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ESTMORF, A model for long-term
morphological development of estuaries
and tidal lagoons

Overall review of the development of the model

Report

November 2001



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ABSTRACT:

The development of the ESTMORF software as well as its applications to the various areas have been carried out in a series of projects. Each of these projects has been described in the corresponding technical reports. An overview of these reports is given in Appendix A.1. Now that the model has become operational there is a need for an overall reviewing document for all these activities and projects. The present report serves for this purpose. It is set up such that the report can be read stand alone to answer questions of readers like: what is ESTMORF? how does it work? what can it simulate / predict (possibilities) and what can it not (restrictions)? On the other hand it also gives an overview of all the available documents related to the ESTMORF model so that readers can get access to the relevant document when a particular aspect of the model or a certain application of the model is of interest.

Chapter 2 describes the development of the ESTMORF model. First an historic overview of the development is given and then the model principles are described followed by a summary of the functionality's of the model. In Chapter 3 the applications of the model are described. After an overview of all application models the Western Scheldt model is described in more detail, followed by brief descriptions of each of the others. Finally an evaluation of the present state, the possibilities and the restrictions of the ESTMORF model is given in Chapter 4. The relevant references are given in Appendix A. Here a distinction is made between the technical reports of the ESTMORF studies (A.1) and the general literature (A.2). A brief summary is given for each of the technical reports of the ESTMORF studies in A.1. In Appendix B a number of papers published at international conferences and in technical journals concerning the ESTMORF studies are included.

REFERENCES:

VER.	ORIGINATOR	DATE	REMARKS	REVIEW	APPROVED BY
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Z.B. Wang

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I Introduction

I.1 Background

Morphological development is the result of interactions between flow and alluvial bed. The relevant processes for morphological development are flow, sediment transport and bed level change. A mathematical model for morphological development can be set-up by simulating each of these processes using physical laws. Such a process-based morphological model is called a dynamic model.

At present (2001), the dynamic type of models, one-dimensional as well as two-dimensional, are already commonly used in engineering practice for rivers. For estuaries, however, the long-term morphological development under the influence of natural processes, e.g. sea level rise, and/or under the influence of human activities, e.g. land reclamation, dredging and dumping, can still not be predicted by dynamic models. In practice, prediction of long-term morphological development in estuaries still relies to a large extent on empirical relations, in which the morphological variables, such as the cross-sectional area of channels, are related to integrated hydrodynamic parameters, e.g. the tidal volume.

Since the nineties of the last century, ESTMORF is developed by WL | DELFT HYDRAULICS and Rijkswaterstaat. ESTMORF is a mathematical model for predicting the long-term (decades) morphological development of estuaries and tidal lagoons, under the influence of natural processes and human interference. The model is partly based on process descriptions and partly on empirical relations which combines the advantages of the dynamic type of models with those of the empirical ones. Such a model did not exist up to then.

The original direct motive of the development of this model was the need of Rijkswaterstaat for a tool predicting the long-term morphological development of the Western Scheldt, an estuary in the Southwest of the Netherlands. This estuary connects the Antwerp Harbour in Belgium to the North Sea and has therefore an important navigational function. For maintenance of the navigation channel through the estuary large amounts of dredging (more than 10 million m³ per year at present) are required. The dredging including sand mining and dumping of the dredged material have been the most important human interference on the morphological development of the estuary since the seventies of the last century. The most important driving force of the morphological development in the estuary is the tidal flow. The bottom of the estuary can consists of mainly fine sand. Suspended sand transport is the most important sediment transport mode.

In addition to the navigation, or accessibility, the other important relevant managing aspects for the estuary are safety (flood control) and naturalness (ecological environment). Initially, the natural conditions and the relevant problems in the Western Scheldt have been used as reference for the development of the ESTMORF model.

The development of the ESTMORF model started in the early nineteen nineties. After a literature survey and an evaluation of the available modelling techniques for morphological development in estuaries and tidal lagoons it was decided that the model should be based on a dynamic-empirical or semi-empirical approach, thus combining the advantages of the dynamic process-based models and the empirical models. The resulted formulations of the model combined the approach of the existing EMPREL model (Allersma, 1988) with the long-term averaged equilibrium concentration concept of Di Silvio (1989). A one-dimensional network tidal flow model is used as tidal flow module for the model. Because of the significance of the inter tidal areas for the ecological system in an estuary the morphological changes of the channels and the inter tidal areas are considered separately.

The first version of the model was developed in 1994. Although it was initially meant for the Western Scheldt, the first successful application of the model was to the Friesche Zeegat, a tidal lagoon in the Dutch Wadden Sea. The model reproduced the morphological changes in the tidal lagoon due to the closure of the Lauwerszee in 1969 well. The ESTMORF model for the Western Scheldt has been calibrated against the field observations of the morphological changes since 1968. Various improvements of the software as well as the application model to the Western Scheldt have been carried out. Up to now the Western Scheldt model has been successfully applied in the projects MOVE and Long-Term Vision Scheldt Estuary (see Chapter 3). At present it has become an operational model for evaluating long-term morphological development of the estuary under influence of various human interference and natural development.

The ESTMORF model appears also to be applicable to many other estuaries. Successful applications of the model have been carried out for the Southampton Water and the Humber Estuary in the UK and the Yangtze Estuary in China. A pilot application of the model to the Noordelijk Delta Bekken in the Netherlands also shows promising results. Furthermore, the model has also been implemented into the ecomorphological module of the Estuarine Decision Support System (EDSS) developed within the framework of the LWI-project Estuary and Coast (Wang et al, 1997).

1.2 About this document

The development of the ESTMORF software as well as its applications to the various areas have been carried out in a series of projects. Each of these projects have been described in the corresponding technical reports. An overview of these reports is given in Appendix A.1. Now that the model has become operational there is a need for an overall reviewing document for all these projects. The present report serves for this purpose. It is set up such that the report can be read stand alone to answer questions of readers like: what is ESTMORF? how does it work? what can it simulate / predict (possibilities) and what can it not (restrictions)? On the other hand it also give an overview of all the available documents related to the ESTMORF model so that readers can get access to the relevant document when a particular aspect of the model or a certain application of the model is interested.

Chapter 2 describes the development of the ESTMORF model. First an historic overview of the development is given and then the model principles are described followed by a summary of the functionalities of the model. In Chapter 3 the applications of the model are

described. After an overview of all applications the application to the Western Scheldt model is described in more detail, followed by brief descriptions of each of the other applications. Finally an evaluation of the present state, the possibilities and the restrictions of the ESTMORF model is given in Chapter 4. The relevant references are given in Appendix A. Here a distinction is made between the technical reports of the ESTMORF studies (A.1) and the general literature (A.2). A brief summary is given for each of the technical reports of the ESTMORF studies in A.1. In Appendix B a number of papers published at international conferences and in technical journals concerning the ESTMORF studies are included.

1.3 Acknowledgement

The ESTMORF model has been developed by WL | DELFT HYDRAULICS together with Rijkswaterstaat. This report is dedicated to all who have contributed to this development. Most of the work has been carried out in a series of commissions of Rijkswaterstaat to WL | DELFT HYDRAULICS. In this almost 10 year development period many people at Rijkswaterstaat and WL | DELFT HYDRAULICS have made their contributions to the model. The idea of developing such a model was initiated in a series of discussions within a commission consisting of Jan Mulder and Ad Langerak from Rijkswaterstaat and Huib de Vriend and Zheng Bing Wang from WL | DELFT HYDRAULICS. Among others the development work at WL | DELFT HYDRAULICS has been carried out by Bert Karszen, Rinze Bruinsma, Robbert Fokkink and Zheng Bing Wang. In most of the projects Ad Langerak functioned as project leader at Rijkswaterstaat. Later his role has been taken over by Bart Kornman, Marijn van Helvert who later joined the development and especially application work at WL | DELFT HYDRAULICS, and Cornelis Israel. This report has been drawn up by Zheng Bing Wang.

Fundings for developing of the ESTMORF model came from Rijkswaterstaat projects like DYNASTAR, ZEEKENNIS, COAST2000 and COAST2005 and from the Directorate Zeeland of Rijkswaterstaat.

2 Development of the model

2.1 Historic overview of the development

The development of the ESTMORF model started in the early nineteen nineties. The initiation of the development of is from Rijkswaterstaat, who is responsible for the management of waters including estuaries and tidal lagoons in the Netherlands. Morphological development of estuaries and tidal lagoons is important for all the management aspects since morphological changes can cause changes of all other (physical, biological, ...) processes. A typical problem area is the Western Scheldt, where navigation is an important issue since it connects the Antwerp harbour to the North Sea. Dredging activities for improving and maintaining the navigation channels cause changes of the morphology and the morphological development of the estuary. Morphological changes in the estuary will influence the high water levels under extreme conditions, requiring adjustments to the flood control system for guarantying safety, and will cause changes of the ecological system, impacting the naturalness of the estuary. Therefore for keeping balance between the management aspects safety, (navigational) accessibility and naturalness of the estuary, a tool is required for predicting morphological development.

Having identified the need of such a tool, a number of experts from Rijkswaterstaat and from WL | DELFT HYDRAULICS discussed the problem in a series of meetings. The functional requirements of the tool were further specified. An important requirement is that the tool should be able to predict long-term (decades to century) morphological development. The tool should be able to predict the impact of human interference e.g. land reclamation and dredging-dumping activities, as well as morphological changes caused by natural development such as sea level rise. It became clear from the discussions that the required tool was not available yet at that moment, and therefore the tool needed to be developed. It was also soon concluded that the tool would be a mathematical model and not a physical model. It was also decided that a literature survey should be carried out before the development of the model started.

The literature survey and an evaluation of the available modelling techniques for morphological development in estuaries and tidal lagoons was carried out by Karssen and Wang (1991). It was concluded that a model fulfilling the requirements was not available at any institute in the Netherlands or elsewhere in the world. Mathematical models for morphological development in estuaries reported in the literature were divided into two types, the dynamic or process-based ones and the empirical ones. One-dimensional as well as two-dimensional process-based models for sediment transport and morphological changes were available, but successful applications of such models for simulating long-term morphological development in tidal areas had not been found in the literature. Studies on long-term morphological development of estuaries relied on empirical approaches. It was concluded the most promising approach is probably a combination of the two types of models. Based on the findings of the literature survey and based on practical considerations, it was decided that the model to be developed would be a 1D network model. It was also

decided two lines of development would be followed, one based on the process-based dynamic approach using available software (EENDMORF), and the other based on a new concept combining the two available approaches in the literature (ESTMORF). The idea was that the EENDMORF model would cover the middle long-term development and ESTMORF would cover the long-term development.

The actual development of the ESTMORF model could be divided into three phases. In the first phase (till approximately 1995) the development of ESTMORF was carried out parallel with the development of EENDMORF. The basic concept was set up and the mathematical physical formulations for the ESTMORF model were made (Karssen and Wang, 1993) and the first version of the software was developed Karssen (1994a, 1994b). The software uses IMPLIC, a 1D network tidal flow model, as flow module. The software was applied to set up the Friesche Zeegat model and the Western Scheldt model (Karssen, 1994a, 1994b, 1995). The development of EENDMORF concentrated on fundamental problems hindering the application 1D network process-based models. One of the problems appears to be the nodal point relations required for the calculation of sediment transport at bifurcations. The existing software only contains nodal point-relations which lead to unstable development of bifurcations. Estuaries characterised by multiple channel structures cannot be modelled herewith because such channel structures could not exist according to the model then. Therefore a new nodal point relation was formulated, which could represent both stable and unstable bifurcations (Wang et al, 1993, 1995). The results of this fundamental analysis has later also become the theoretical basis of the cell-concept applied in the Long Term Vision (LTV) Scheldt Estuary project (Winterwerp et al, 2001, Wang and Winterwerp, 2001). The EENDMORF development ended with a pilot application of SOBEK-MOR to the Western Scheldt (Fokkink et al, 1996). Although some encouraging results were achieved the development of EENDMORF were not continued. The crucial problem with this type of model appears to be that the residual sediment transport in an estuary like the Western Scheldt is determined by subtle factors like residual flow circulations and tidal asymmetry, which were difficult to be modelled in a 1D network tidal flow model.

The second phase of the development (1995-1998) focussed on the calibration of the ESTMORF model for the Western Scheldt (Fokkink, 1996, 1997, 1998). The observed morphological development in the period 1968-1995 is used to calibrate the model. The calibration was not only a matter of adjusting the model parameters in order to obtain the best agreement between the calculation results and the observations, but many practical and theoretical problems needed to be solved. One of the practical problems was e.g. that the network schematisation originally made for the tidal flow simulations causes problems in the application of the empirical relations. A theoretical problem concerns the treatment of the bifurcations. Without any special measure the same problem as in EENDMORF also occurs in ESTMORF: all bifurcations would be unstable. Because ESTMORF assumes suspended sediment transport and because the difference in the concept the solution as for the EENDMORF model was not applicable in ESTMORF. The problem was eventually solved by relating the equilibrium cross-sectional area of a branch to the total of tidal volumes in all branches in the same bifurcation, instead of to the local tidal volume in the branch (Fokkink, 1998). After this phase a version of the ESTMORF Western Scheldt model was ready for applications (Fokkink, 1998).

The third phase (1999-2001) of the development was characterised by further improvement and extension of the software as well as of the Western Scheldt model. After the first application of the Western Scheldt model in the MOVE project (Van Helvert, 1999) the shortcomings of the model were evaluated. The following improvements were carried out in 1999, in order to extend the functionality and to make the model more user-friendly (Wang and Bruinsma, 1999):

1. SOBEK was implemented as flow module instead of IMPLIC, because SOBEK is developed and widely supported as the 1D hydrodynamic software.
2. The empirical relations for the inter tidal areas were improved.
3. The input file containing the dredging-dumping information was changed so it can be easier prepared by users.
4. A dredging strategy option was implemented so the model now can predict the required amount of dredging itself for forecasting simulations.
5. A new post-processing tool kit was developed.

After this first round of improvement further improvements / extensions of the model have been carried out on two fronts:

1. Representation of inter tidal areas in the model. The model appears to simulate the morphological changes in the channels much better than for the inter tidal areas. Therefore the modelling of the inter tidal areas was further evaluated (Jeuken and Wang, 2000) and a literature study on the morphological development of inter tidal areas was carried out (Hibma et al, 2000). Based on the results of these two studies various measures were implemented to improve the representation of the inter tidal areas in the model (Wang and Van Helvert, 2000).
2. Extension of the model schematisation. The schematisation of the Western Scheldt model has been improved in the area of Land van Saeftinge and extended at the downstream boundary to include the ebb tidal delta. The sea side boundary was moved from Vlissingen to Westkappelle (Jeuken and Van de Weck, 1999, Thoolen, 2000, Wang and Van Helvert, 2001). The last version of the ESTMORF Western Scheldt model is described by Wang and Van Helvert (2001).

2.2 Basic principles

2.2.1 General model concept

The most important hypothesis used in the ESTMORF model concept is that an equilibrium state can be defined for each morphological element of the system depending on the hydrodynamic conditions. For each element an empirical relation is required to define the morphological equilibrium state. This kind of empirical relations are commonly used for tidal systems.

Various morphological models for estuaries and tidal inlets are based on such relations in combination with a transient model describing the evolution of the actual state with respect to its equilibrium as an exponential decay process (O'Connor et al., 1990, Eysink, 1990,

Eysink, 1992). When this model concept is applied to a system consisting of more than one element, linked with each other, extra assumptions are required to guarantee the mass-balance of sediment (Allersma, 1988, Van Dongeren and De Vriend, 1994). This can make the model results sensitive to the sequence in which the various elements are dealt with in the computation: e.g. computations starting from the sea side give different results than computations starting from the land side.

In the tidal basin model of Di Silvio (1989) this problem is overcome by introducing a characteristic sediment concentration in each element of the model. The concentration field is governed by the advection-diffusion equation based on a residual flow field, which guarantees the fulfilment of the sediment mass-balance. This concept is adopted in the ESTMORF model.

The basic philosophy is as follows: If all elements in the morphological system are in equilibrium, there is no accumulation of sediment or water anywhere in the area. If the sediment is mainly transported in suspension, the sediment flux field is therefore likely to be proportional to the flow rate. The ratio between sediment flux and flow rate can be considered as a sediment concentration and is called in this paper the overall equilibrium concentration c_E . For each element in the system a local equilibrium sediment concentration c_e is defined such that it equals c_E if the element is in morphological equilibrium, that it is larger than c_E if a tendency for erosion exist (e.g. the cross-sectional area of a channel is smaller than the equilibrium value), and smaller than c_E if a tendency for sedimentation exists. Morphological changes occur when the local sediment concentration deviates from its local equilibrium. Erosion occurs when the sediment concentration is smaller than its equilibrium value and sedimentation occurs if it is larger than its equilibrium value.

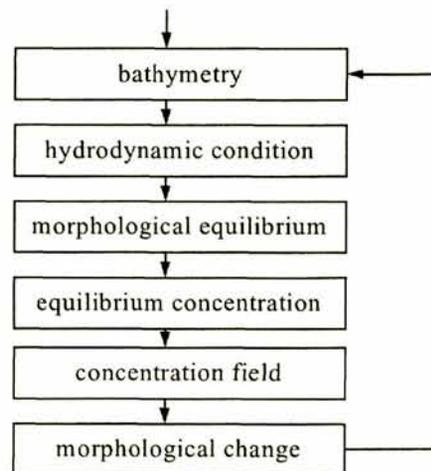


Fig.2.1 Computational procedure

The ESTMORF model described here belongs to the semi-empirical type according to the classification due to De Vriend (1996). An important difference between the present model and the process-based models is that the equilibrium concentration is not directly computed from the hydrodynamic parameters, but via the equilibrium morphological state (see Fig.2.1). This makes the model always converging to a state of which the equilibrium relations are satisfied.

2.2.2 Geometrical schematisation

The model uses an existing one-dimensional network flow model to simulate the flow. Therefore, the modelling area is schematised into a network consisting of branches.

The cross-sections of the branches are schematised as shown in Fig.2.2. It is divided into three parts: the channel part (under the low water level, MLW), the low tidal flat between MLW and the mean water level (MSL), and the high tidal flat between MSL and the high water level (MHW). The channel part is assumed to have a trapezoidal cross-section. The two parts of the tidal flat are described by their widths as well as their heights. This schematisation of the cross-section is adopted from Eysink (1992).

Morphological changes in the three parts are calculated separately, and can be due to sedimentation/erosion and to changes in the relative water level e.g. sea level rise/land subsidence.

