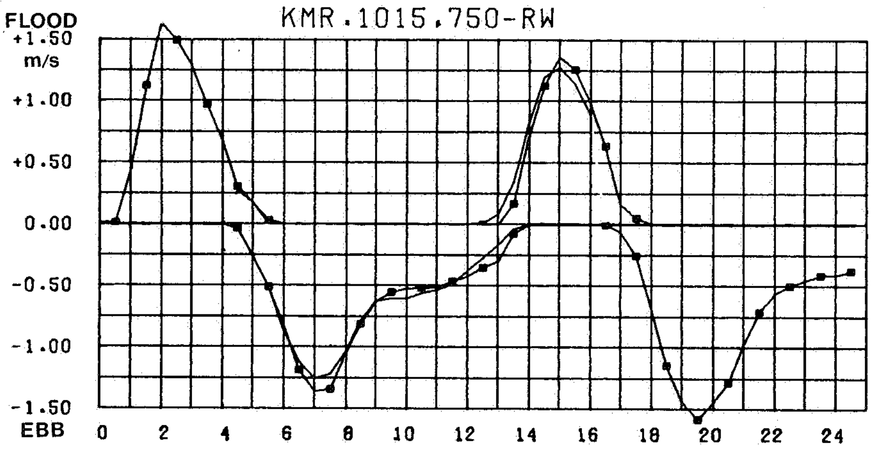
For the optimum condition with respect to the reproduction of tidal propagation, the velocity and density distribution was compared for model and prototype without any further adjustment of the model (no air injection, etc.). Some results for the measuring station at km 1015 are presented in fig. 9. Fig. 9a shows a comparison of some velocity profiles, fig. 9b the distribution of the relative density (difference between the local density and the river water density divided by the difference in density between sea and river water). Fig. 9c shows the velocity averaged over the vertical. These velocities are averaged for each flow direction (ebb vs. flood); thus the density currents round slack tide become visible. Fig. 9d shows the depth averaged



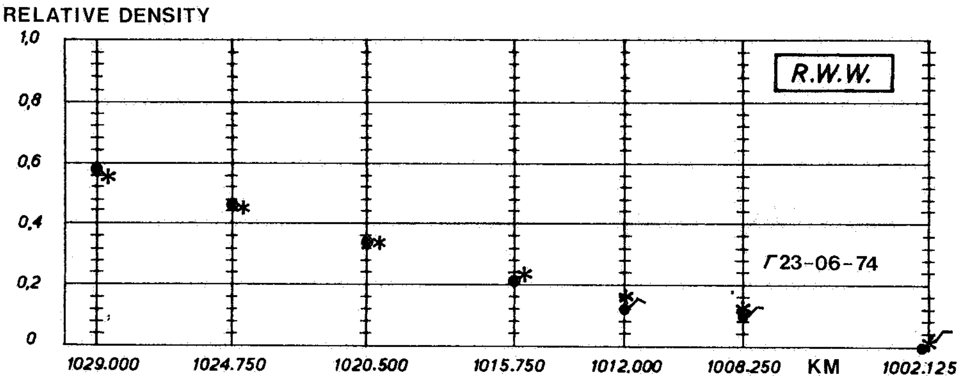
a VELOCITY KM 1015.75 —■— MODEL —— NATURE



b RELATIVE DENSITY KM 1015.75 —— MODEL ---- NATURE



c AVERAGE VELOCITY —■— MODEL —— NATURE TIME -hours-



d LONGITUDINAL DENSITY DISTRIBUTION AT L.W. SLACK * MODEL ● NATURE

Fig. 9 Verification of density and velocity distribution, 22-06-1974 salinity distribution at Low Water Slack. The river discharge during the period preceeding the measurements in nature was relatively constant. Further, it was proven before that the history effects of the tidal movement can be neglected for the salinity distribution in practical cases. So it can be concluded that the prototype situation was a "quasi-steady state" which can be compared with the "cyclic-steady state" results of the model. The agreement is generally quite good. Further adjustments were not considered because of the uncertainties in the boundary conditions which have such a great influence on the salinity intrusion. It may be concluded, however, that for the present model a good reproduction of tidal propagation also gives a good reproduction of the salinity intrusion. For new situations, the knowledge of the boundary condition forms the weakest point in the accuracy of the model reproduction.

7. APPLICATION OF THE MODEL

Without going into details a short review of model applications will be given. The first part of the model studies was mainly related to navigational problems around the new Europoort harbour.

The studies included the determination of the flow pattern and the hindrance for navigation during the various phases of construction of the harbour works. The effects of these works on the salinity intrusion was equally studied. Later the attention shifted gradually to the influence of modification of the inner estuary (removal or construction of groynes, deepening or shallowing of the river bed, modification of harbour entrances) on the salinity intrusion. Special studies included the dispersion of cooling water from a large power plant in the Europoort area, exchange currents in harbours and possible ways to reduce them in view of a reduction of sedimentation and the dispersion of pollutants in the river system.

In all these cases the model assisted in predicting the effects of these measures which are very difficult to predict in another way. It has proven to be very useful in supporting decisions related to the management of the estuary.

SUMMARY AND CONCLUSIONS

Salt intrusion and water quality modeling of a complicated estuary like the Rotterdamse Waterweg Estuary makes high demands upon the capabilities of modeling techniques. Increased environmental problems and the impact of the large infrastructural works have stressed the requirements. A thorough evaluation of research possibilities proved that for the time being only a complimentary approach with hydraulic and mathematical modeling is feasible. With respect to modeling of the estuary phenomena the following can be concluded:

1. Mathematical models do not yet yield the possibilities to predict the flow velocity and salinity field in sufficient detail.
   Therefore the main tool for estuarine problems at present is the physical scale model.
   Mathematical models can be used successfully for the study of transport of pollutants and sediments.

2. Although the scaling of all phenomena in a hydraulic scale model is not yet completely understood, which gives the model a partial black-box character, it proves to be the most powerful tool for the study of estuaries, provided certain requirements are fulfilled.

3. The hydraulic model should be calibrated very carefully with special emphasis on the influence of possible scale effects due to distortion and Reynolds number influences.

4. The verification tests of the physical model of the Rotterdamse Waterweg Estuary: (a Froude scale model with a length scale 640 and a distortion 10) proved that reproduction of waterlevels and flow pattern is possible to the required accuracy if the proper boundary conditions are known. Once the tidal propagation in the river system was reproduced correctly, the simulation of salinity intrusion proved to be good.

5. The model should be provided with good boundary conditions. In the present case the knowledge of the river boundary conditions is the weakest point in the accuracy of the model. This makes the verification of the salinity intrusion uncertain.

6. Mathematical models are useful in predicting discharges at model boundaries. However, for reasons of flexibility in model operation and accuracy of boundary control an integrated system (extension of the model beyond the tidal limits) is preferable.

7. The model "sea" boundary should preferably be operated with discharge control, if the accuracy of the data permits this.

8. In the present case, where wall roughness is dominating, no additional mixing proved to be necessary after calibration of the total roughness on the tidal propagation with bed elements.

9. It is advisable to operate the model automatically both for the control of the boundary conditions as well as for the data processing. This permits flexible operation and increases the accuracy of the reproduction.

10. The purpose of the model research and the required accuracy have a large impact on the cost of the research. A close cooperation between principal and laboratory in the problem-definition phase is therefore essential.

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