Simulation of long-term morphological development in the Western Scheldt

Z.B. Wang[a,b], A. Langerak[c] & R.J. Fokkink[d]

[a] *WL | Delft Hydraulics, P.O. Box 177, 2600 MH Delft, The Netherlands*
[b] *Delft University of Technology, Faculty of Civil Engineering and Geosciences*
[c] *National Institute for Coastal and Marine Management, PO box 8039, 4330 EA Middelburg, The Netherlands*
[d] *Delft University of Technology, Faculty of Mathematics*

ABSTRACT

The geo-morphology of the Western Scheldt estuary, one of the two remaining open estuaries in The Netherlands, has been strongly influenced by human interference over a number of centuries. In recent years the dredging and dumping activities has increased from less than 0.5 Mm^3/year in 1950 to over 15 Mm^3/year in the 1975. In 1997 a second deepening program for the navigation channel is started and a new dredging program is initiated.

For the optimalization of the dredging and dumping operation and for the identification of the impact of the operation to the long-term morphological development of the estuary the ESTMORF model was built. ESTMORF is a program package for 1D network modelling of long-term morphological development of estuaries and tidal lagoons. It is based on empirical relations for the morphological equilibrium, combined with hydrodynamic and sediment transport models based on physical laws. The present paper describes the calibration / verification of Western Scheldt the model using data in the period 1968-1993.

1. INTRODUCTION

The Western Scheldt estuary, located in the south-west of The Netherlands, is one of the two remaining open estuaries in the Netherlands. The total length of the estuary is approximately 160 km, 60 km of which is Dutch territory (Fig.3). The estuary is 5 km wide at Vlissingen and gradually diminishes to 1 to 2 km at the border between The Netherlands and Belgium.

The morphological development of the estuary has been far from natural as it has been continuously influenced by human interference ever since data is available (around 1600). In the early days (before 1950) land reclamation was the most important human interference. Since the middle of the 20^{th} century dredging activities, required for deepening and maintaining the navigation channel to Antwerp, has become the most important human interference influencing the morphology of the estuary. The total dredging amount in the estuary has increased from 0.5 Mm^3/year in 1950 to over 15 Mm^3/year during the first deepening period (1970-1975) (Van den Berg[1]). At present a new deepening program, increasing the minimum water depth from 14.5 m to 16 m below mean sea level, is being carried out.

The intensified dredging and dumping activities will not only influence the morphology of the estuary, but they will also have influence on the other management aspects e.g. flood control and ecological system. Various mitigation measures have been proposed against the negative effect of this human interference. The mitigating measures include various dredging-dumping strategies and increasing tidal volume by sacrificing polders to the estuary.

To investigate the impact of the dredging activities to the morphological development and to evaluate the effect of the mitigating measures a series of mathematical models have been employed, ranging from 1D to 3D, from behaviour-oriented to process-based (De Jong[2], Wang[3], Verbeek[4]).

Among these models the ESTMORF model is used to simulate long-term, large scale morphological development of the estuary. At present this model is applied for evaluating various dredging and dumping strategies. The present paper will focus on the calibration / verification of the model.

2. MODEL DESCRIPTION

ESTMORF is a 1D network model for predicting long-term morphological development of estuaries and tidal lagoons. 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 WL | DELFT HYDRAULICS.

2.1 Model concept

The model consists of two modules, a hydrodynamic module and a morphological module. For the hydrodynamic module the existing 1D network hydrodynamic model IMPLIC is used, which supplies the tidal levels, tidal volume and residual flow field to the morphological module.

A detailed description of morphological module is given by Wang. Here a brief description of the model concept for the morphological module is given.

The basic principle of the model can be summarised as follows:

- At each time step, a morphological equilibrium state exists if the hydrodynamic condition is given.
- The net sediment transport can be described by advection-dispersion equation based on residual flow field. A consequence is then that there exists an overall equilibrium sediment concentration that is present in the whole model area when the whole system is in equilibrium.
- When an area is out of equilibrium, a tendency of sedimentation or erosion exists. This is expressed in the locally adjusted equilibrium concentration.
- The exchange between the bottom and water, thus also the morphological change, is determined by the difference between the local concentration en de local equilibrium concentration.