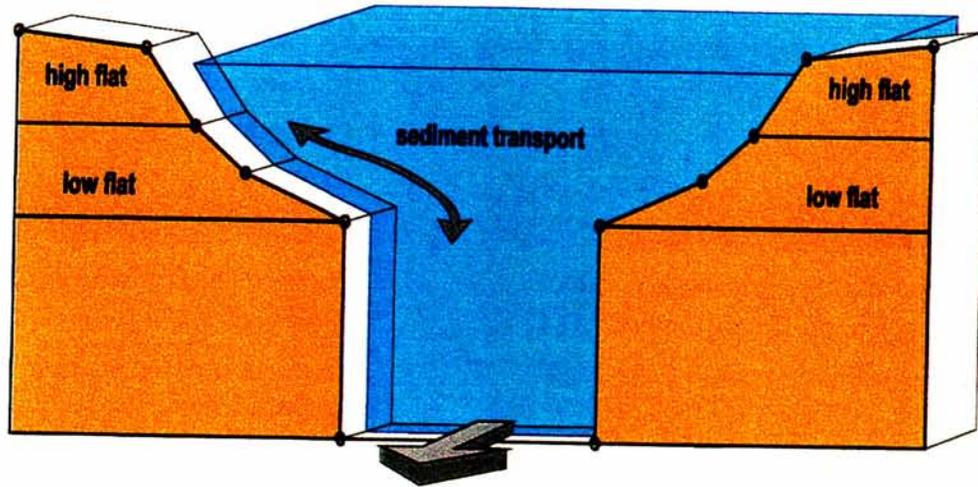


Fig.2.2: Principle of sediment exchange between flats and the channel in ESTMORF.

2.2.3 The equilibrium state

The model uses three variables, the cross-sectional area of the channel, the height of the low tidal flat and the height of the high tidal flat. For each of these variables an empirical relation is required defining the morphological equilibrium state of the system.

The equilibrium cross-sectional area of the channel is related to the tidal volume. For the Wadden Sea such a relation is given by e.g. Eysink (1992).

$$A_{ce} = f_1(P_v) \quad (2.1)$$

Herein

$$\begin{aligned} A_{ce} &= \text{equilibrium cross-sectional area under MSL,} \\ P_v &= \text{tidal volume.} \end{aligned}$$

The equilibrium heights (measured from MLW) of the two parts of the tidal flat are related to the tidal range and the total area of the basin (see e.g. Eysink 1992).

$$H_{he} = f_2(H, A_b) \quad (2.2)$$

$$H_{le} = f_3(H, A_b) \quad (2.3)$$

In these two equations

- H_{he} = equilibrium height of the high tidal flat measured from mean low water
- H_{le} = equilibrium height of the low tidal flat measured from mean low water,
- H = tidal range,
- A_b = total area of the basin.

In equations (2.1) through (2.3) no specific relations are given. They have to be chosen on the basis of field data when the model is applied for a specific area. This part is kept as flexible as possible to guarantee a wide applicability of the model. The coefficients in the equations may also vary spatially such that an existing equilibrium state can be represented throughout the system.

2.2.4 Morphological development

When the system is not in equilibrium, morphological changes will occur. The sedimentation and/or erosion rate is assumed to be proportional to the deficit/excess of the local sediment concentration, following the formulation of Galappatti and Vreugdenhil (1985). The bed level change is then described by the following simple formulation:

$$\frac{\partial z}{\partial t} = w_s (c - c_e) - \alpha_s \quad (2.4)$$

Herein

- z = bed level,
- w_s = coefficient having the dimension of velocity, vertical exchange velocity,
- t = morphological time,
- c = sediment concentration,
- c_e = local and instantaneous equilibrium sediment concentration,
- α_s = rate of land subsidence.

Applied to the three parts of the cross-section, the following equations are derived:

$$\frac{\partial A_c}{\partial t} = W_c [w_s (c_{ce} - c_c) + \alpha_s + \alpha_r] \quad (2.5)$$

$$\frac{\partial A_l}{\partial t} = W_l [w_s (c_{le} - c_l) + \alpha_s + \alpha_r] \quad (2.6)$$

$$\frac{\partial A_h}{\partial t} = W_h [w_s (c_{he} - c_h) + \alpha_s + \alpha_r] \quad (2.7)$$

In these three equations we define (see Fig.2.2):

A_c	=	cross-sectional area of the channel part (below MSL),
A_h	=	cross-sectional area of the high tidal flat,
A_l	=	cross-sectional area of the low tidal flat,
c_c	=	sediment concentration in the channel part,
c_h	=	sediment concentration in the high tidal flat part,
c_l	=	sediment concentration in the low tidal flat part,
c_{ce}	=	local equilibrium sediment concentration in the channel part,
c_{he}	=	local equilibrium sediment concentration in the high tidal flat part,
c_{le}	=	local equilibrium sediment concentration in the low tidal flat part,
W_c	=	width of the channel part,
W_h	=	width of the high part of the tidal flat,
W_l	=	width of the low part of the tidal flat,
α_r	=	rate of sea level rise.

2.2.5 Sediment Transport

The equilibrium concentrations are determined as follows:

$$c_{ce} = C_E \left(\frac{A_{ce}}{A_c} \right)^{n_c} \quad (2.8)$$

$$c_{le} = C_E \left(\frac{H_l}{H_{le}} \right)^{n_l} \quad (2.9)$$

$$c_{he} = C_E \left(\frac{H_h}{H_{he}} \right)^{n_h} \quad (2.10)$$

In these equations:

C_E	=	overall equilibrium sediment concentration,
A_c	=	cross-sectional area of the channel,
H_h	=	height of the high tidal flat measured from MLW,
H_l	=	height of the low tidal flat measured from MLW,
n_l	=	constant coefficient,
n_h	=	constant coefficient,
n_c	=	constant coefficient

When the whole system is in equilibrium, the sediment concentration will be equal to its overall equilibrium value. When for example the cross-sectional area is larger than the equilibrium value it means in fact that the local flow velocity will be lower by the same factor as the ratio A_{ce}/A_c . The formulation (2.8) of the local equilibrium sediment concentration is thus similar to the sediment transport capacity formula using power law.

The actual sediment concentration is governed by an advection-diffusion model. It is further assumed that the tidal flat can only exchange sediment with the channel in the same section. In other words, there is no longitudinal sediment transport over the inter tidal flats.

The mass balance equation for sediment in the channel may be written as:

$$\begin{aligned} \frac{\partial A_c c_c}{\partial t} + \frac{\partial A_c u c_c}{\partial x} - \frac{\partial}{\partial x} \left(A_c D_c \frac{\partial c_c}{\partial x} \right) &= \\ &= W_c w_s (c_{ce} - c_c) + F_{lc} \end{aligned} \quad (2.11)$$

where:

- c_c = sediment concentration by volume in the channel,
- D_c = horizontal dispersion coefficient in the channel,
- F_{lc} = exchange rate of sediment between the channel and the low tidal flat,
- t = time,
- u = residual flow velocity.

The sediment flux from the tidal flat to the channel F_{lc} is elaborated as follows:

$$F_{lc} = D_l \overline{\Delta h_l} \frac{c_l - c_c}{L_{lc}} \quad (2.12)$$

Herein:

- D_l = diffusion coefficient,
- L_{lc} = distance between the centre of the channel and that of the low part of the tidal flat,
- $\overline{\Delta h_l}$ = time-averaged water depth at MLW.

The mass balance for sediment at the low part of the tidal flat is given by the following equation:

$$\frac{\partial (A_l c_l)}{\partial t} = W_l w_s (c_{le} - c_l) - F_{lc} + F_{hl} \quad (2.13)$$

And at the high part of the tidal flat the mass-balance reads

$$\frac{\partial (A_h c_h)}{\partial t} = W_h w_s (c_{he} - c_h) - F_{hl} \quad (2.14)$$

The exchange rate between the two parts of the tidal flat is formulated as

$$F_{hl} = D_h \overline{\Delta h_h} \frac{c_h - c_l}{L_{hl}} \quad (2.15)$$

Herein:

- D_h = diffusion coefficient,
- L_{hl} = distance between the centre of the high flat and that of the low flat,

$\overline{\Delta h_h}$ = time-averaged water depth at MSL.

2.2.6 Boundary conditions

At an open boundary the model requires the sediment concentrations to be prescribed as boundary condition. In all the applications up to now the overall equilibrium concentration is prescribed at the open boundaries. This implicitly assumes that the area outside the model is in morphological equilibrium.

2.3 Functionalities

The ESTMORF model is meant as to help decision makers in managing estuaries and tidal lagoons with aspects like navigation, safety and ecological system. The model has been developed with the Western Scheldt as reference estuary. Besides the basic model principles as described in the previous section, the model is characterised by its many convenient functionalities available for the user to deal with practical situations. In the following a summary is made of these functionalities.

Morphological developments of channels and inter tidal areas are simulated separately in the model

Inter tidal areas are very important for the ecological system in an estuary, since they form habitats for benthos, birds, etc. This is the reason why the morphological changes of the inter tidal areas are simulated separately from the changes of the channels, although a one-dimensional network schematisation is implemented in the model. The cross-section of each branch is divided into three parts: the channel (the part below low water), the lower inter tidal area (between low water and mean water level) and the higher inter tidal area (between mean water and high water). The area of the channel part and the heights of the lower and higher inter tidal areas are used as morphological state variables, and their variations in time are simulated in the model.

As output of the model the schematised cross-sectional profiles as shown in Fig.2.2 for each branch and at each time step can be required. Post processing facilities are available to obtain the for managing estuaries relevant parameters like water volume, cross-sectional area, horizontal area and height of inter tidal areas and their changes of an individual branch or of a group of branches.

Sea level rise

For long-term morphological changes, at a time scale of decades to centuries, sea level rise becomes important. Therefore sea level rise is taken into account in the ESTMORF model. The sea level rate can be specified as a constant in (centi)meters per century or be specified in a file by giving the sea level change in (centi)meters in each morphological time step.

The sea level rise has the effect that the values of the morphological state variables (cross-sectional area and heights of inter tidal areas) change without sedimentation / erosion, and it can thereby also influence the water movement in the model area. All these effects can be

taken into account in the model. In case that more than one morphological time steps follow after a tidal flow computation, the influence on the tidal flow is not directly taken into account in each time step.

Time varying tidal range

As the sea level changes the tidal range at the sea outside of an estuary can also change. This is e.g. the case for the Western Scheldt. The tidal range at the mouth of the estuary (Vlissingen) increases at a rate of about 4% per century. This effect is also implemented in the ESTMORF model. Similarly to the sea level rise rate the rate of tidal range change at the open sea boundary can be prescribed as constant (e.g. 1.04 for the case of 4% per century) or as the factor of change in each time step in the input of the model.

This functionality can also be used for simulating the effect of the 18.6 year tidal cycle with the model.

Land subsidence

Morphology of an estuary or a tidal lagoon can also be influenced by land subsidence due to e.g. gas mining, a practically actual problem in the Dutch Wadden Sea. This effect is therefore implemented in the ESTMORF model.

Prescribed dredging, dumping and sand mining

Dredging activities for the improvement and the maintenance of the navigation channel and for sand mining have been the most important human interference influencing the morphological development of the Western Scheldt estuary, the reference problem area for the development of ESTMORF. Therefore special attention has been paid to the influence of dredging and dumping on the morphological changes in the model. Dredging and dumping amounts can be prescribed via a separate file in the input. Two different types for models can be used for this purpose. The first implemented type of file simply specifies the dredging and /or dumping amounts in the individual branches at each time step. Later a second type of file is implemented, much more from the point of view of the user of the model. The file first defines the dredging, dumping and sand mining areas, in terms of which branch is involved for how much, followed by a table specifying the dredging / dumping amounts as function of time. Compared to the first type of the file the required pre-processing of the dredging and dumping data is reduced to a large extent and the size of the file is often much smaller.

The dredged and dumped amount of sediment in each morphological time step is directly processed into the change of the cross-sectional profile of the corresponding branches in the model. In reality dredging and dumping can influence the depth as well as the width of a cross section. Therefore a parameter is introduced in the input file for dredging and dumping, in order to specify which fraction of the dredging / dumping is on the bottom of the cross section and which fraction is on the side banks of the cross section (Fig.2.3).

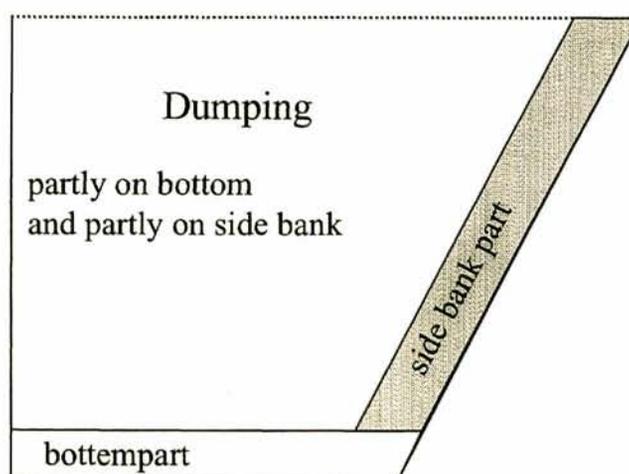


Fig.2.3: Distribution of dumped sediment.

Prescribed dredging strategy

For hind-casting simulations the dredging-dumping functionality as described above is sufficient since the amounts of dredging and dumping are known. For forecasting simulations, however, this is not convenient because the dredging and dumping amounts are not yet known. Forecasting simulations using this functionality will require an estimation of the dredging and dumping amounts, which is not an easy task since e.g. the required maintenance dredging for a navigation channel depends on the morphological changes. Therefore a new functionality, “dredging strategy”, is implemented in the ESTMORF model.

For forecasting a “dredging-strategy” file can be given, including the information like the location and size of the navigation channel to be maintained, the required depth, the potential dumping area for the dredged material, the available dredging capacity, the over depth when dredging is carried out, etc. With this information the model calculates itself the required dredging based on the calculated morphological changes and keeps records where the dredged material is dumped.

2.4 Behaviour of the model

2.4.1 Comparison with dynamic models

The behaviour of the model can be analysed by considering some simplified cases. Here two extreme cases are considered. It will be shown that in both cases the behaviour of the model is very similar to a process-based model.

The first case concerns the unidirectional steady flow in a river without tidal influence (hence no tidal flats exist). In this case the tidal volume is proportional to the river discharge, so the equations describing the sediment transport and the morphological development used in the model become identical to those in a process-based one-dimensional model using depth-averaged model for suspended sediment transport (see e.g. Galappatti and Vreugdenhil, 1985). The only difference is that the morphological equilibrium state in the

Galappatti and Vreugdenhil, 1985). The only difference is that the morphological equilibrium state in the present model is merely determined by the river discharge, whereas in a 1D process-based model it is determined by the discharge, the upstream sediment supply and the river width. It is obvious that the empirical relations used in the model should be site-specific.

The second case concerns a rectangular tidal basin, with one end closed and the other end connected with the sea. This case has been used for extensive sensitivity analysis with respect to the various model-parameters (Karssen, 1994). A typical example of the results is shown in Fig.2.4. The simulation start with a horizontal bed and ends with a linear bottom, which is in full agreement with the commonly used empirical relation that the cross-sectional area is proportional to the tidal volume through that cross-section (note that the diffusion coefficient at the end of the basin is not set to zero). Also in this case the simulated morphological development is very similar to that simulated with a process-based model (see Wang, 1992, Schuttelaars and De Swart, 1996). From the sensitivity analyses it is further concluded that the vertical exchange velocity, the overall equilibrium concentration, the dispersion coefficient and the power in the equilibrium concentration equations are the most important parameters influencing the simulated morphological development.

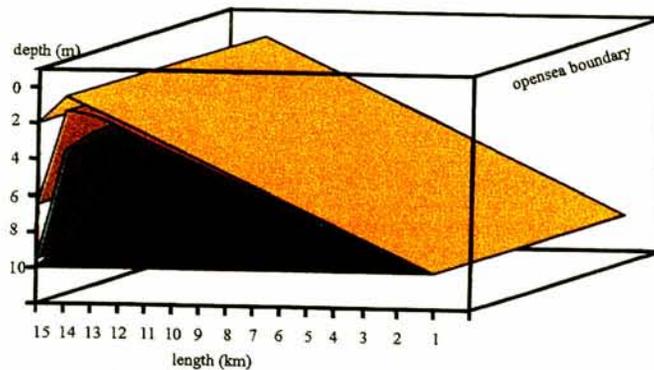


Fig.2.4 Filling of a prismatic tidal basin

2.4.2 Morphological time scale

Another way of examining the behaviour of the model is by analysing how the morphological time scale is related to the relevant length scale. Knowledge of how the morphological time scale is determined by the model parameters is very important for the calibration of the model. For this purpose a linear analysis is carried out for a small disturbance on a system in equilibrium. The time scale defined is the time in which the disturbance decreases its amplitude with a factor e . For the sake of simplicity only the channel is considered, and the residual flow is neglected. The time scale in this case is:

$$T = \frac{T_s + T_D}{c_E n_c} \quad (2.16)$$

Herein $T_s = \frac{a}{w_s}$ $T_D = \frac{1}{k^2 D}$

of sediment. It is also clear that the parameters D , w_s , c_E and n are the important model parameters determining the morphological time scale. More extensive and detailed analysis of the morphological time scale related to the model parameters is given by Fokkink (1996).

3 Applications

3.1 Overview

The first version of the model was developed in 1994. Although it was initially meant for the Western Scheldt, the first successful application of the model is to “Het Friesche Zeegat”, a tidal lagoon in the Dutch Wadden Sea. The model reproduced the morphological changes in the tidal lagoon due to the closure of the Lauwerszee in 1969 well. The ESTMORF model for the Western Scheldt has been calibrated against the field observations of the morphological changes since 1968. Various improvements of the software as well as the application model to the Western Scheldt have been carried out. Up to now the Western Scheldt model has been successfully applied in the projects MOVE and Long-Term Vision Scheldt Estuary. At present it has become an operational model for evaluating long-term morphological development of the estuary under influence of various human interference and natural development in the project COAST2005. Another application of the model within the Netherlands is to “Het Noordelijk Delta Bekken (NDB)”. At present a first pilot application with the NDB model is carried out and it is expected that the set up model will be further improved in the coming years.

The model has further been applied to a number of estuaries abroad up to now. The model has been successfully applied to the Southampton Water in order to evaluate the impact of a proposed reclamation together with the accompanying measures. It also had been applied to another estuary in UK, the Humber Estuary within the framework of a fundamental research programme with the aim to show the ability of the model in simulating the effect of land reclamation and sea level rise on the long-term morphological development. As a part of the Ecomorphological module of the Estuarine Decision Support System the model is also applied for the Yangtze Estuary in China within the framework of the LWI project.

Further in this Chapter a more detailed description for the Western Scheldt model is given in 3.2. In section 3.3 a brief description of each of the other applications is given.

3.2 Western Scheldt Model

3.2.1 Model schematisation

The schematisation of the Western Scheldt (Fig.3.1) model was based on a IMPLIC model for the estuary, originally set up only for simulating tidal flows (Fig.3.2). The downstream boundary of the model is located at Vlissingen and the upstream boundary of the model is as far as to Gent in Belgium. However, it is assumed that no morphological changes take place in the upstream part of the model (upstream of the Belgian border, and not shown in Fig.3.2). This schematisation has been used in all model runs up to 1998. Later the model schematisation has been improved in the area of “Land van Saeftinge”, and the downstream

boundary of the model has been moved from Vlissingen to Westkappelle so that the ebb tidal delta of the estuary is included in the model as well (Fig.3.3).

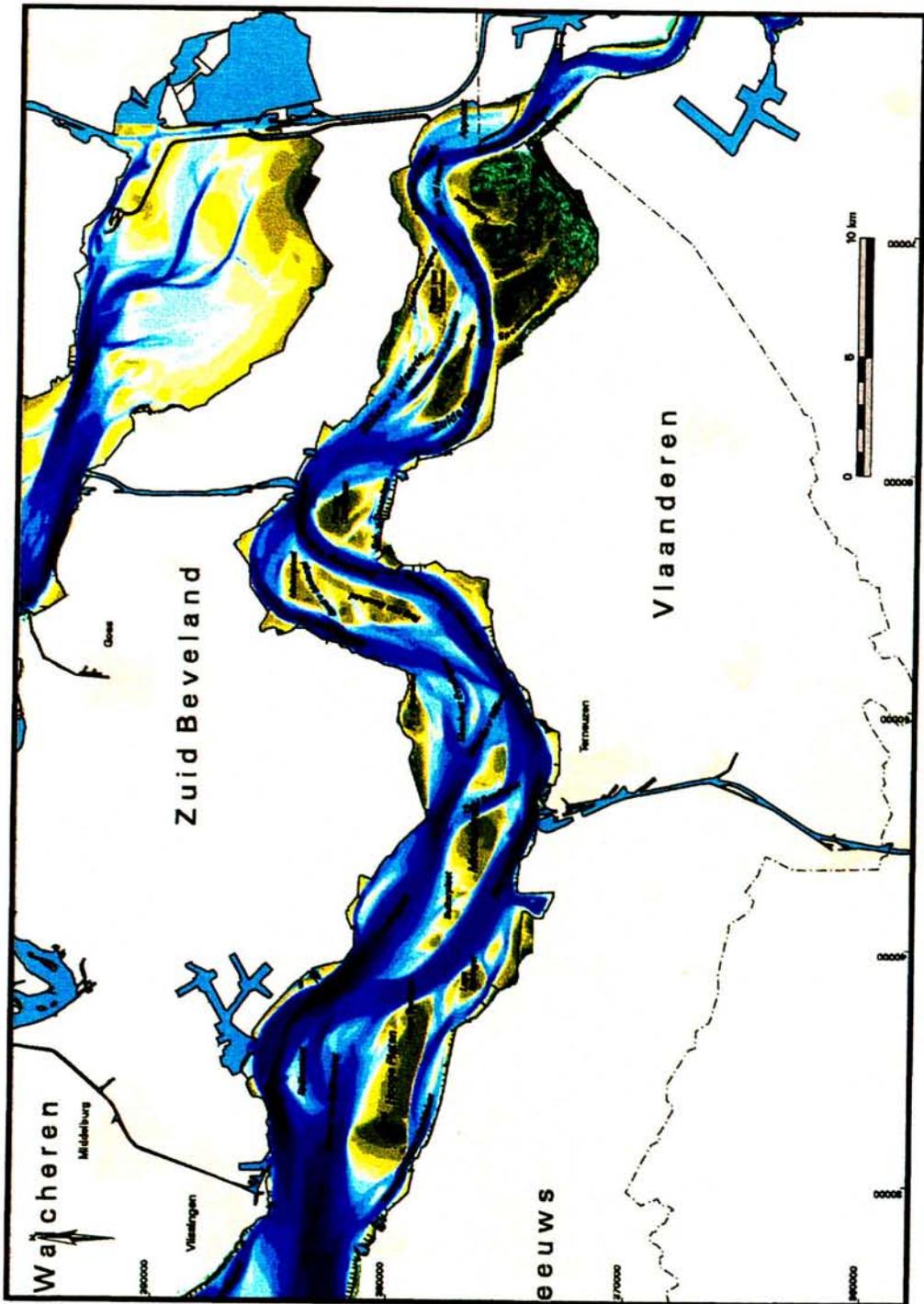


Fig.3.1 Western Scheldt

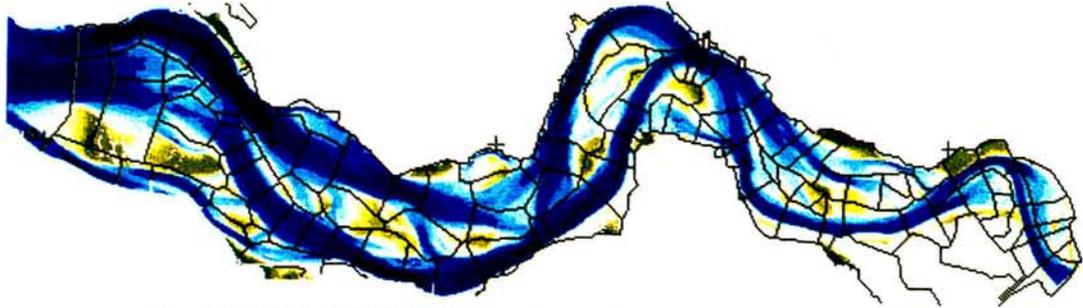


Fig.3.2 Original IMPLIC schematisation of the Dutch estuary part

Basically there are thus two versions of the Western Scheldt model. The one based on the old schematisation uses IMPLIC as flow module and the other one based on the new schematisation uses SOBEK as flow module.

3.2.2 Calibration

The calibration of the model is based on field observations since 1968, when the deepening of the navigational channel started. Before 1968 human interference on the estuary with its present shape is limited. Therefore the calibration of the model started with the assumption that the morphology in 1968 (the initial state) was in equilibrium. This implies that the morphological changes since then is mainly driven by the dredging and dumping activities. The ratio between the cross-sectional area and the tidal volumes, i.e. a coefficient in the applied equilibrium relations, at this initial state shows strong variations from branch to branch. The variation cannot only be explained by the deviation of this state from the morphological equilibrium. It is partly because of problems in the schematisation and it also indicates that the equilibrium relations for different channels are different, e.g. depending whether it is a ebb or a flood channel. Therefore no attempt is made to apply a constant value for this coefficient in the model, but it is kept spatially varying. Adjustment of the coefficient during the calibration is made by multiplying the local value by a certain factor.

Basically the following steps have been followed for the calibration of the model:

1. Calibrating the total sedimentation / erosion amount of the six large parts (divided on the basis of the sounding maps) of the estuary. The adjustment of the model parameters are only changed per part of the estuary, such that the development of the total volume of these large parts is well reproduced by the model (Karszen, 1994).
2. Calibrating the model on the scale of morphological development of individual branches. Here mainly the model parameters influencing the morphological time scale had been adjusted. Parameters like the dispersion coefficient, which are physically space varying, have been adjusted from branch to branch in order to get the best agreement (Fokkink, 1996, 1997, 1998).

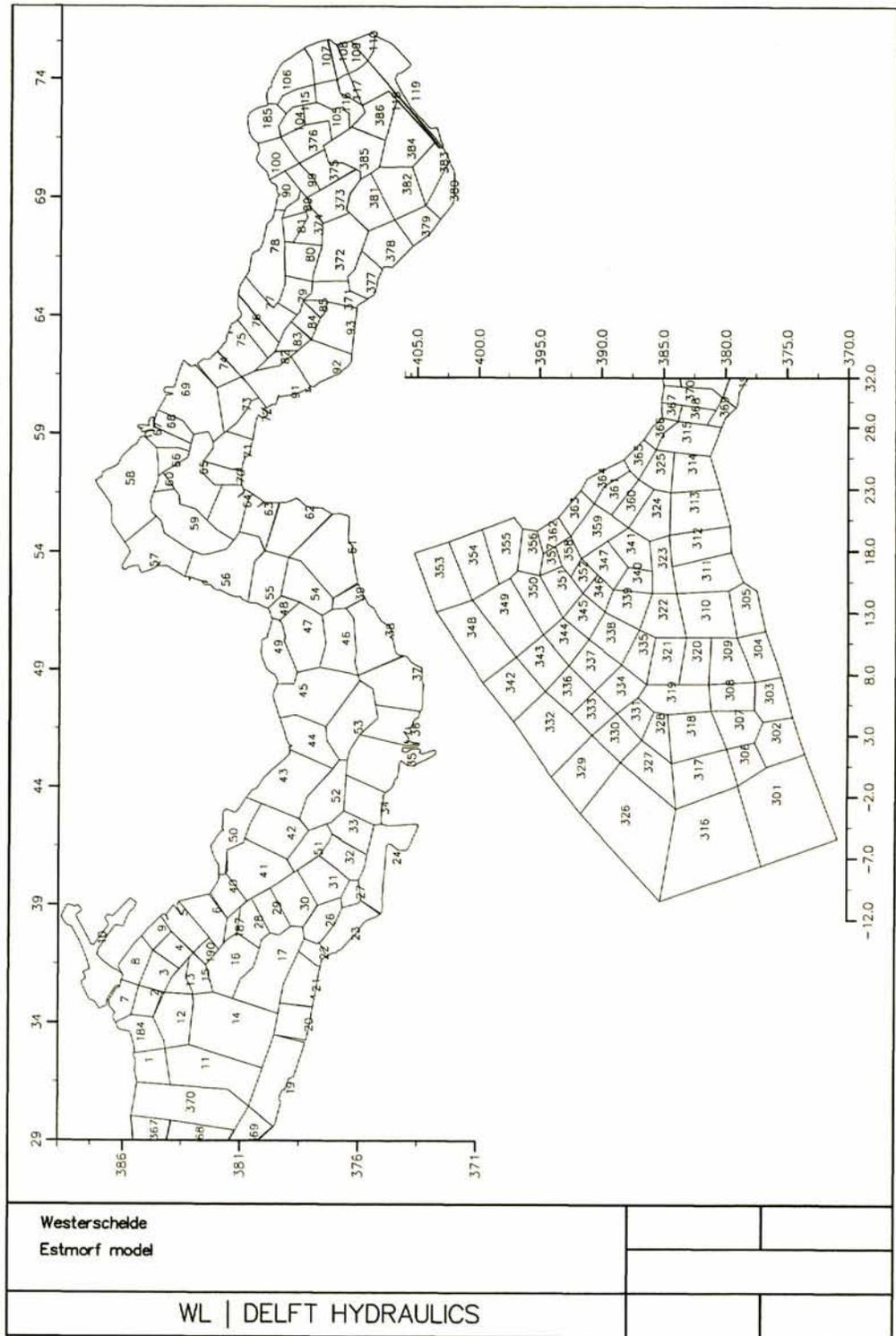


Fig.3.3 New improved and extended model schematisation

3. Calibrating the inter tidal areas. After step 2 the model reproduces the development of the channel part of the estuary well, but the accuracy of the model concerning the development of the inter tidal areas is much lower. Therefore an extra step of the calibration was carried out after implementing a number of measures in the model for improving the representation of the inter tidal areas in the model (Wang and Van Helvert, 2000). Considerable improvement of the model is achieved in this step but the development of the inter tidal areas is still not reproduced by the model as good as for the channels.
4. Calibration of the model based on the new schematisation. After that the model schematisation has been improved and extended the model calibration has been repeated. As an extra complication the new version of the software using SOBEK instead of IMPLIC as flow module is used. However, based on the calibration of the previous version of the model most input parameters of the model could be theoretically derived. With limited effort the same level of accuracy of the model, in the estuary as well as in the extended ebb tidal delta area, could be achieved (Wang and Van Helvert, 2001).

3.2.3 Applications in projects

As mentioned before, the primary application area of the ESTMORF model is the Western Scheldt Estuary. Since the first version of the model was made available it has been applied for various projects in the estuary, among them:

- Study of the morphological aspects for the environmental impact assessment of dumping of dredged material in the estuary (Wang et al, 1997).
- VERDIEP, a project to study the impact of the deepening of the navigation channel in the Western Scheldt.
- MOVE, Monitoring of the impact of the deepening of the navigation channel carried out since 1997 (Helvert, 1999, 2000).
- LTV Scheldt Estuary, a study meant for developing long-term (up to 30 years) vision for the management of the estuary concerning the (navigational) accessibility, safety and naturalness of the estuary.

So far, all these applications have been carried out with the first version of the Western Scheldt Model, i.e. the one with the original IMPLIC schematisation using the software with IMPLIC as flow module. Application of the newer version of the model, with improved and extended schematisation and with SOBEK as flow module is planned in the near future (end 2001 to begin 2002, projects ZEEKENNIS & COAST2005). In the following the projects MOVE and Long-Term Vision Scheldt Estuary are described in brief.

MOVE

The Western Scheldt Estuary has an important economic function due to its harbours along the estuary. But there are more interests like ecology and safety against floods. All these interests are related to each other via the morphology of the estuary. Deepening and widening of the navigation channel for economic interest e.g. will have influence on the

morphology of the estuary, and thereby impact the ecological system and the safety aspects of the estuary.

The MOVE project aim was, to research the effects of deepening and widening of the navigation channel in the Western Scheldt Estuary meant for allowing larger ships to reach the harbour of Antwerp. Not only capital dredging is required for the deepening but a deeper navigation channel will also cause an increase of the dredging and dumping quantities for the maintenance. It also means that the policy towards dumping of dredged material had to be reviewed. A new strategy had to be developed for both capital and maintenance dredging and dumping activities.

ESTMORF was used in this project to research the impact and effects of the dredging and dumping activities on the long-term morphological development of the estuary. Various strategies of dredging and dumping, considering both the quantities and the dumping locations, have been considered in the study. The situation previous to the deepening of the navigation channel has been used as the reference case. Simulations were carried out for the period from 1998 till 2050. Some examples of the simulated results are shown in Fig.3.4.

From mid 1997 till mid 1998 the capital dredging for the considered deepening was carried out. The period from mid 1998 till 2050 covers the maintenance dredging and dumping activity.

The motive for the development of a new proposed dumping strategy was to decrease the dredging quantities during the maintenance period. This would be achieved by increasing the distance between dredging and dumping areas. Before 1997 the main dredging and dumping areas were in the east of the Western Scheldt. The new strategies considered in the study provide more dumping in the west of the estuary.

ESTMORF simulations showed that the changed strategy indeed will result in a decrease of maintenance dredging. However, there will also be side effects of dumping in the west of the estuary. A certain amount of the sediment is transported out the estuary. In the previous period the system imports sediment. ESTMORF computations also show that dumping in the west will in the long-term switch the importing system to an exporting system.

Another effect because of this new strategy, is the existence of a deficiency of sediment in the east of the system. Only a part of the dumped sediment will be transported back to the east. But this is not sufficient enough to satisfy the deficiency. This could result in a erosion of the inter tidal flats in the east of the system. From an ecological point of view this is not desirable.

The application of ESTMORF in the MOVE project was successful, not only because the model supplied useful information to the project but also because new ideas to improve the model were generated. One of the improvements is an option to let ESTMORF generate a dredging and dumping scenario. This has led to the dredging strategy option of the model. In the MOVE project the ESTMORF simulations were carried out with prescribed dredging and dumping in the input file. This means that location and amount of dredging and dumping at every time step during the simulation period have to be predicted before the

simulation is carried out. This is not very logical since the required dredging for the deepening and maintenance of the navigation channel depends on the morphological changes. The simulations show that some of the predicted scenario's can lead to unrealistic developments because the predicted dredging amount is much more than required. The newly implemented dredging strategy option calculates itself the required dredging on the basis of information like the required width and depth of the navigation channel.

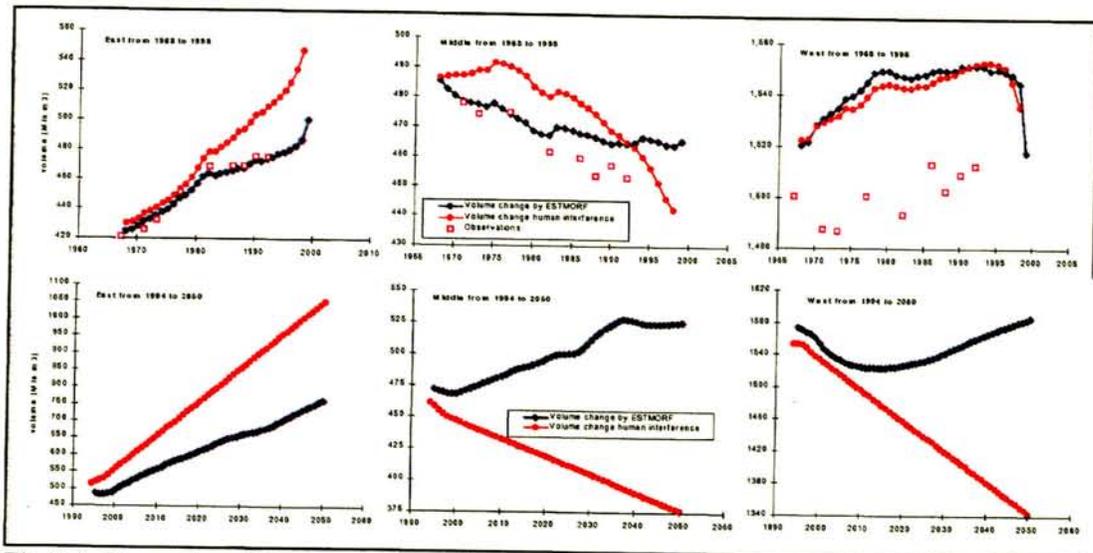


Fig.3.4: Examples of the results from the ESTMORF Western Scheldt model, development of the three parts of the estuary for one of the scenario carried out in the MOVE project. *Top three panels: hindcasting results until 1998 and comparison with observations. Bottom three panels: prediction for the period 1998-2050.*

Long-Term Vision Scheldt Estuary

The aim of this project was developing a long-term (up to 30 years) vision for the management of the estuary concerning the (navigational) accessibility, safety and naturalness of the estuary. A major issue of the project was to assess the maximum deepening and widening of the navigation channel in the estuary without harming the naturalness and the safety aspect of the estuary.