The model uses an existing 1D network flow model as flow module. Therefore the modelling area is schematised into a network consisting of branches. The cross-sections of each branche is divided into three parts: the channel part (under the low water level, MLW), the low tidal flat between MLW and the mean sea level (MSL), and the high tidal flat between MSL and the high water level (MHW) (Fig.1).

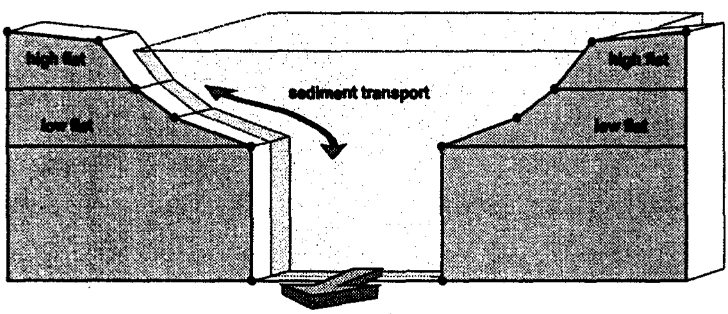


Fig.1 Schematisation of the cross-section

The model schematisation can be considered as a network consisting of morphological elements connected to each other. The morphological model concept is illustrated by giving the discretized equations. For each element a variable describing the morphological state is defined, cross-sectional area for the channel elements and heights for the tidal flat elements. For simplicity reason the wet volume is used here as a variable for all elements. Furthermore per element a sediment concentration c, and an equilibrium concentration c_e are defined. The following equations apply per element:

Morphological equilibrium:

$$V_e = f(hydrodynamic\ parameters) \tag{1}$$

Equilibrium concentration:

$$c_e = c_E \left(\frac{V_e}{V}\right)^n \tag{2}$$

Mass-balance in the water phase:

$$\sum_i T_i = w_s A(c_e - c) \tag{3}$$

Morphological change:

$$\frac{dV}{dt} = w_s A(c_e - c) - I + A\frac{d\zeta}{dt} \tag{4}$$

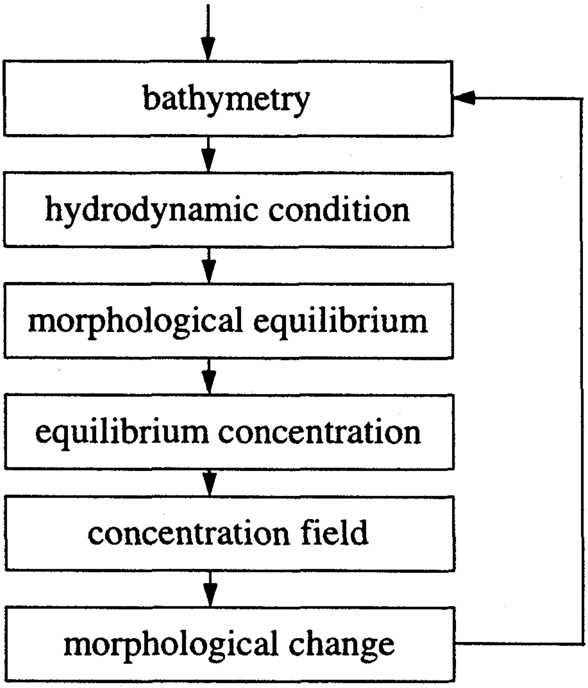
The transport in equation (3) is defined per connection between two elements. This consists of a diffusive part and an advective part (due to residual flow):

$$T = \delta(c_1 - c_2) + Q(c_1 + c_2)/2 \tag{5}$$

In these equations

V_e	= equilibrium volume.
c_E	= overall equilibrium concentration,
n	= constant.
T_i	= transports along the boundaries of the element (outgoing is positive),
A	= horizontal area of the element,
w_s	= exchange velocity between water en bottom.
I	= dredging and dumping (dumping = positive);
ζ	= sea level.
T	= transport from element 1 to element 2,
δ	= horizontal exchanging coefficient between the two elements due to dispersion, determined by the dispersion coefficient, etc.
Q	= discharge of residual flow from element 1 to element 2.