The naturalness of the Western Scheldt is determined by the multiple-channel-system. If uncontrolled deepening and widening of the navigation will be carried out in the near future, this multiple-channel-system will convert or degenerate into an one-channel-system. If this happens the naturalness will seriously be damaged.

On the basis of sediment transport dumping-capacities were determined for certain areas. If dumping exceeds the dumping-capacity in a certain area, the multiple-channel-system degenerate into a one-channel-system. The annual dumping-capacities formed the input for ESTMORF. During the simulation period from 1998 till 2030 the accompanying dredging quantities were simulated using the dredging strategy option of the model.

In this study it was shown that by carefully selecting of dumping areas with accompanying dumping-capacities the system can be kept resilient.

3.3 Other applications

3.3.1 Het Friesche Zeegat

“Het Friesche Zeegat” is a tidal inlet in the Wadden Sea (Fig.3.5). Since 1969, this tidal inlet system, with an area of about 450 km², has undergone significant morphological changes due to the reclamation of a large part, the Lauwerszee. As a consequence the in- and out-going tidal volume has been reduced by about 34%. The response of this tidal inlet system to the closure of the Lauwerszee is well documented. The deeper parts of the outer delta are eroding, large bars are forming, the tidal channels are shoaling and the eastern watershed is shifting eastward.

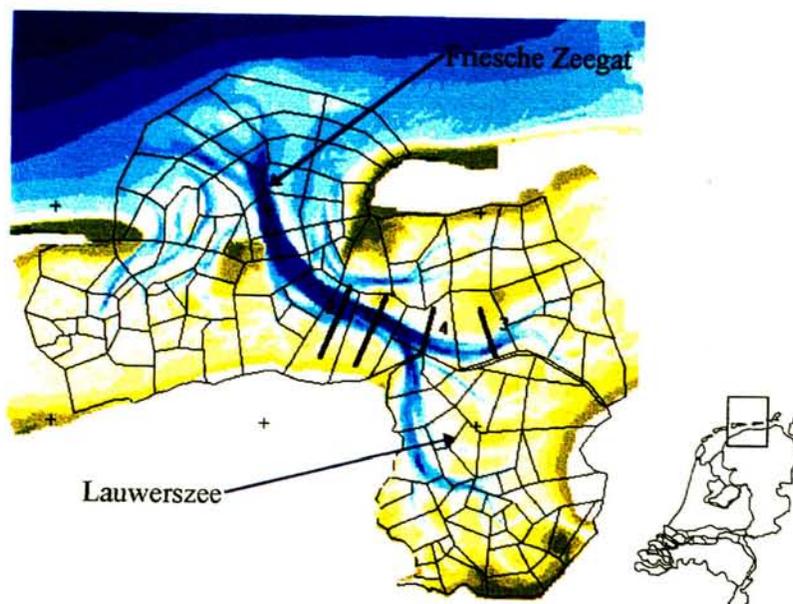


Fig.3.5 Het Friesche Zeegat and model schematisation

The ESTMORF model is applied to simulate the morphological development induced by the closure of the Lauwerszee in 1969. The simulation focuses on the morphological development of the tidal basin, especially the channels.

The model is set-up based on an existing 1D network model for this inlet. The schematisation is also shown in Fig.3.5. The application has been rather successful in hindcasting the evolution of the channels' cross-sectional areas throughout the basin as shown in Fig.3.6, which presents the morphological evolution of some of the channel cross-sections. As can be observed in Fig.3.5, there is a channel bifurcation at the entrance of the Lauwerszee. The closure in 1969 has cut off one of the branches of this bifurcation. After the closure sedimentation has occurred in the channel west of the bifurcation and erosion took place east of the bifurcation. This agrees with the observations. The sedimentation in the western part (cross-sections 1 and 2) of the channel as well as the erosion in the eastern part (cross-sections 3 and 4) are well reproduced (Fig.3.6).

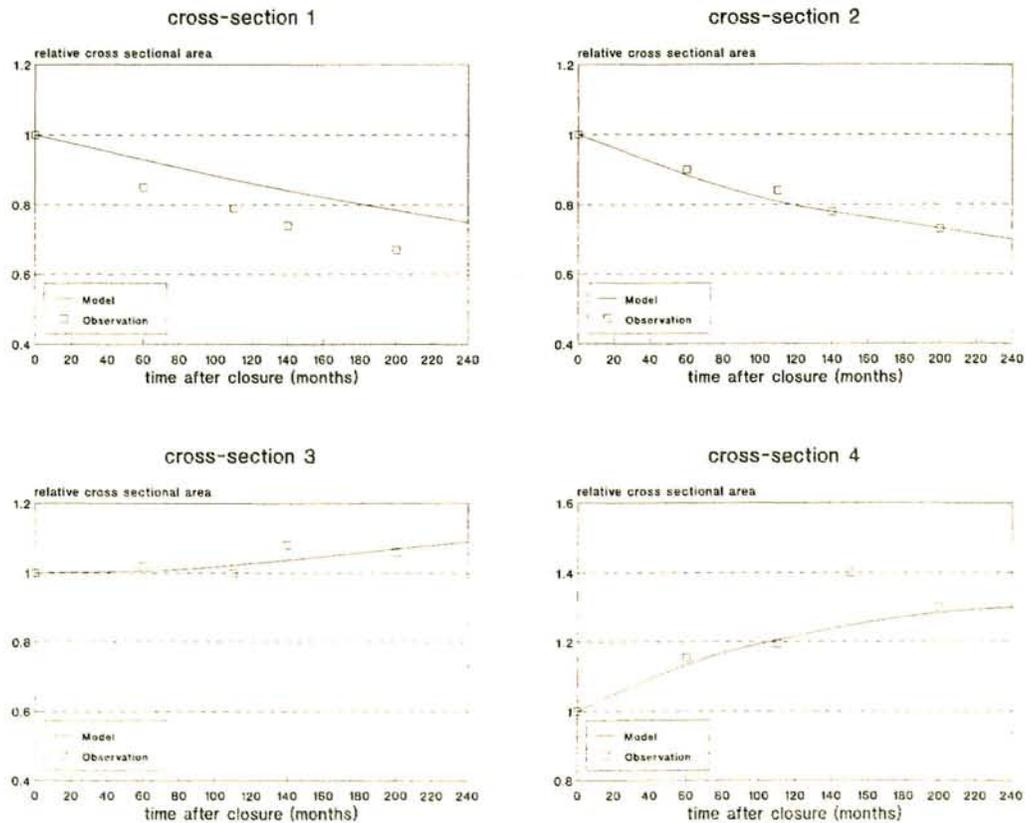


Fig.3.6 Computed and measured cross-sectional areas

3.3.2 Southampton Water

ABP (Associated British Ports) propose to construct a new deep sea terminal at Dibden Bay on the western side of Southampton Water (Fig.3.7). In support of the terminal approximately 13 million m^3 will be dredged from the adjacent inter tidal and subtidal environments.

The hydrodynamics of the estuary is dominated by tidal flow. The tidal range is up to 4 m and the estuary has an area of about 30 km^2 , giving a tidal prism in the order of 100 million m^3 . The total river inflow in the winter is about $30 \text{ m}^3/\text{s}$, or in the order of 1 million m^3 per tidal period, i.e. about 1% of the tidal prism. In the summer this is even less.

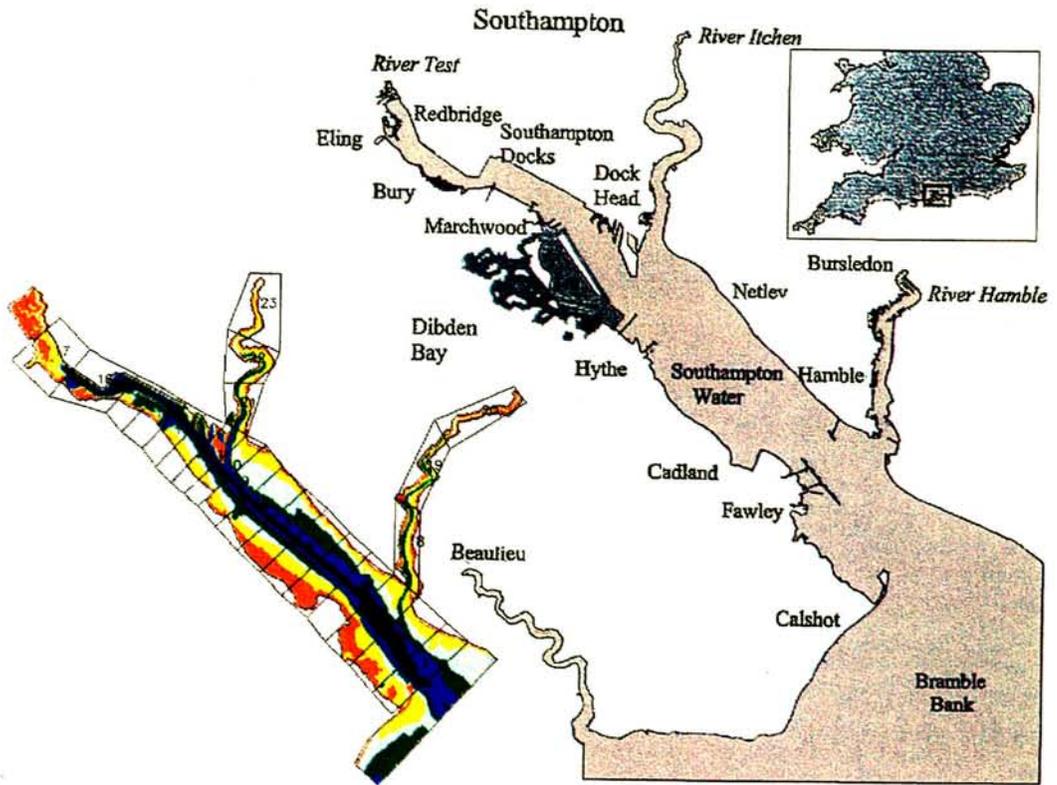


Fig.3.7 Southampton Water and the model schematisation

Based on ESTMORF, a long-term morphological model has been set up for the Southampton water, to study the impact of the Dibden bay terminal development. Two scenario's of the associated environmental enhancements have been considered: one without and one with inter tidal recharge along the shore of Hythe. Further two different rate of sea level rise have been considered in the study.

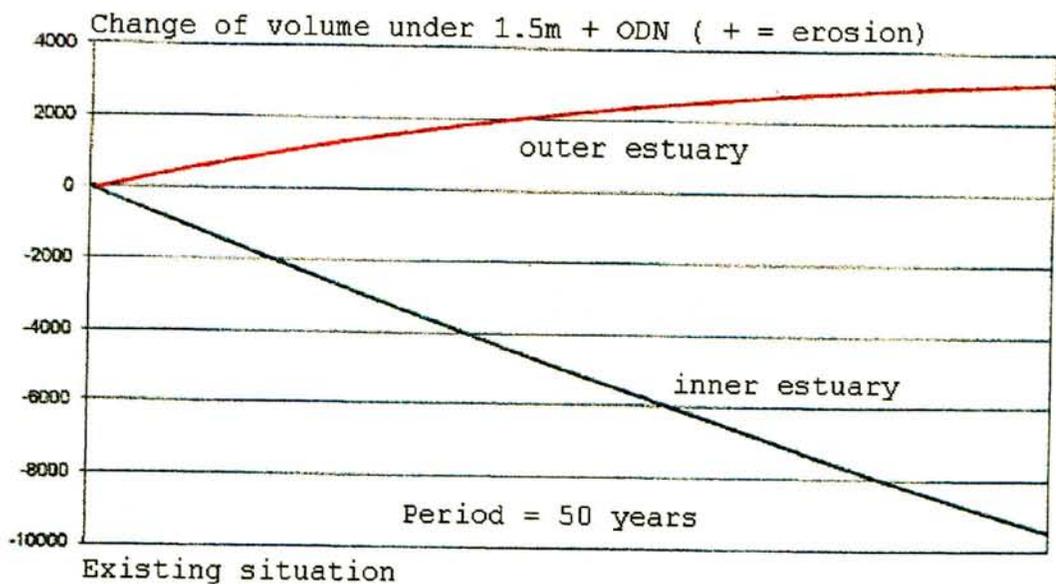


Fig.3.8 Results of calibration run showing a sedimentation rate in the inner estuary (upstream of Dockhead) of 188,500 m³/year

3.3.3 Humber

The Humber estuary located at the eastern coast of England is a macro tidal estuary with a tidal range varying from 3 m during neap tide to 6 m during spring tide. The long-term averaged total river inflow is $240 \text{ m}^3/\text{s}$ and under extreme conditions it can go up to $700 \text{ m}^3/\text{s}$. The estuary has a horizontal area (from Spurn Head to Trent Falls) of about 200 km^2 . The tidal prism at averaged tide is thus in the order of 900 Million m^3 , about 80 times the averaged river inflow during a tidal period. These figures indicate that the hydrodynamics of the estuary is dominated by the tidal flow.

A sediment budget for the estuary based on field data indicates that the long-term averaged sedimentation in the whole estuary is about 170 ton/tide, or about 0.1 million m^3/year , which is only a small fraction of the flood and ebb sediment transport at the mouth. The sedimentation in the estuary cannot compensate the volume increase due to relative sea-level rise in the estuary which is about 0.4 million m^3/year .

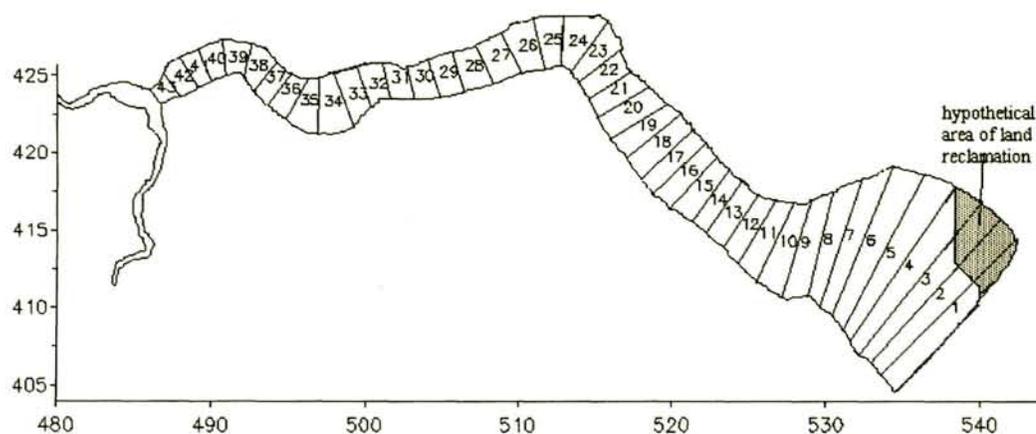


Fig.3.9 Humber estuary and model schematisation

Within the framework of the EMPHASYS project, a strategic Estuaries Research Programme within the United Kingdom, a pilot application of the ESTMORF model to the Humber estuary is carried out. The major purpose of the study is to evaluate the ability of the ESTMORF model for studying long-term morphological developments in estuaries and to provide morphological data for ecological assessments. As an example of human interference a hypothetical land reclamation project is considered (Fig.3.9). Sea level rise has been included with different rates. Simulations of 50 years have been carried out for analysing the impact of the land reclamation project in combination with sea level rise (Fig.3.10-3.11). The simulated morphological changes due to sea level rise of 0.2 m/century (the present situation) agree quite well with the observations (Fig.3.10). The ability of the model for studying impacts of an accelerated sea-level rise and of human interference is well demonstrated.

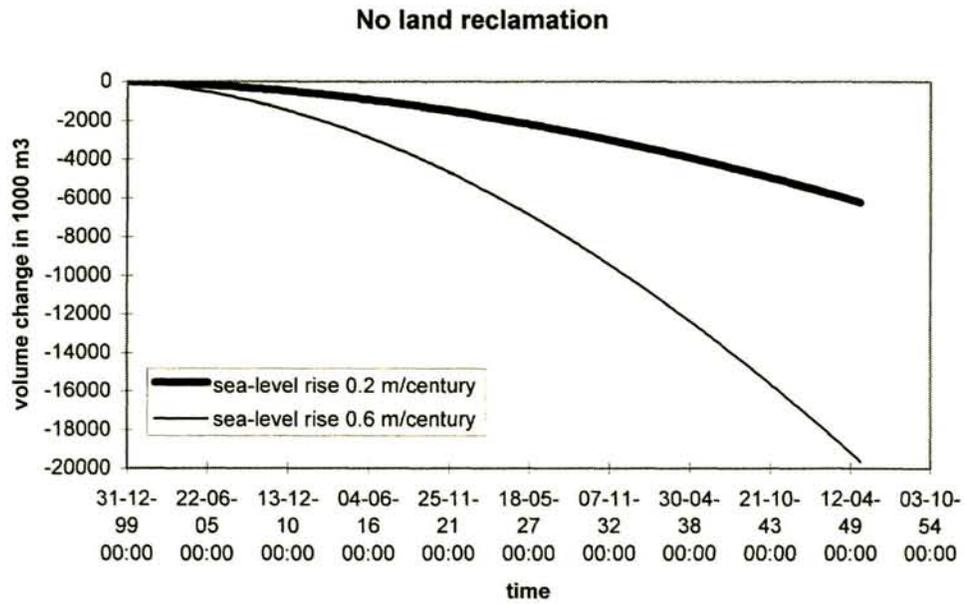


Fig.3.10 Simulated change of the total wet volume under 4m + ODN of the estuary due to sea-level rise

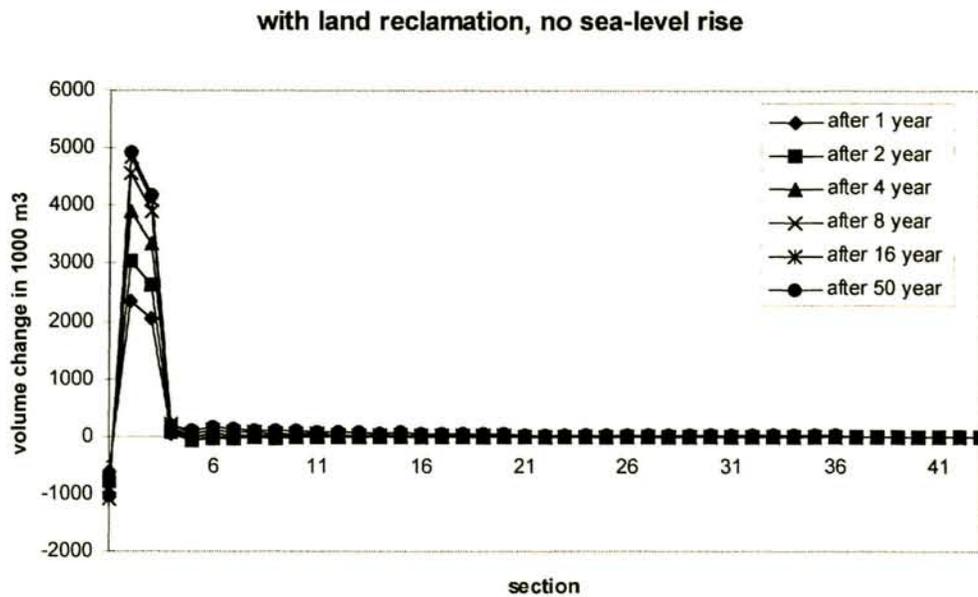


Fig.3.11 Simulated volume changes along the estuary due to land reclamation

3.3.4 Yangtze

The Yangtze Estuary is located on the east coast of China, north of the large harbour city Shanghai. It has been chosen for the pilot application abroad of the Estuarine Decision Support System (EDSS), developed within the framework of the LWI (Land Water environment Information technology) project Estuary and Coast. The ESTMORF model has

been implemented in the Ecomorphological module of the EDSS, therefore an ESTMORF model has been set up within the framework of the LWI project (Fig.3.12). Because the major objective of the project was to show the applicability of the model and because of the lack of long-term morphological data the model was only briefly calibrated with 10 year data of morphological development.

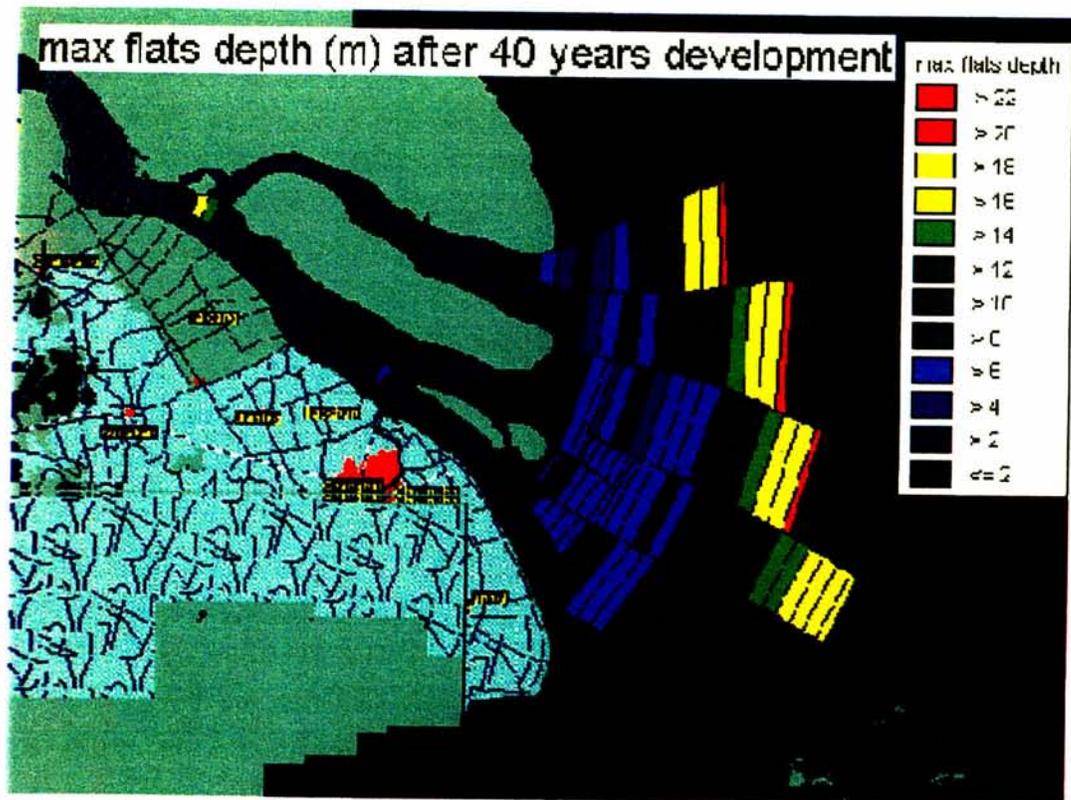
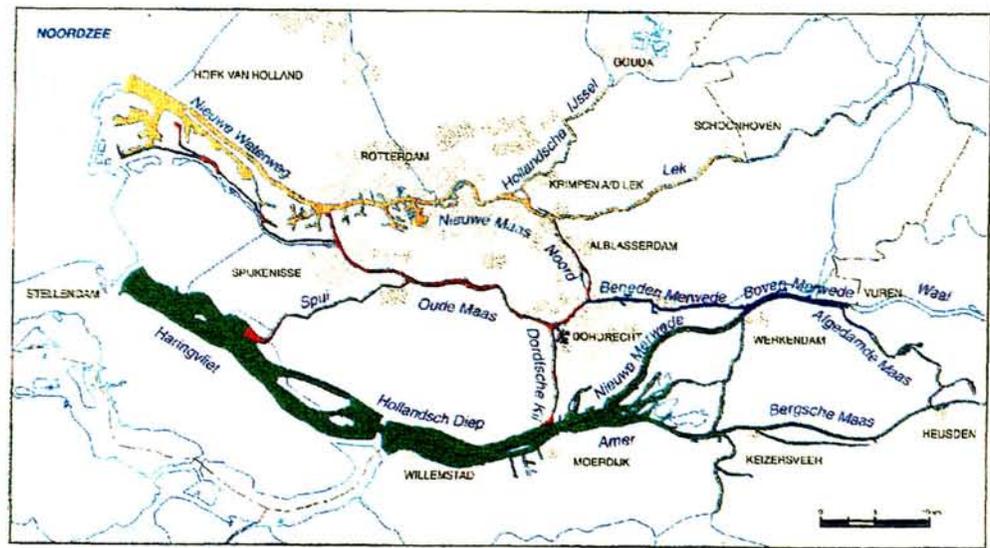


Fig.3.12 The ESTMORF Yangtze in the EDSS

3.3.5 Het Noordelijk Deltabekken

“Het Noordelijk Delta Bekken” is the Rhine - Meuse estuary containing the Rotterdam Harbour area, the Haringvliet and the connecting river branches between these two areas (Fig.3.13). As a part of the Delta project a sluice has been built at the mouth of the Haringvliet in 1969. This has turned the Haringvliet from an estuary into a fresh water basin almost without tidal flow. A large amount of sedimentation has been taken place in the area. At present changes of the operation of the Haringvliet Sluice are planned for allowing more intrusion of salt water and tide into the area. For studying the effect of such kind of changes a long-term morphological model on the basis of ESTMORF is set up for the area. So far a pilot application with the model is carried out in order to evaluate the potentials as well as the restrictions and possible problems of the model (Wang, 2001). Encouraging results have been obtained from the pilot application (see as example Fig.3.14) and further set up and calibration of the model is recommended.



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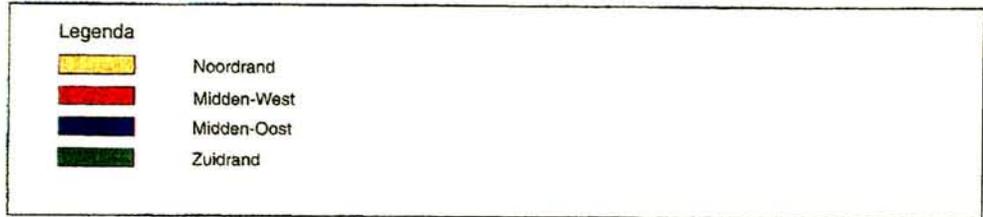


Fig.3.13 “Het Noordelijk Deltabekken”

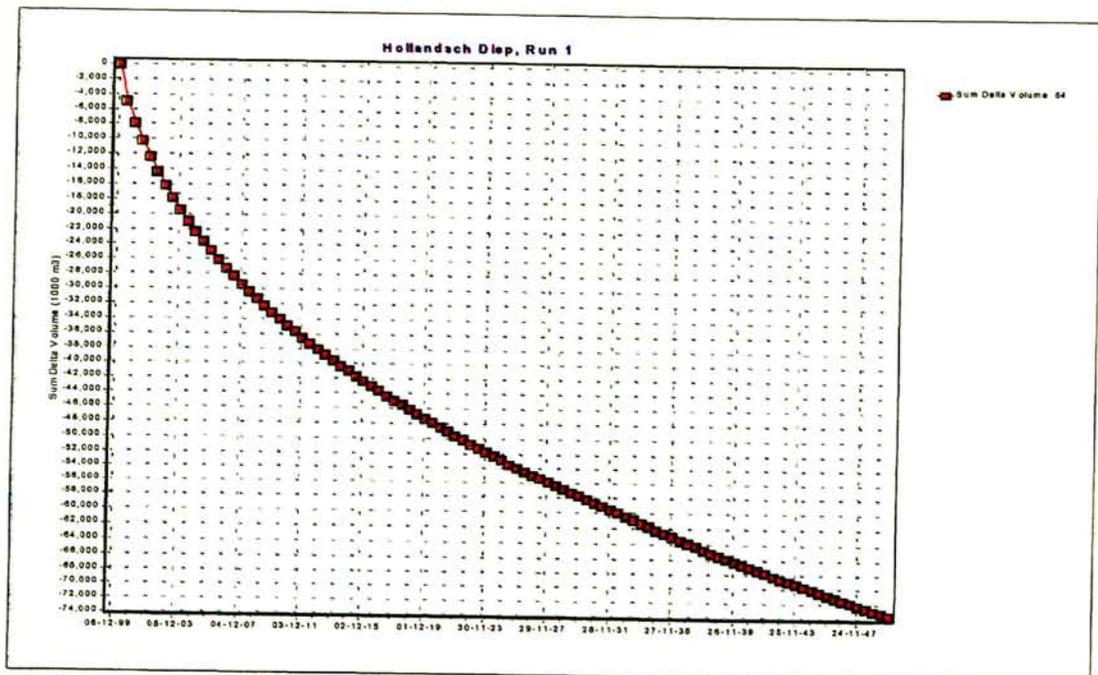


Fig.3.14 Simulated volume change (negative = sedimentation) of Hollandsch Diep, present situation

4 Evaluation and conclusions

4.1 Present state

The ESTMORF model can now be considered as operational. This applies for the software system as well as for the Western Scheldt model. Applications of ESTMORF to various projects in the Western Scheldt as well as to other estuaries within and outside the Netherlands have shown that the model is a useful tool for supporting management of estuaries and tidal lagoons.

There are two versions of the ESTMORF software. The only difference between the two versions is the used flow module: one uses the tidal flow model IMPLIC and the other uses SOBEK. Basically there is not any difference between the two qua functionalities. Although the IMPLIC version has the advantage that it is faster in computation, the SOBEK version deserves preference because SOBEK is the state of art 1D modelling system.

There are also two versions of the Western Scheldt model, one based on the model schematisation of the original IMPLIC model for the estuary and the other with the improved and extended model schematisation. With respect to the first the second schematisation is improved in the area of "Land van Saeftinge" and at the downstream end it is extended to include the ebb tidal delta. It is noted that the first schematisation should only be used in combination with the IMPLIC version of the software, whereas the second schematisation should only be used in combination with the SOBEK version of the software.

There are still several potentials of the system which have not been fully used in the Western Scheldt model. The functionality of taking into account the sea level rise has hardly been used. The possibility of taking into account the variation of tidal range at the open sea has not been used at all. These two functionalities will be used in the planned next application of the model (projects ZEEKENNIS & COAST2005). Furthermore, the functionality of dividing dumping on channel bottom and on side banks was implemented in the software in order to improve the representation of the inter tidal areas by the model. However, an extra calibration round will be required before that this possibility is exploited.

A software and /or a model needs maintenance, even if it is operational. So far the necessary maintenance has been carried out within the framework of the application projects. This situation needs to be improved by e.g. reserving special budget for the maintenance.

4.2 Possibilities

The most important strong point of the ESTMORF model is its possibility of doing long-term simulations of morphological development. Applications up to now show that simulations up to 50 years can be carried out without much difficulties. The required computation time on a PC is usually less than an hour.

Another strong point of the model is that it makes distinction between the channel and inter tidal areas in simulating the morphological development. Its possibility to simulate changes on inter tidal areas makes it a useful help tool for ecological studies. Inter tidal areas form important ecotopes in estuaries and tidal lagoons.

The model has extended functionalities for practical applications. Especially its functionality in dealing with dredging and dumping data and dealing with dredging strategies is very practical. Its possibility in handling sea level rise and the long-term variation of tidal range should also be mentioned.

4.3 Restrictions

Fixed grid

Due to the choice of using a 1D network schematisation the model has the restriction that shift of channels and generation of new channels cannot be simulated by the model. The model will keep the network structure fixed during the simulation. Disappearance of a channel can so far be simulated that the size of the channel reaches a minimum size. Closing of a channel is not allowed because drying cannot be handled in 1D tidal flow computations. This restriction implies that long-term simulations should be done for large scale developments.

Bottom composition

The model simulate morphological changes. It does not give any information on changes of bottom composition.

Long branches

Because the software has been set up such that it can use both IMPLIC and SOBEK for the flow module, there is a restriction for setting up of the SOBEK model for an ESTMORF application. In ESTMORF every branch is considered as a single element in the morphological model. This means that the possibility of SOBEK that a long branch can be defined and divided into many computational grid points cannot be used. A long branch has to be divided in more smaller branches by adding nodes.

navigation channel

When the dredging strategy option of the model is applied it should be noted that the branches containing the navigation channels should not be much wider than the navigation channel. Otherwise the required maintenance dredging can be underestimated. This restriction can be solved by implementing sub-grid processes in the software.

4.4 Conclusions

Applications of the model in practise have proven that ESTMORF has become a useful tool for the Western Scheldt estuary, the original problem area of the model. It has also been shown that the developed software is applicable to other estuaries and tidal lagoons within and outside the Netherlands as well.

The software as well as the Western Scheldt model can be considered as operational. However, there are still potentials of the model which can be utilised in the applications of the model in the future. There are also some promising improvements of the software and the Western Scheldt model which can be implemented in the future. Especially the implementation of a sub-grid processes for predicting sedimentation rate in navigation channels, and modification of the (SOBEK-version) software for a more efficient treatment of long branches are recommended.

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A.1 Reports of ESTMORF studies

Karssen, B. and Z.B. Wang (1991)

Morphological modelling in estuaries and tidal inlets, A literature survey, Report Z473, WL | Delft Hydraulics.

In this literature survey the models for morphological development in estuaries and tidal lagoons are inventoried and evaluated. The models described in the literature can be divided into three types: empirical, dynamic (process-based) and dynamic-empirical. Further distinction can be made between 1D, 2DH, etc. models depending on the schematisation on which a model is based. It is concluded that a 1D dynamic-empirical (semi-empirical) model will be most promising for the long-term morphological modelling.

Karssen, B en Wang Z.B. (1993)

A dynamic/empirical model for the long-term morphological development of estuaries; Part I: Physical relations, WL-Delft Z622, April 1993

This report describes the mathematical-physical formulation of the ESTMORF model. The basic model concept, the schematisations as well as the equations in the model are described.

Karssen, B (1994a)

A dynamic/empirical model for the long-term morphological development of estuaries; Development of the model, Phase I, WL-Delft Z715, Februari 1994

This report describes the first of the in total three phases of the development of the ESTMORF model. The functional requirement, the basic assumptions and the technical design of the ESTMORF software are described. In this study the first version of the program is developed. Some test results with the model including the application to the Friesche Zeegat are described as well.

Karssen, B (1994b)

A dynamic/empirical model for the long-term morphological development of estuaries; Development of the model, Phase II, WL-Delft Z715, November 1994

This report describes the further development of the ESTMORF model. Especially the set up and the calibration of the Western Scheldt model are described. The calibration is based on the observations of the volume changes of the six large parts of the estuary since 1968.

Karssen, B (1995)

Evaluation of ESTMORF; Mass balance and additional simulation, WL-Delft Z891, Maart 1995

During the calibration of the Western Scheldt model some questions raised. Some extra simulations are carried out and the results are evaluated, with the purpose to check the correctness of the numerical calculations, especially concerning the sediment balance of sediment.

Tank, F.T.G. (1995)

Empirische relaties tussen de plaat- en slikhoogte en getijkarakteristieken in de Westerschelde, UU IMAU Rapport R95-7, juni 1995

The purpose of this research was to set up empirical relations for the equilibrium heights of the inter tidal areas in the Western Scheldt. These relations are required in the ESTMORF model for the estuary.

Fokkink, R.J. (1996)

A new evaluation of ESTMORF; phase III New physical relations and refinement of the calibration, WL-Delft Z930, Maart 1996

With new empirical relations for the inter tidal areas and with more detailed data the calibration of the Western Scheldt model is refined, by calibrating the development of the channel of each section in the model, by calibrating the inter tidal areas. Some theoretical analysis on the morphological time scale depending on the model parameters is carried out in order to support the calibration.

Fokkink, R.J. (1997)

Analysis of the ESTMORF-model, WL-Delft Z2039, april 1997

This report describes extensively the nodal point relations. It is made clear that a network of channels can become unstable in ESTMORF, similar as in a 1D network morphodynamic model. This is recognised as an important reason why the Western Scheldt model was difficult to calibrate. The proposed nodal point relation to solve the problem is based on the same principle as that for the 1D network morphodynamic models with bed load transport.