At an open boundary the transport is determined in the same way. The concentration outside the model area should be given as boundary condition and it is usually assumed to be equal to the overall equilibrium concentration. At a closed boundary the transport equals zero.



The computational procedure in the model is as shown in Fig.2. At each time step the equilibrium volumes of the element are determined first from the hydrodynamic parameters (1). Then the equilibrium concentrations per element are determined with equation (2). The concentrations in the elements are determined by solving a system of equations, which is set up by substituting (5) into equation (3). Then the morphological change can be determined from equation (4).

Fig.2 Computational procedure

2.2 Western Scheldt model

The Western Scheldt model is based on an existing 1D network tidal flow model for the estuary, the IMPLIC model. The model schematisation in the Dutch part of the estuary is shown in Fig.3.

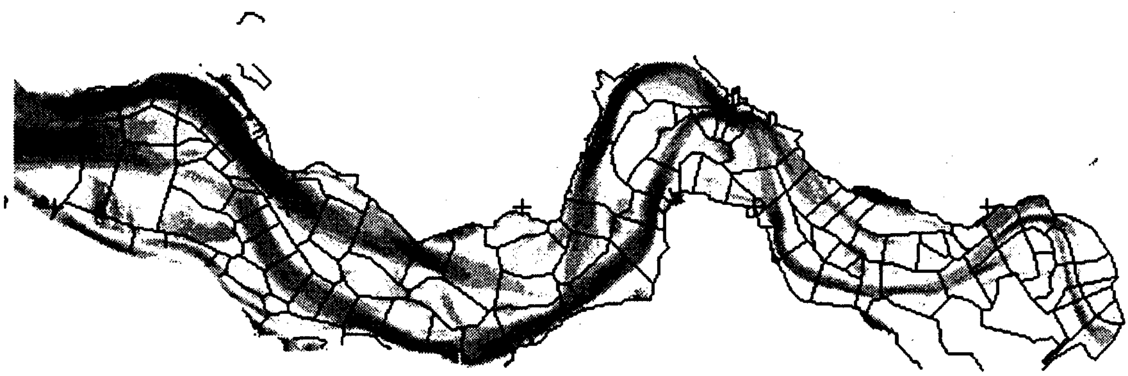


Fig.3 Schematisation of the Western Scheldt model

3. CALIBRATION OF THE WESTERN SCHELDT MODEL

3.1 Calibration data

The model is calibrated using data collected in the period 1968-1993. A overview of the total morphological change in this period is given in Fig.4. The depicted morphological change is a result of human interference in combination with natural development. The major human interference in this period is dredging and dumping for improving and maintaining the navigation channel. Figure 5 shows a overview of the dredging and dumping activities carried out during this period.

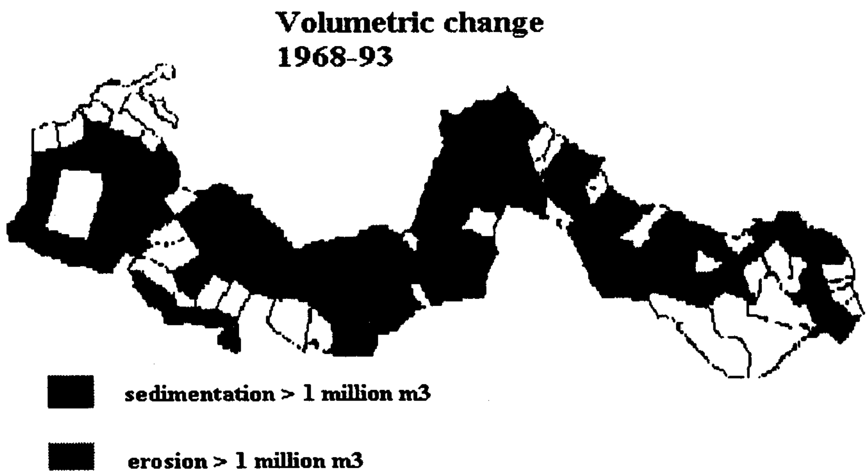


Fig.4 Morphological changes in the Western Scheldt, expressed as volume change per model branch

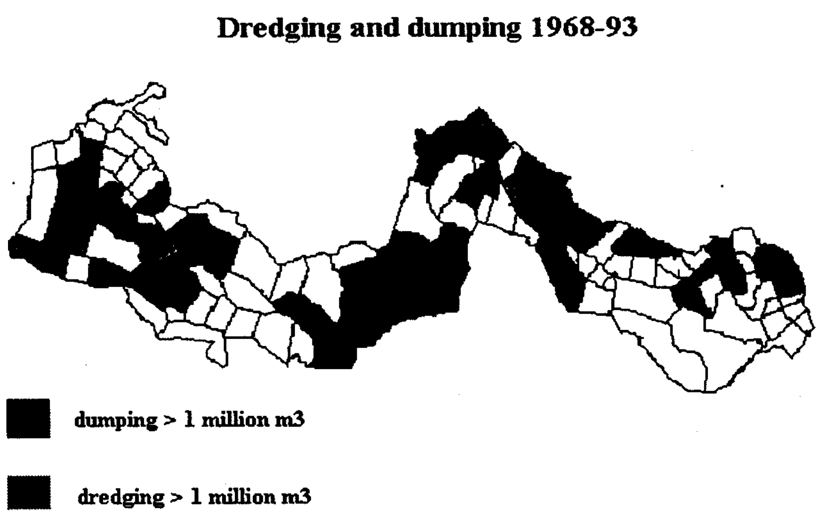


Fig.5 Dredging and dumping activities in the Westerschelde during 1968-93 expressed per model branch

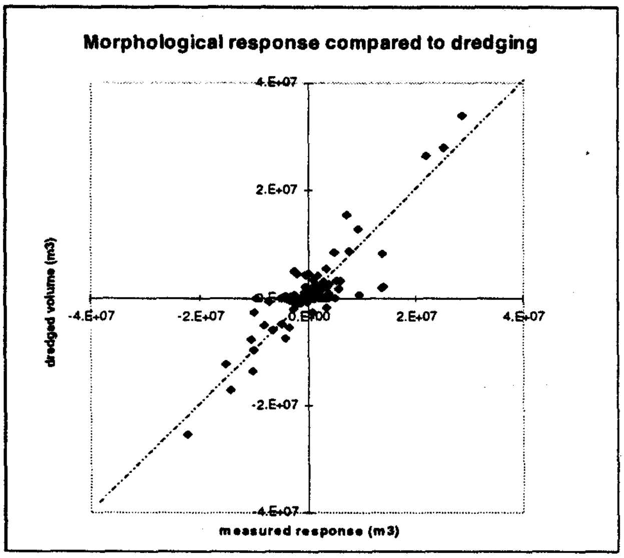


Fig.6 Measured morphological response related to dredging and dumping

The dredging and dumping activities have had an important impact to the morphological development of the estuary as shown in Fig.6, in which the measured morphological response is related to the amount of dredging. The morphological response is defined as the dredged volume minus the volume change of the branch. Physically it means the volume change of the branch due to sedimentation. The figure shows that the morphological response is well correlated to the dredging activities. Especially in the branches where the amount of dredging (or dumping) is large, the dredged volume is almost completely balanced by the morphological response.

3.2 Calibration procedure

Two categories of physical parameters in the model can be distinguished, which are varied during the calibration process. The first category includes the parameters in the empirical relations determining the morphological equilibrium. The second category includes the parameters influencing the morphological time scale of the model: c_E, w_s, dispersion coefficients, etc. As the two categories of parameters determine two different aspects of the model they have been calibrated in two steps.

First the coefficients determining the morphological equilibrium have been adjusted. To start with, the situation in 1968 is assumed to be in equilibrium first. Then the estuary is divided into a number of morphological sub-systems and the coefficients are adjusted per sub-system in order to obtain the roughly correct sedimentation-erosion pattern. Finally the coefficients in a number of branches, which still do not have the correct morphological response, haven been adjusted. After this step the total morphological changes in the whole period are well reproduced by the model.

Then the parameters determining the morphological time scale of the model are adjusted till the simulated morphological development in time agrees with the data. These parameters are also adjusted step by step. First they are kept uniform over the whole model area and adjusted such that the overall time scale is correct. Then the parameters are changed per sub-regions and finally they have been adjusted for a number of “problem-branches”. During this step the results of the analysis on the morphological time scale is used (Wang[3]).