Fokkink, R.J. en Weck, A van der (1998)

Final version of the ESTMORF-model; final version 4.0, WL-Delft Z2262, juni 1998

This report describes the final calibration of the first operational version of the Western Scheldt model. After this round of the calibration the model is installed at Rijkswaterstaat (Middelburg). The solution of the nodal point relation problem is eventually found by relating the equilibrium cross-sectional area of a branch to the total tidal volume through a group of branches instead of to the tidal volume through the branch itself.

Fokkink, R.J. en Graaf, F de (1998)

Vergelijking Estmorf en meetgegevens, WL-Delft Z2547, december 1998

During the calibration of the Western Scheldt model is noticed that there is already a difference between the model and the data at the initial state. The study described in this report is meant to find out where this difference comes from.

Helvert, M.A.G. van, (1999)

Onderzoek naar de effecten van baggeren, storten en zandwinning in de Westerschelde met behulp van het ESTMORF-model in het kader van MOVE; Project Monitoring Verruiming Westerschelde 48'/43', werkdocument RIKZ/OS-99.817x, juli 1999

This report describes the application of ESTMORF Western Scheldt model, carried out within the framework of the MOVE (monitoring effect of the deepening of the navigation channel) project. This concerns the first application of the model for evaluating various future scenario's.

Wang, Z.B. en Bruinsma, R. (1999)

Verbetering ESTMORF, WL-Delft Z2760, december 1999 met bijbehorend ESTMORF-manual version 2.0; Model principles and User manual, WL-Delft december 1999

After the first application of the model a number of improvements of the model, concerning functionality and especially concerning user friendliness, were recommended. This report describes the implementation of these improvements:

1. SOBEK is implemented instead of IMPLIC as flow module of the model.
2. The software is extended concerning the empirical relation for the inter tidal area such that the equilibrium heights of the inter tidal area in a section can be related to the water level elsewhere as well as to the local water level.
3. The input file containing the dredging and dumping data is changed. The set up of the new file is entirely user-oriented instead.
4. A dredging strategy option is implemented, with which the model is able to make predictions of the required dredging for forecasting simulations.
5. A new set of programs for post-processing the model results is developed.

Jeuken, M.C.J.L. en Weck, A.W. van de (1999)

Uitbreiding ESTMORF-model Westerschelde; Afregelen van het waterbewegingsmodel IMPLIC, WL-Delft Z2701, december 1999

This report describes the calibration of the IMPLIC flow model with the new extended schematisation. This extended model also covers the ebb tidal delta area. The open sea boundary condition is located at Westkappelle instead of Vlissingen. The calibration focuses on the ebb tidal delta area because the model was already calibrated for the estuary area.

Jeuken, M.C.J.L. en Wang, Z.B. (2000)

Morfologische ontwikkeling van intergetijde-gebieden en modellering met ESTMORF, Deel I: Evaluatie modelresultaten, WL-Delft Z2776-I, augustus 2000

ESTMORF simulates the morphological changes on the inter tidal area separately from that in the channel. The calibration of the Western Scheldt model shows that the model gives better results for the channel than for the inter tidal area. The objective of this study is to evaluate the performance of the ESTMORF Western Scheldt model concerning the representation of the inter tidal area. By comparing the model results with the field observations it is determined how large the differences. The differences are analysed with the purpose to determine the causes of them.

Hibma, A, Jeuken, M.C.J.L. en Wang, Z.B. (2000)

Morfologische ontwikkeling van intergetijde-gebieden en modellering met ESTMORF, Deel II: Literatuurstudie, WL-Delft Z2776, augustus 2000

The objective of this literature survey is to make an inventory of the relevant processes and mechanisms for the development of the inter tidal areas. It is meant to answer the following questions:

1. What is the relative importance of the various forcing for the development of the inter tidal areas?
2. Which influence is exerted by the shape, size and location of inter tidal areas on the tidal flow?
3. What is the role of the inter tidal areas on the development of an estuary?
4. What are the time scales of the processes which determine the development of the inter tidal areas?

Recommendations are made for improvement of the formulations in ESTMORF with respect to the development of inter tidal areas.

Helvert, M.A.G. van, (2000)

Verslag overig gemaakte ESTMORF-berekeningen, MOVE, werkdocument RIKZ/OS-2000.810x, september 2000

This document describes the results of the simulations with the ESTMORF Western Scheldt model, carried out within the framework of the MOVE project.

Thoolen, P.M.C. (2000)

Uitbreiding en verbetering ESTMORF, WL-Delft Z2934 oktober 2000

This report describes the following activities meant for the extension and improvement of the ESTMORF Western Scheldt model:

1. Analyse the representation of the connecting channels (small channels e.g. at the end of a flood channel and connecting it to an ebb channel) by the model.
2. Improve the computational speed of the model in the case that SOBEM is used as flow module.
3. Analyse the extended model schematisation including the ebb tidal area.
4. Implement an improved new schematisation for “het Land van Saeftinge” in the flow model.
5. Analyse the influence of the initial conditions on the model.

Wang, Z.B. en van Helvert M.A.G. (2000)

Verbetering weergave intergetijdengebied in ESTMORF; Implementatie van diverse maatregelen, WL-Delft Z3002 november 2000

This report describes the implementation of a part of the recommended improvement of the ESTMORF Western Scheldt model with respect of the representation of inter tidal areas:

1. Improve the calibration of the model concerning the development of inter tidal areas.
2. Improve the procedure which processes the dredging and dumping into changes of the cross-sections. In the old version of the model all dredging and dumping are assumed to be carried out on the channel bottom. After the improvement a part of dredging and dumping can be assigned to the side bank of the channel according to the user defined input.
3. Investigate the feasibility of implementing an extra empirical relation for the development of inter tidal areas. The extra relation will be related to the shape of the channel cross sections.

Wang, Z.B. en van Helvert M.A.G. (2001)

ESTMORF model voor de Westerschelde inclusief de monding, WL-Delft Z3105 september 2001

This report describes the last activities for the development of the model up to now. After this study, the Western Scheldt model, with the SOBEM version of ESTMORF and with the extended and improved model schematisation, is calibrated and made operational.

The following activities have been carried out:

1. Software improvement. The functionality for dividing the dredging and dumping to the channel bottom and side banks finished. Further the error messages of the software are improved.
2. The morphological model is extended with the ebb tidal area.
3. The morphological model is refined by using the improved schematisation of “het Land van Saeftinge”.

4. The extended and improved model is calibrated using the SOBEK version of ESTMORF.

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B Publications related to ESTMORF

A Dynamic-Empirical Model for Estuarine Morphology

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ABSTRACT: The mathematical model ESTMORF predicts the morphological development of estuaries and tidal lagoons on a time scale of decades. The model is dynamic-empirical, which means that it is based on empirical relations for the morphological equilibrium, combined with hydrodynamic and sediment transport models based on physical laws. The model is developed by Rijkswaterstaat in collaboration with DELFT HYDRAULICS.

In this paper a description of the model is given, followed by some analysis of the behaviour of the model. Furthermore, the first applications of the model to a tidal lagoon in the Wadden Sea and to the Western Scheldt Estuary are described.

INTRODUCTION

Morphological development is the result of interactions between flow and alluvial bed. The relevant processes for morphological development are flow, sediment transport and bed level change. A mathematical model for morphological development can be set-up by simulating each of these processes using physical laws. Such a process-based morphological model is called a dynamic model.

At present (1996), the dynamic type of models, one-dimensional as well as two-dimensional, are already commonly used in engineering practice for rivers. For estuaries, however, the long-term morphological development under the influence of natural processes, e.g. sea level rise, and/or under the influence of human activities, e.g. land reclamation, dredging and dumping, can still not be predicted by dynamic models. In practice, prediction of long-term morphological development in estuaries still relies to a large extent on empirical relations, in which the morphological variables, such as the cross-sectional area of channels, are related to integrated hydrodynamic parameters, e.g. the tidal volume.

Recently, ESTMORF is developed by DELFT HYDRAULICS and Rijkswaterstaat, a mathematical model for

predicting the long-term (decades) morphological development of estuaries and tidal lagoons, under the influence of natural processes and human interference. The model is partly based on process descriptions and partly on empirical relations which combines the advantages of the dynamic type of models with those of the empirical ones.

MODEL DESCRIPTION

General model concept

The most important hypothesis used in the ESTMORF model concept is that an equilibrium state can be defined for each morphological element of the system depending on the hydrodynamic conditions. An empirical relation is required for each element to define the morphological equilibrium state. This kind of empirical relations are commonly used for tidal systems.

Various morphological models for estuaries and tidal inlets are based on such relations in combination with a transient model describing the evolution of the actual state with respect to its equilibrium as an exponential decay process (O'Connor et al., 1990, Eysink, 1990,

Eysink, 1992). When this model concept is applied to a system consisting of more than one element, linked with each other, extra assumptions are required to guarantee the mass-balance of sediment (Allersma, 1988, Van Dongeren and De Vriend, 1994). This can make the model results sensitive to the sequence in which the various elements are dealt with in the computation: e.g. computations starting from the sea side give different results than computations starting from the land side.

In the tidal basin model of Di Silvio (1989) this problem is overcome by introducing a characteristic sediment concentration in each element of the model. The concentration field is governed by the advection-diffusion equation based on a residual flow field, which guarantees the fulfilment of the sediment mass-balance. This concept is adopted in the ESTMORF model.

The basic philosophy is as follows. If all elements in the morphological system are in equilibrium, there is no accumulation of sediment or water anywhere in the area. If the sediment is mainly transported in suspension, the sediment flux field is therefore likely to be proportional to the flow rate. The ratio between sediment flux and flow rate can be considered as a sediment concentration and is called in this paper the overall equilibrium concentration c_E . For each element in the system a local equilibrium sediment concentration c_e is defined such that it equals c_E if the element is in morphological equilibrium, that it is larger than c_E if a tendency for erosion exist (e.g. the cross-sectional area of a channel is smaller than the equilibrium value), and smaller than c_E if a tendency for sedimentation exists. Morphological changes occur when the local sediment concentration deviates from its local equilibrium. Erosion occurs when the sediment concentration is smaller than its equilibrium value and sedimentation occurs if it is larger than its equilibrium value.

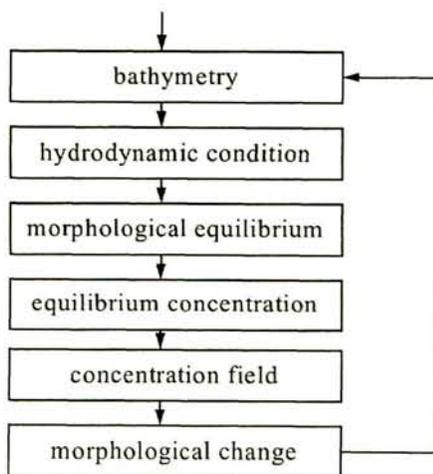


Fig.1 Computational procedure

The ESTMORF model described here belongs to the semi-empirical type according to the classification due to De

Vriend (1996). An important difference between the present model and the process-based models is that the equilibrium concentration is not directly computed from the hydrodynamic parameters, but via the equilibrium morphological state (see Fig.1). This makes the model always converging to a state of which the equilibrium relations are satisfied.

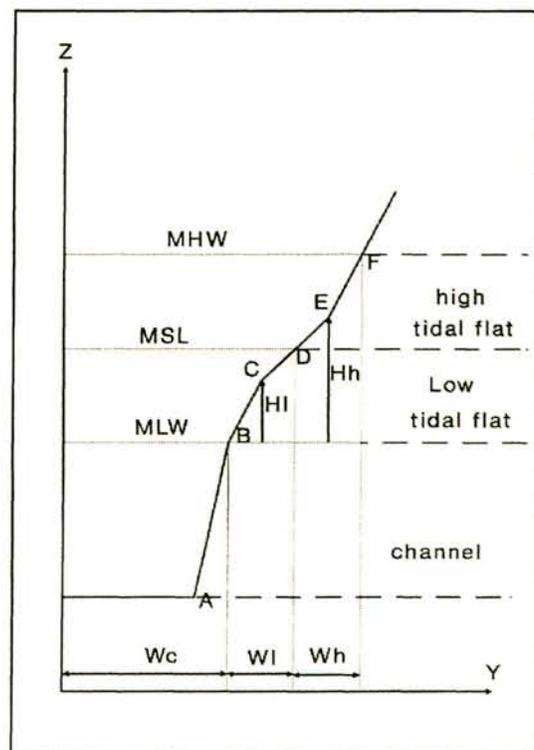
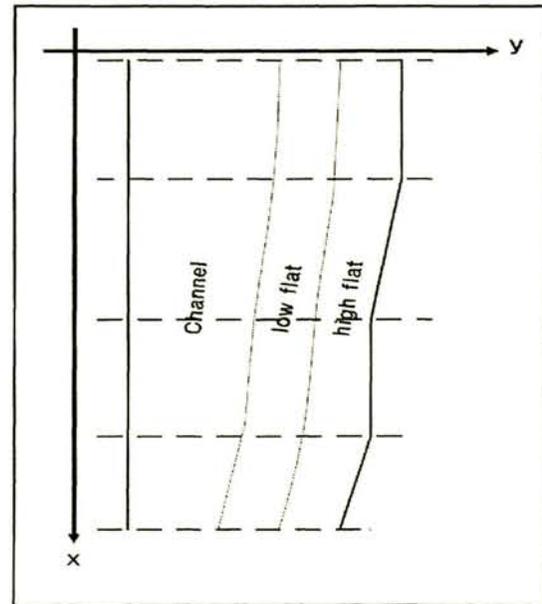


Fig.2 Schematisation of geometry

Geometrical schematisation

The model uses an existing one-dimensional network flow model to simulate the flow. Therefore, the modelling area is schematised into a network consisting of branches.

The cross-sections of the branches are schematised as shown in Fig.2 (Note that in the figure the tidal flat is shown only at one side of the channel). It is divided into three parts: the channel part (under the low water level, MLW), the low tidal flat between MLW and the mean water level (MSL), and the high tidal flat between MSL and the high water level (MHW). The channel part is assumed to have a trapezoidal cross-section. The two parts of the tidal flat are described by their widths as well as their heights. This schematisation of the cross-section is adopted from Eysink (1992).

Morphological changes in the three parts are calculated separately, and can be due to sedimentation/erosion and to changes in the relative water level e.g. sea level rise/land subsidence.

The equilibrium state

The model uses three variables, the cross-sectional area of the channel, the height of the low tidal flat and the height of the high tidal flat. For each of these variables an empirical relation is required defining the morphological equilibrium state of the system.

The equilibrium cross-sectional area of the channel is related to the tidal volume. For the Wadden Sea such a relation is given by e.g. Eysink (1992).

$$A_{ce} = f_1(P_v) \quad (1)$$

Herein A_{ce} = equilibrium cross-sectional area under MSL
 P_v = tidal volume.

The equilibrium heights (measured from MLW) of the two parts of the tidal flat are related to the tidal range and the total area of the basin (see e.g. Eysink 1992).

$$H_{he} = f_2(H, A_b) \quad (2)$$

$$H_{le} = f_3(H, A_b) \quad (3)$$

In these two equations

H_{he} = equilibrium height of the high tidal flat measured from mean low water,

H_{le} = equilibrium height of the low tidal flat measured from mean low water,

H = tidal range,

A_b = total area of the basin.

In equations (1) through (3) no specific relations are given. They have to be chosen on the basis of field data when the model is applied for a specific area. This part is kept as flexible as possible to guarantee a wide applicability of the model. The coefficients in the equations may also

vary spatially such that an existing equilibrium state can be represented throughout the system.

Morphological development

When the system is not in equilibrium, morphological changes will occur. The sedimentation and/or erosion rate is assumed to be proportional to the deficit/excess of the local sediment concentration, following the formulation of Galappatti and Vreugdenhil (19985). The bed level change is then described by the following simple formulation:

$$\frac{\partial z}{\partial t} = w_s (c - c_e) - \alpha_s \quad (4)$$

Herein z = bed level,

w_s = coefficient having the dimension of velocity, to be called vertical exchange velocity,

t = morphological time,

c = sediment concentration,

c_e = local and instantaneous equilibrium sediment concentration,

α_s = rate of land subsidence.

Applied to the three parts of the cross-section, the following equations are derived:

$$\frac{\partial A_c}{\partial t} = W_c [w_s (c_{ce} - c_c) + \alpha_s + \alpha_r] \quad (5)$$

$$\frac{\partial A_l}{\partial t} = W_l [w_s (c_{le} - c_l) + \alpha_s + \alpha_r] \quad (6)$$

$$\frac{\partial A_h}{\partial t} = W_h [w_s (c_{he} - c_h) + \alpha_s + \alpha_r] \quad (7)$$

In these three equations we define (see Fig.1):

A_c = cross-sectional area of the channel part (below MSL),

A_h = cross-sectional area of the high tidal flat,

A_l = cross-sectional area of the low tidal flat,

c_c = sediment concentration in the channel part,

c_h = sediment concentration in the high tidal flat part,

c_l = sediment concentration in the low tidal flat part,

c_{ce} = local equilibrium sediment concentration in the channel part,

c_{he} = local equilibrium sediment concentration in the high tidal flat part,

c_{le} = local equilibrium sediment concentration in the low tidal flat part,

W_c = width of the channel part,

W_h = width of the high part of the tidal flat,

W_l = width of the low part of the tidal flat,

α_r = rate of sea level rise.

Sediment Transport

The equilibrium concentrations are determined as follows:

$$c_{ce} = C_E \left(\frac{A_{ce}}{A_c} \right)^{n_c} \quad (8)$$

$$c_{le} = C_E \left(\frac{H_l}{H_{le}} \right)^{n_l} \quad (9)$$

$$c_{he} = C_E \left(\frac{H_h}{H_{he}} \right)^{n_h} \quad (10)$$

In these equations:

- C_E = overall equilibrium sediment concentration,
- A_c = cross-sectional area of the channel,
- H_h = height of the high tidal flat measured from MLW,
- H_l = height of the low tidal flat measured from MLW,
- n_l = constant coefficient,
- n_h = constant coefficient,
- n_c = constant coefficient

When the whole system is in equilibrium, the sediment concentration will be equal to its overall equilibrium value. When for example the cross-sectional area is larger than the equilibrium value it means in fact that the local flow velocity will be lower by the same factor as the ratio A_c/A_{ce} . The formulation (8) of the local equilibrium sediment concentration is thus similar to the sediment transport capacity formula using power law.

The actual sediment concentration is governed by an advection-diffusion model. It is further assumed that the tidal flat can only exchange sediment with the channel in the same section. In other words, there is no longitudinal sediment transport over the inter tidal flats.

The mass balance equation for sediment in the channel may be written as:

$$\begin{aligned} \frac{\partial A_c c_c}{\partial t} + \frac{\partial A_c u c_c}{\partial x} - \frac{\partial}{\partial x} \left(A_c D_c \frac{\partial c_c}{\partial x} \right) = \\ = W_c w_s (c_{ce} - c_c) + F_{lc} \end{aligned} \quad (12)$$

- where: c_c = sediment concentration by volume in the channel,
- D_c = horizontal dispersion coefficient in the channel,
- F_{lc} = exchange rate of sediment between the channel and the low tidal flat,
- t = time,
- u = residual flow velocity.

The sediment flux from the tidal flat to the channel F_{lc} is elaborated as follows:

$$F_{lc} = D_l \overline{\Delta h_l} \frac{c_l - c_c}{L_{lc}} \quad (13)$$

- Herein: D_l = diffusion coefficient,
- L_{lc} = distance between the centre of the channel and that of the low part of the tidal flat,
- $\overline{\Delta h_l}$ = time-averaged water depth at MLW.

The mass balance for sediment at the low part of the tidal flat is given by the following equation:

$$\frac{\partial (A_l c_l)}{\partial t} = W_l w_s (c_{le} - c_l) - F_{lc} + F_{hl} \quad (14)$$

And at the high part of the tidal flat the mass-balance reads

$$\frac{\partial (A_h c_h)}{\partial t} = W_h w_s (c_{he} - c_h) - F_{hl} \quad (15)$$

The exchange rate between the two parts of the tidal flat is formulated as

$$F_{hl} = D_h \overline{\Delta h_h} \frac{c_h - c_l}{L_{hl}} \quad (16)$$

- Herein: D_h = diffusion coefficient,
- L_{hl} = distance between the centre of the high flat and that of the low flat,
- $\overline{\Delta h_h}$ = time-averaged water depth at MSL.

COMPARISON WITH DYNAMIC MODELS

The behaviour of the model can be analysed by considering some simplified cases. Here two extreme cases are considered. It will be shown that in both cases the behaviour of the model is very similar to a process-based model.

The first case concerns the unidirectional steady flow in a river without tidal influence (hence no tidal flats exist). In this case the tidal volume is proportional to the river discharge, so the equations describing the sediment transport and the morphological development used in the model become identical to those in a process-based one-dimensional model using depth-averaged model for suspended sediment transport (see e.g. Galappatti and Vreugdenhil, 1985). The only difference is that the morphological equilibrium state in the present model is merely determined by the river discharge, whereas in a 1D process-based model it is determined by the

discharge, the upstream sediment supply and the river width. It is obvious that the empirical relations used in the model should be site-specific.

The second case concerns a rectangular tidal basin, with one end closed and the other end connected with the sea. This case has been used for extensive sensitivity analysis with respect to the various model-parameters (Karszen, 1994). A typical example of the results is shown in Fig.3. The simulation start with a horizontal bed and ends with a linear bottom, which is in full agreement with the commonly used empirical relation that the cross-sectional area is proportional to the tidal volume through that cross-section (note that the diffusion coefficient at the end of the basin is not set to zero). Also in this case the simulated morphological development is very similar to that simulated with a process-based model (see Wang, 1992, Schuttelaars and De Swart, 1996). From the sensitivity analyses it is further concluded that the vertical exchange velocity, the overall equilibrium concentration, the dispersion coefficient and the power in the equilibrium concentration equations are the most important parameters influencing the simulated morphological development.

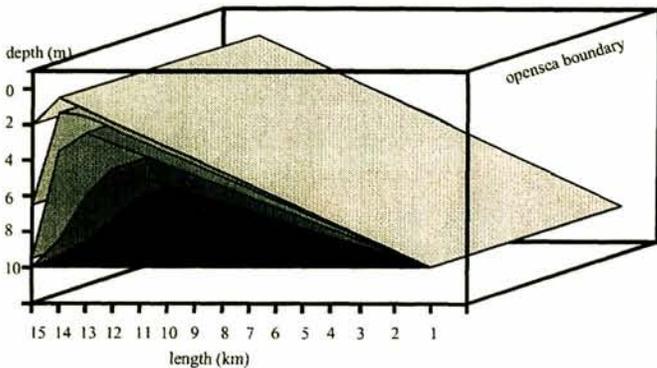


Fig.3 Filling of a prismatic tidal basin

MORPHOLOGICAL TIME SCALE

Another way of examining the behaviour of the model is by analysing how the morphological time scale is related to the relevant length scale. Knowledge of how the morphological time scale is determined by the model parameters is very important for the calibration of the model. For this purpose a linear analysis is carried out for a small disturbance on a system in equilibrium. The time scale defined is the time in which the disturbance decreases its amplitude with a factor *e*. For the sake of simplicity only the channel is considered, and the residual flow is neglected. The time scale in this case is:

$$T = \frac{T_s + T_D}{c_E n_c} \tag{17}$$

Herein $T_s = \frac{a}{w_s}$ $T_D = \frac{1}{k^2 D}$

and *k* is the wave number of the disturbance. It is clear that the time scale consists of two parts, one related to the vertical exchange of sediment and the other related to the horizontal exchange of sediment. It is also clear that the parameters *D*, *w_s*, *c_E* and *n* are the important model parameters determining the morphological time scale. More extensive and detailed analysis of the morphological time scale related to the model parameters is given by Fokkink (1996).

APPLICATIONS

Het Friesche Zeegat

“Het Friesche Zeegat” is a tidal inlet in the Wadden Sea (Fig.4). Since 1969, this tidal inlet system, with an area of about 450 km², has undergone significant morphological changes due to the reclamation of a large part, the Lauwerszee. As a consequence the in- and outgoing tidal volume has been reduced by about 34%. The response of this tidal inlet system to the closure of the Lauwerszee is well documented. The deeper parts of the outer delta are eroding, large bars are forming, the tidal channels are shoaling and the eastern watershed is shifting eastward.

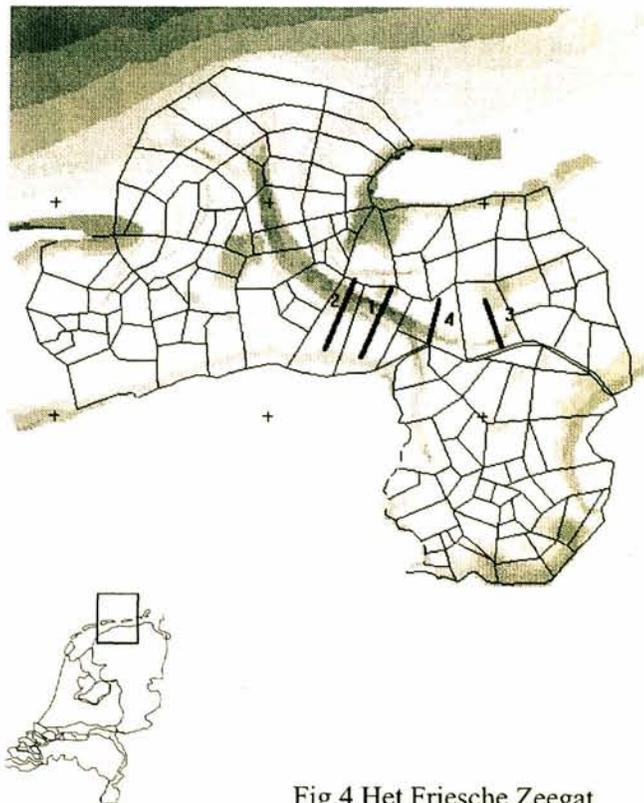


Fig.4 Het Friesche Zeegat

The ESTMORF model is applied to simulate the morphological development induced by the closure of the Lauwerszee in 1969. The simulation focuses on the morphological development of the tidal basin, especially the channels.

The model is set-up based on an existing 1D network model for this inlet. The schematisation is also shown in Fig.4. It must be pointed out that the schematisation was originally designed for flow simulation purposes only. From the morphological modelling point of view it is not an ideal schematisation. Nevertheless the application has been rather successful in hindcasting the evolution of the

channels' cross-sectional areas throughout the basin as shown in Fig.5, which presents the morphological evolution of some of the channel cross-sections. As can be observed in Fig.4, there is a channel bifurcation at the entrance of the Lauwerszee. The closure has cut off one of the branches of this bifurcation. After the closure sedimentation has occurred in the channel west of the bifurcation and erosion took place east of the bifurcation. The sedimentation in the western part (cross-sections 1 and 2) of the channel as well as the erosion in the eastern part (cross-sections 3 and 4) are well reproduced (Fig.5).

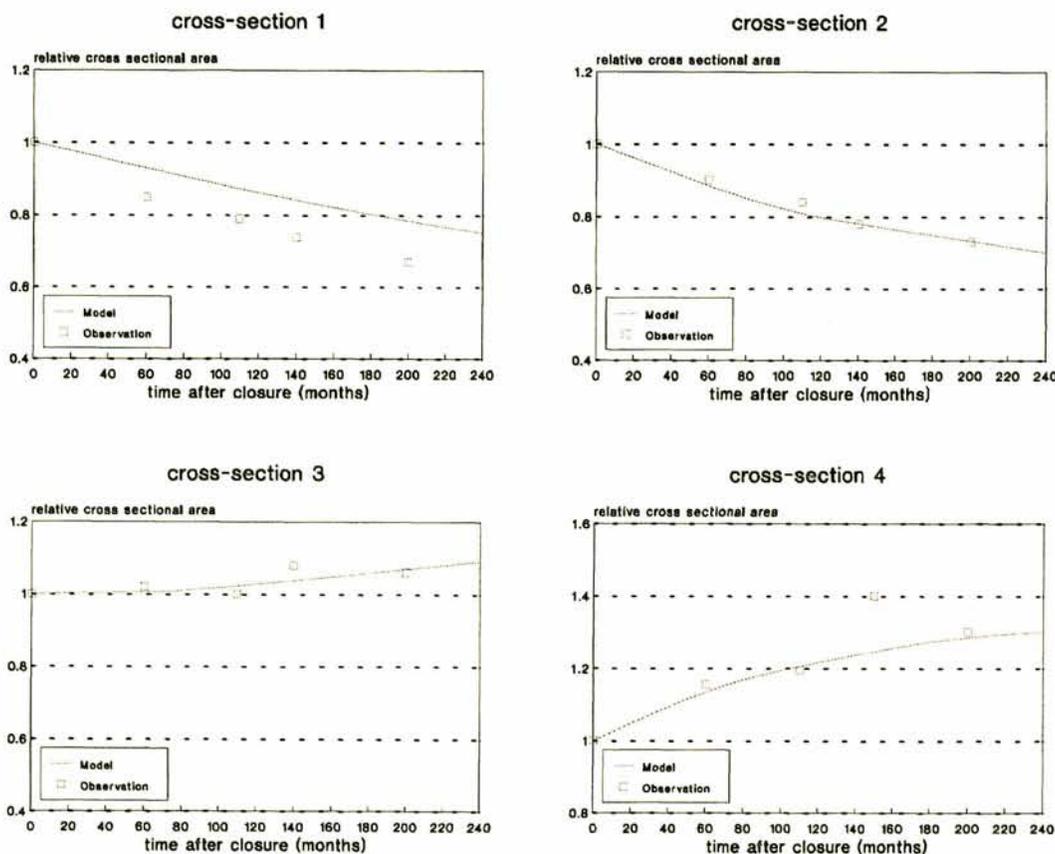


Fig.5 Computed and measured cross-sectional areas

The Western Scheldt

The Western Scheldt is an estuary located in the South-west of The Netherlands. It is the entrance to Antwerp Harbour. Dredging operations maintaining and improving the navigation conditions can have significant impact on the morphological development, which in turn can influence the ecological conditions in the estuary. In the near future a significant deepening of the navigation channel is planned. It is very important to predict the

morphological and ecological impacts of the capital dredging and of the increased maintenance dredging in the future.

An ESTMORF model is set-up for the estuary to simulate the morphological developments under influence of human activities, like dredging and dumping, and under influence of natural processes, like sea level rise. Also in this case the model is based on an existing 1D-network tidal flow model. The schematisation of the model is shown in Fig.6. As an example of the model results, the simulated bed level change after 25 years is shown in Fig.7. The results have also been used for

ecological modelling. For this purpose a two-dimensional interpretation is made of the simulated morphological changes in order to evaluate the changes of relevant habitats.

At present the study is still continuing. More detailed discussion on the morphological modelling for the Western Scheldt is given by Fokkink et al. (1996).

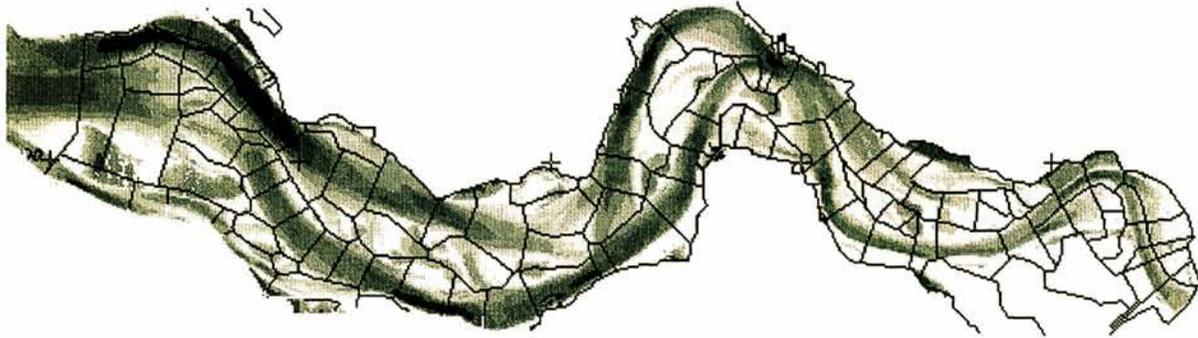


Fig.6 Schematisation of the Westernscheldt estuary

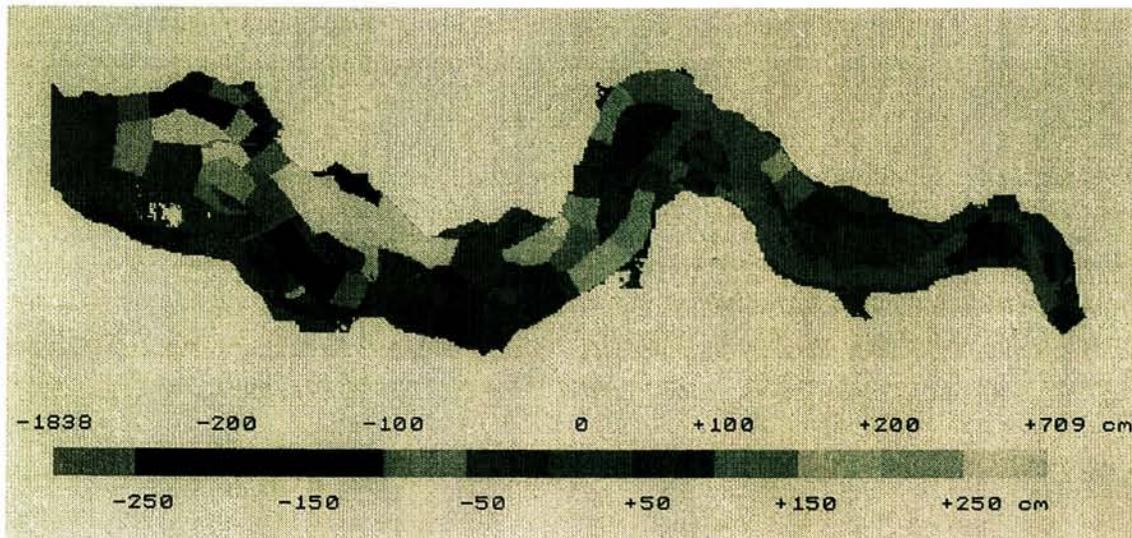


Fig.7 Computed bed level change after 25 year

CONCLUSIONS

A semi-empirical model for morphological changes in estuaries and tidal lagoons is developed on the basis of a one-dimensional network tidal flow model. The model uses well-established empirical relations between the morphological equilibrium state and integrated tidal flow parameters. The sediment is assumed to be transported primarily as suspended load.

Tidal flow is considered as the major force causing morphological changes, but the influences of other factors like sea level rise and human activities (e.g. dredging and dumping) can also be included. The model can be used for predicting morphological changes on a time scale of decades.

The model makes a distinction between the morphological changes in the channel and those on the inter tidal flats. Morphological changes on these flats are important for the ecosystem, and morphological changes in the channel for navigation.

For two extreme cases, a river flow without tidal action and a prismatic tidal basin without river input, the model behaves the same as the process-based morphodynamic models. This gives the confidence that the model is widely applicable to estuaries. In addition to the empirical relations defining the morphological equilibrium, the most important parameters determining the behaviour of the model are the overall equilibrium concentration, the vertical exchange velocity of sediment, the horizontal diffusion coefficient for sediment and the power in the equilibrium concentration formula.

The model has been applied to "Het Friesche Zeegat", a tidal inlet in the Wadden Sea, and The Western Scheldt, an estuary in the Southwest of The Netherlands. In the first case the morphological changes, especially in the channel, caused by the closure of a part of the tidal basin, have been successfully simulated by the model. Good agreement between the computed and observed changes of the cross-sectional areas of the channels has been obtained. In the second case the study is still going on but encouraging results have already been achieved in simulating the impact of dredging and dumping activities in the navigation channel.

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LONG-TERM MORPHOLOGICAL MODELLING FOR HUMBER ESTUARY WITH ESTMORF

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ABSTRACT

Within his task as a manager / regulator of an estuary, the responsible officer often has to ask how will this estuary look like in the future? How it will develop due to natural changes, such as sea-level rise or due to human made interventions such as harbour extensions, reclamation works etc., and how may these developments affect the variety of the estuarine functions? The hybrid long-term morphological model ESTMORF has been developed in particular to assist in answering these questions. A pilot application of this model to the Humber estuary in England is described in the present paper. The major purpose of the study is to evaluate the ability of the ESTMORF model for studying long-term morphological developments in estuaries and to provide morphological data for ecological assessments. As an example of human interference a hypothetical land reclamation project is considered. Sea level rise has been included with different rates. Simulations of 50 years have been carried out for analysing the impact of the land reclamation project in combination with sea level rise. The simulated morphological changes due to sea level rise of 0.2 m/century (the present situation) agree quite well with the observations. The ability of the model for studying impacts of an accelerated sea-level rise and of human interference is well demonstrated.