3.3 Results of hind-casting

The final results are presented in Fig.7, Fig.8 and Fig.9. Figure 7 shows an overview of the computed sedimentation-erosion pattern and a comparison between the computed and measured morphological response is made in Fig.8.

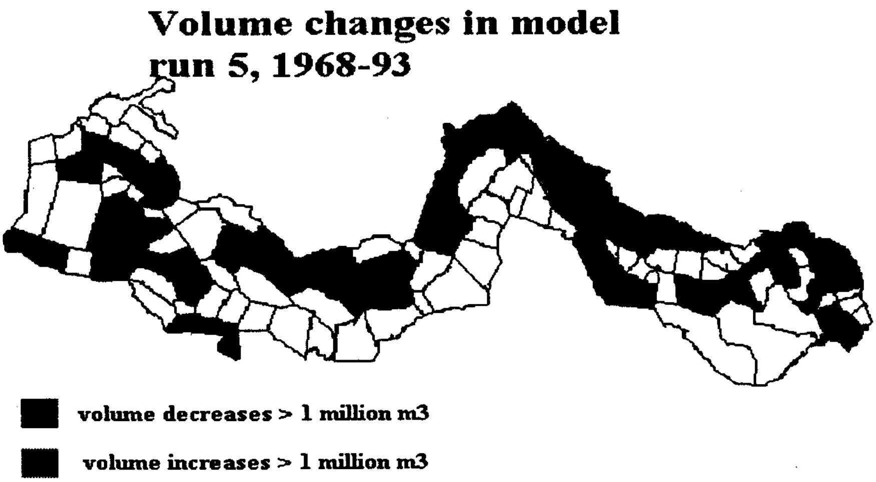


Fig.7 The simulated sedimentation/erosion pattern

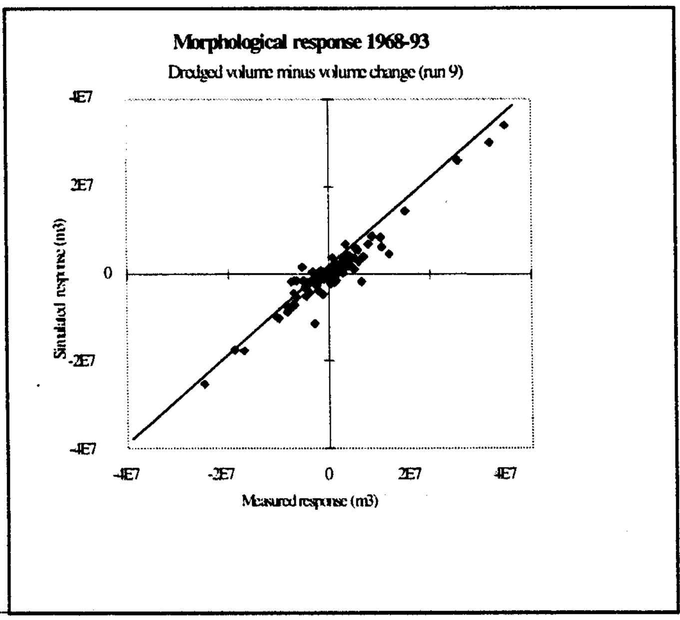


Fig.8 Computed and measured morphological response

Form Fig.8 it can be observed that the agreement between the simulation and measurement is better for branches with relatively large morphological responses than for those with almost no morphological response. This means that the model simulates the forced response to dredging and dumping better than the natural development within the estuary.

Figure 9 presents the computed and measured morphological development in time of a number of branches. Per branch the dredging and dumping activity is also depicted by presenting the change of the volume only due to dredging / dumping, i.e. if there is no morphological response. It is shown that the time scale of the morphological response is correctly reproduced.