KEYWORDS

Humber ESTUARY, Long-term morphological modelling, Sea-level rise, Land reclamation.

INTRODUCTION

Within the framework of the EMPHASYS project, a strategic Estuaries Research Programme within the United Kingdom, the capabilities of various model systems are tested by applying them to various estuaries in UK (EMPHASYS Consortium, 2000). The objective of the first phase of the EMPHASYS programme is to demonstrate the possibilities and restrictions of the models. One of the model systems under consideration is the morphological model ESTMORF, which belongs to the hybrid class of the models. For testing its capabilities a pilot application to the Humber Estuary is carried out. The impact of sea level rise and a land reclamation project to the long-term morphological developments is studied by this pilot application.

HUMBER ESTUARY

The Humber estuary located at the eastern coast of England is a macro tidal estuary with a tidal range varying from 3 m during neap tide to 6 m during spring tide. The

long-term averaged total river inflow is $240 \text{ m}^3/\text{s}$ and under extreme conditions it can go up to $700 \text{ m}^3/\text{s}$. The estuary has a horizontal area (from Spurn Head to Trent Falls) of about 200 km^2 . The tidal prism at averaged tide is thus in the order of 900 Million m^3 , about 80 times the averaged river inflow during a tidal period. These figures indicate that the hydrodynamics of the estuary is dominated by the tidal flow.

A sediment budget for the estuary based on the data available within the EMPHASYS project (ABP, 1999) indicates that the long-term averaged sedimentation in the whole estuary is about 170 ton/tide, or about 0.1 million m^3/year , which is only a small fraction of the flood and ebb sediment transport at the mouth. The sedimentation in the estuary cannot compensate the volume increase due to relative sea-level rise in the estuary which is about 0.4 million m^3/year .

THE ESTMORF MODEL

The morphological modelling work is carried out with ESTMORF, a model for long-term morphological development of estuaries. This model is developed by WL | Delft Hydraulics in co-operation with The Dutch Rijkswaterstaat. The model is special designed for predicting the impact of natural development like sea level rise and of human interference e.g. land-reclamation, dredging works etc. to the long-term morphological development of estuaries.

ESTMORF is a hybrid type (semi-empirical) morphological model. It combines the description of physical processes (hydrodynamics & sediment transport) and empirical relations for morphological equilibrium, in order to obtain optimal description of the long-term morphological development. The model uses a one-dimensional network hydrodynamic model simulating the tidal flow. The simulated flow data are used to define the morphological equilibrium of the channels as well as the inter tidal areas. The deviation of the actual morphological state with respect to the morphological equilibrium and the flow data together determine the sediment transport and the morphological changes. Not only the changes in the channel but also the changes of the inter tidal areas are calculated by the model. More information of the ESTMORF model can be found in Wang et al (1998, 1999).

The schematisation of the ESTMORF-HUMBER model is shown in Fig.1. The model consists of one single branch representing the estuary from Spurn to Trent Fall. The branch is divided into 43 sections, with a length of about 1 to 1.5 km. The cross-section profiles of each section have been derived from the 1993 bathymetric data set using a GIS system.

IMPACT OF SEA-LEVEL RISE

Two simulations have been carried out for analysing the impact of sea-level rise over a 50 year period, one with a rate of 0.2 m/century and the other with 0.6 m/century. The volume change of various parts of the estuary according to the first simulation are shown in Fig.2, and that of the total estuary is shown in Fig.3.

Under the influence of sea level rise of 0.2 m/century sedimentation occurs in the estuary, as can be expected because sea level rise causes an over depth in the

estuary. However, the over depth needs to be built up first before the morphological development will compensate it. This explains the increasing rate of sedimentation in all the parts in time. After a period of about 35 years a dynamic equilibrium situation is established, indicated by the fact that the sedimentation rate becomes constant. The total sedimentation rate at the end of the simulation is about 0.18 million m^3/year . This is less than the volume increase by sea level rise (about 0.4 million m^3). There are two reasons for this. First, sedimentation can only occur if there is an over depth in the estuary, so there is a lag of the morphological reaction to the sea level rise. The second reason is that the tidal volume increases due to the sea level rise. This increase is due to two reasons. First, the storage area becomes larger at higher water level and thereby increasing the tidal prism at the same tidal range. Second, the tidal range within the estuary increases due to sea level rise. The low water at the upper end of the estuary rises less than the sea level rise whereas the higher water rises slightly more, causing an increase of the tidal range. At the dynamic equilibrium state the sedimentation rate is equal to the sediment demand.

The volume change of the total estuary according to simulation 2, with a sea-level rise rate of 0.6 m/century is shown in Fig.3 as well. The conclusions are similar with those from simulation 1. The sedimentation rate at the dynamic equilibrium state is about 0.43 million m^3/year . The time needed to reach this dynamic equilibrium is also for this case about 35 years.

IMPACT OF LAND RECLAMATION

The considered land reclamation causes a decrease of the tidal prism in the estuary. As the reclamation is located at the downstream part of the estuary, only for the few sections near the mouth a decrease of the tidal volume will occur. Further it also directly causes a decrease of the cross-sectional area of a number of sections, especially sections 2 and 3. This explains the simulated morphological development as shown in Fig.4. The largest changes occur in the vicinity of the land reclamation itself. Sedimentation occurs at section 1 because at this section the tidal volume decrease is more important than the decrease of the cross-sectional area. Erosion occurs in sections 2, 3 and 4, where apparently the decrease of the cross-sectional area is the dominant disturbance. The morphological time scale is relatively small, only in the order of about 5 years. This is due to the fact that the length scale of the reclamation is relatively small and that the estuary is morphologically very active.

The volume change of the whole estuary shows also that after the first morphological reaction of the estuary to the disturbance caused by the reclamation with a time scale of about 5 year, morphological change (erosion) with a much larger time scale continues to occur. This can be understood by examining the morphological development in the estuary in more detail. Upstream of the land reclamation first sedimentation occurs and later erosion occurs. Sedimentation in the first phase is due to the deposition of the material eroded in the sections located at the reclamation. When the erosion at the reclamation stops it is also logical that the deposited material then starts to erode. The erosion continues further even after that the original state is established. This is due to the fact that the land reclamation in combination with the induced morphological change have caused a change of the tidal volume further upstream.

Simulations have also been carried out for the land reclamation combined with different rate of sea-level rise. It appears that a combination of sea level rise and land reclamation cause a smaller morphological reaction because the effects of the two are opposite, and that superposition of the effects of land reclamation and those of the sea level rise gives a good estimation of the combined effects.

CONCLUSIONS

The following conclusions are drawn from the model results:

- With a constant sea level rise a dynamic equilibrium situation establishes. The time scale for this development is about 35 years. At this dynamic equilibrium state the sedimentation rate is equal to the sediment demand caused by the sea level rise.
- The sediment demand caused by a sea level rise of 0.2 m/century is according to the model results about 0.18 million m³/year. This is in the same order of magnitude as the observed sedimentation rate in the estuary.
- The sediment demand is smaller than the volume increase due to the sea level rise. This agrees with observation. The reasons of this are the lag between the morphological reaction to the sea level rise and that the tidal volume increases as sea level rise occurs.
- The increase of tidal volume is caused by increase of storage area in the estuary in combination of increase of the tidal range.
- The considered land reclamation causes an erosion at the direct vicinity of it. Downstream of the reclamation sedimentation occurs due to a decrease of the tidal volume. Upstream of the reclamation first sedimentation occurs and later erosion.
- The morphological time scale of the first reaction of the estuary to the land reclamation is about 5 years. This time scale is related to the length scale of the land reclamation itself. This first reaction causes a disturbance in the estuary of much larger length scale. Therefore there is a second reaction of the estuary with a much larger time scale.
- Combination of sea level rise and land reclamation causes a smaller morphological reaction because the effects of the two are opposite. Superposition of the effects of land reclamation and those of the sea level rise gives a good estimation of the combined effects.

The ability of the model to predict long-term morphological changes due to human interference as well as due to natural development such as sea level rise is well demonstrated by the pilot application. Due to the hybrid character (combining process modelling and empirical relations) of the model it supplies the information of long-term morphological development as well as changes of the hydrodynamic conditions, and takes into account the interaction between the two. For the morphological development the model gives not only the changes in the channel part of the estuary but also the changes of the inter tidal areas. All these information is also useful for e.g. ecological assessments. The model can thus supply many and

relevant information for engineering as well as management purposes of estuaries. This combined with the ease of the application of the model makes ESTMORF a powerful tool for managers of estuarine water systems.

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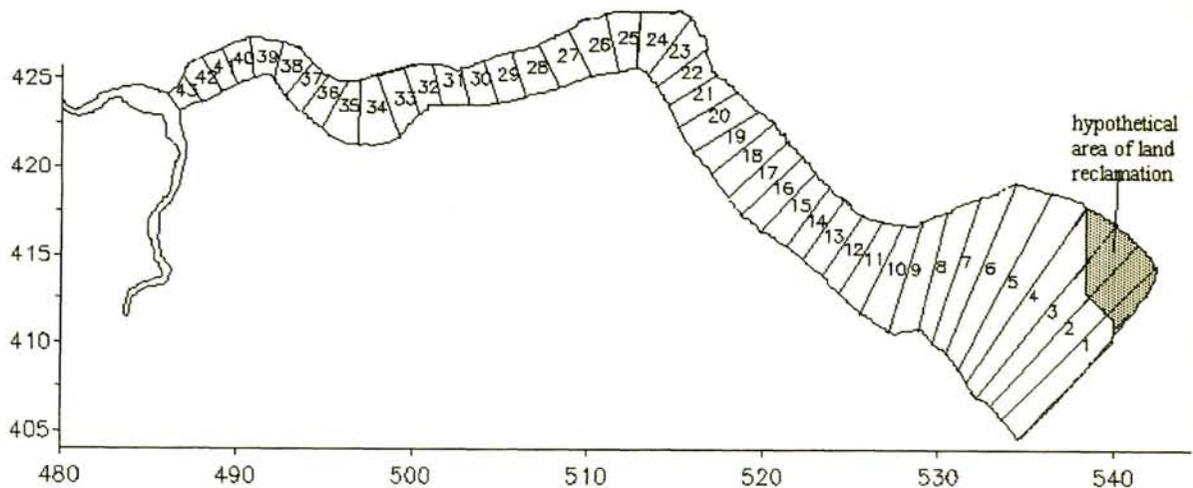


Fig.1 Humber estuary and model schematisation

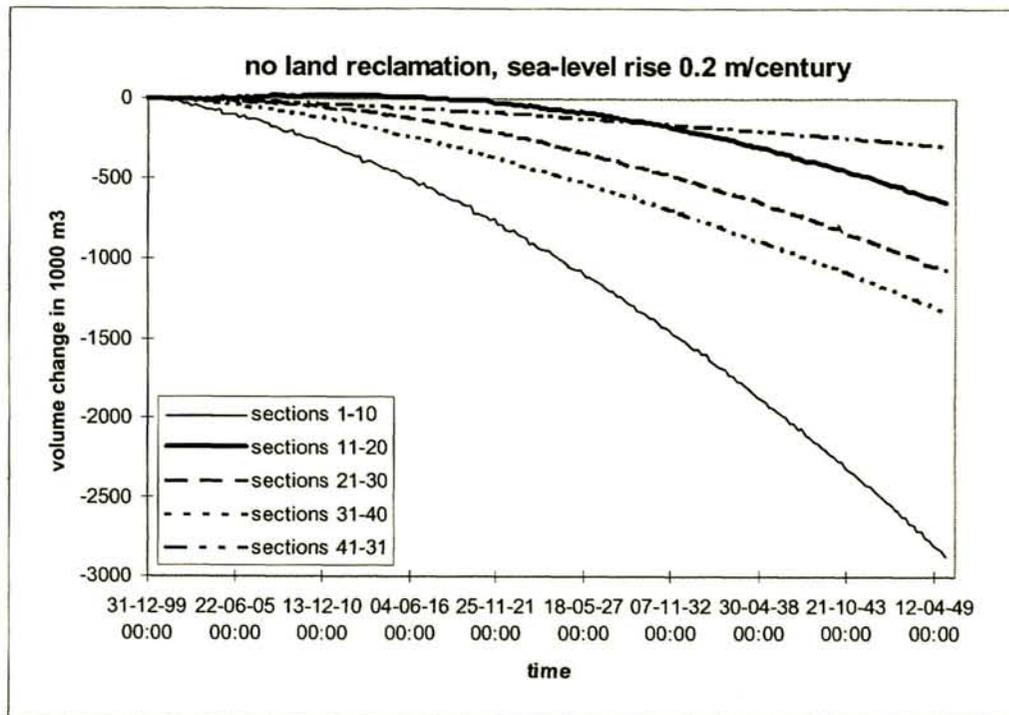


Fig.2 Simulated volume change various part of the estuary

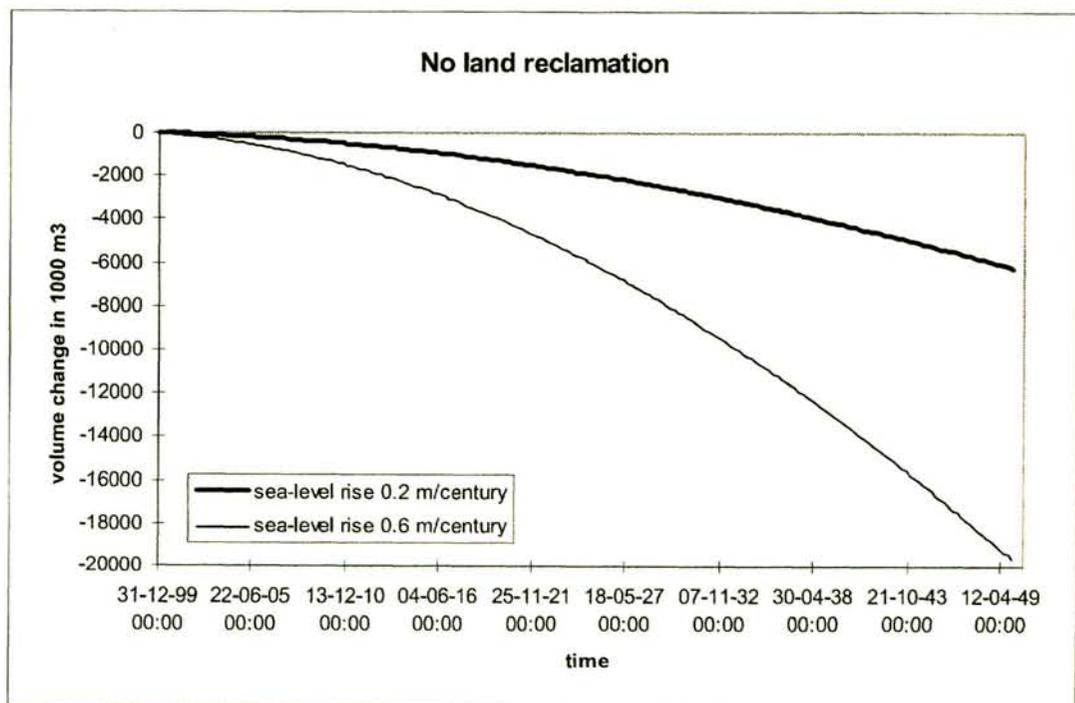


Fig.3 Simulated change of the total volume of the estuary due to sea-level rise

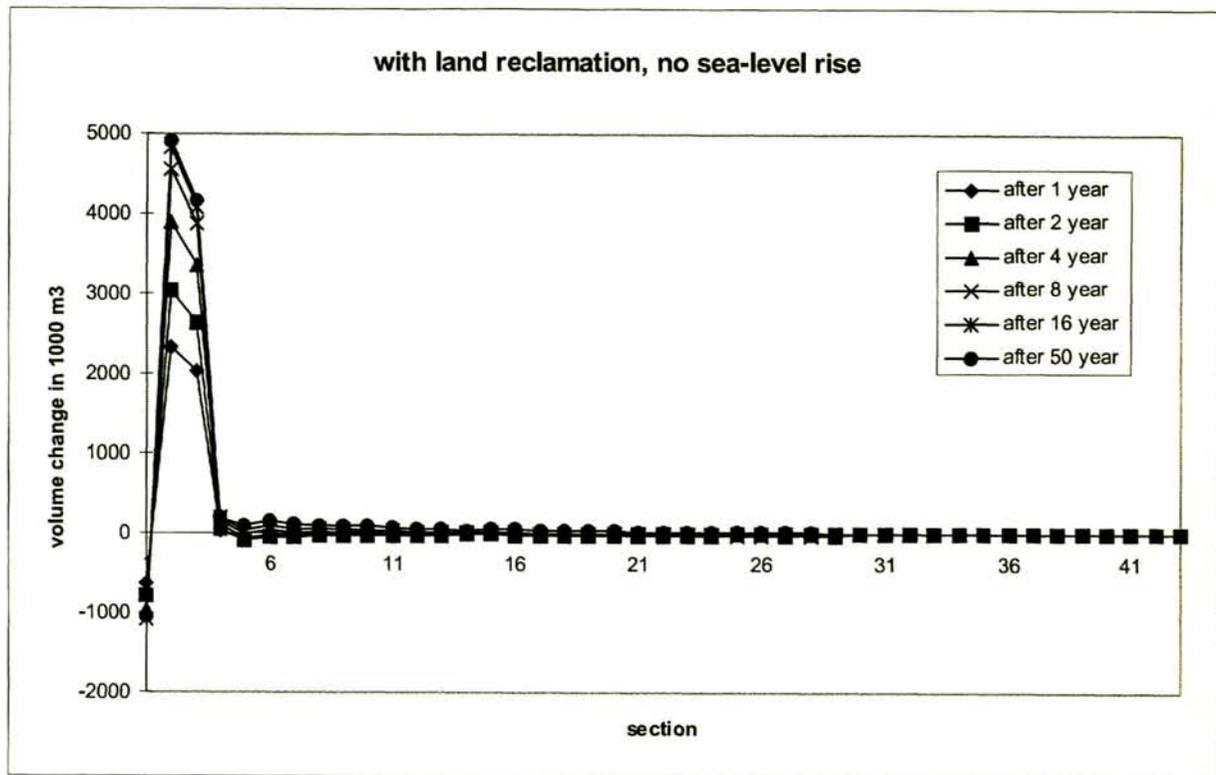


Fig.4 Simulated volume changes along the estuary due to land reclamation



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