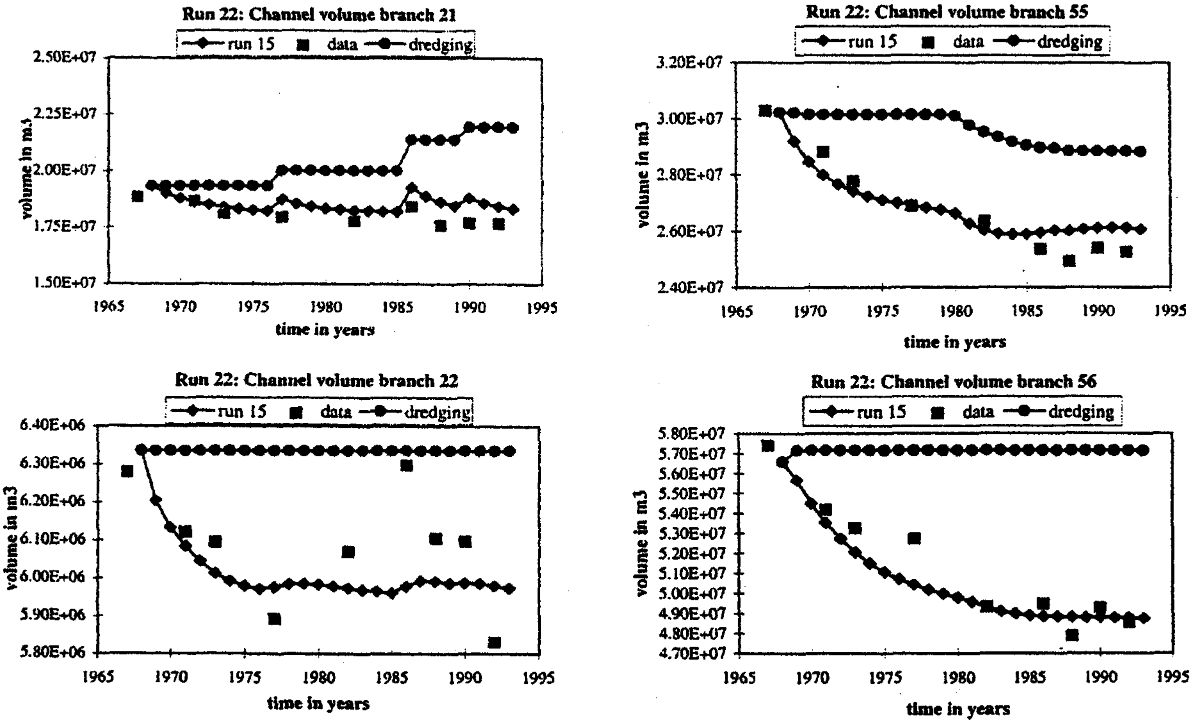


Fig.9 Morphological change in time

4. CONCLUDING REMARKS

The ESTMORF model for the Western Scheldt has been calibrated using the data collected in the period 1968-1993. The model appears to reproduce the morphological responses to the dredging and dumping activities in the estuary well. Therefore it is a useful tool for evaluating various dredging / dumping strategies in the estuary.

The model is less capable in predicting small natural morphological changes in the estuary. This can partly be explained by the fact that the data in the branches with small morphological changes are less accurate.

Another restriction of the model is that the structure of the network is fixed during the simulations, which implies that genesis of new channels cannot be reproduced by the model. This may restrict the time span of predictions.

At present the model is applied to predict the impact of the recently started dredging programme for deepening the navigation channel to Antwerp, and to evaluate the various designed dumping strategies.

REFERENCES

1. Van den Berg, J.H., M.C.J.L. Jeuken & A.J.F. van der Spek (1996), Hydraulic processes affecting the morphology and evolution of the Westerschelde estuary, in: *Estuarine Shores: Evolution, Environments and Human Alternations*, chapter 7, edited by K.F. Nordstrom & C.T. Roman.
2. De Jong, K., 1998, *Tidally averaged transport models*, Ph.D. thesis, Delft University of Technology.
3. Wang, Z.B., Karssen, B., Fokkink, R.J. and A. Langerak, 1998, A dynamic/empirical model for long-term morphological development of estuaries, in Dronkers J & M. Scheffers (editor), *Physics of estuaries and coastal seas*, Balkema, Rotterdam, 1998.
4. Verbeek, H., Wang, Z.B., & P.M.C. Thoolen, 1999, Secondary currents in estuarine morphodynamic modelling, a case study of the Western Scheldt, this volume.