A dynamic/empirical model for the long-term morphological development of estuaries

Part I: Physical relations

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delft hydraulics

Contents

List of symbols

A_b = tidal basin area $[m^2]$
A_c = cross-sectional area of the channel $[m^2]$
A_l = cross-sectional area above low tidal flat $[m^2]$
A_h = *cross-sectional area above high tidal flat* $[m^2]$
A_{MSL} = cross-sectional area below mean water level $[m^2]$
A_{MSLe} = equilibrium value of A_{MSL} $[m^2]$
c_c = sediment concentration by volume in channel [-]
c_{ce} = equilibrium value of c_c,
depending on the cross-section involved [-]
c_l = sediment concentration by volume above low flat [-]
c_{le} = equilibrium concentration above the low flat [-]
c_h = sediment concentration by volume above high flat [-]
c_{he} = equilibrium concentration above the high flat [-]
C_E = overall equilibrium sediment concentration [-]
D_c = dispersion coefficient in the channel $[m^2/s]$
D_l = dispersion coefficient between channel and flat $[m^2/s]$
D_h = dispersion coefficient between low and high flat $[m^2/s]$
F_{lc} = exchange rate between channel and low flat $[m^2/s]$
F_{hl} = exchange rate between low and high flat $[m^2/s]$
H_l = height of the low tidal flat [m]
H_{le} = *equilibrium height of the low tidal flat* [m]
H_h = height of the high tidal flat [m]
H_{he} = equilibrium height of the high tidal flat [m]
L_{lc} = distance between centre of channel
and that of low flat [m]
L_{hl} = distance between centre of high flat
and that of low flat [m]
n_c = constant [-]
n_l = constant [-]
= constant [-]
P_v = virtual tidal volume $[m^3]$
t = time [s]
u = residual flow velocity [m/s]
W_c = width of the channel [m]
W_l = width of the low tidal flat [m]
W_h = width of the high tidal flat [m]
w_s = coefficient having the dimension of "fall velocity" [m/s]
x = *horizontal coordinate* [m]
z = bed level [m]
Δh_l = difference between low water and mean water level [m]
Δh_h = difference between mean water level and high water [m]

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1 Introduction

The Directoraat-Generaal Rijkswaterstaat/Dienst Getijdewateren of the Ministry of Public Works and Transport (RWS/DGW) is interested in morphological models predicting the consequences of (human) interference (e.g. dredging, land reclamation) in the geometry of estuaries.

Two types of models are considered:
- a one-dimensional middle long-term model to predict the morphological development in estuaries for a period of 20 to 30 years.
- a one-dimensional long-term model to predict the morphological development in estuaries for a period of 50 to 100 years.

The middle long-term model (called EENDMORF) is studied in the project DYNASTAR, which is now in the phase of determination of the mathematical and physical properties of the model to be developed.

The long-term model (called ESTMORF), which is the subject of this note, is also studied in the project DYNASTAR. For the latter RWS/DGW commissioned DELFT HYDRAULICS in August 1991 to perform a preliminary study and a literature survey on the subject of the long-term model, as part of the project DYNASTAR. These studies were completed with a note and a report, respectively (Karssen and Wang, 1991a/b).

In Karssen and Wang (1991a, 1991b) two concepts are evaluated for a dynamic-empirical morphological model like ESTMORF: the concept of Di Silvio and the concept of Allersma. Both concepts have their advantages and disadvantages. In Karssen and Wang (1991b) it was concluded that a combination of both concepts in one model would probably result in a model with the required properties.

In Karssen and Wang (1992) the "combined" model concept described above is worked out and it is compared with a concept based on the model of Van Dongeren (1992) (see Langerak, 1992), which can be considered as a improved version of the model of Allersma (1988). It was recommended to add the experience obtained from the application of the model of Van Dongeren to the "combined" model.

In the framework of the ISOS*2-project Eysink (1992) formulated another concept which uses a more sophisticated schematisation of the geometry but uses a less sophisticated formulation for the sediment transport process than in the concept suggested by Karssen and Wang (1992). This more sophisticated schematisation will be implemented in the "combined" model.

With letter GWAO-92.60108, dated 26 November 1992, RWS/DGW commissioned DELFT HYDRAULICS to carry out a part of the development of the so defined model. The first step is to verify the choice of the model concept and work out the physical relations in the model in detail taking into account the work carried out in the ISOS*2-project (Eysink, 1992).

This report contains a description of the model concept and a verification of the choice of the concept. In Chapter 2 the assumptions and requirements of the model are described. Chapter 3 contains the detailed description of the physical relations of the model concept, whereas in Chapter 4 the choice of the present concept is verified. Finally, in Chapter 5 the conclusions and recommendations are summarised.

This study was performed by R. Bruinsma, R. Fokkink, B. Karssen and Z.B. Wang under the guidance of A. Langerak from RWS. The report is drawn up by B. Karssen and Z.B. Wang. The contributions and comments on the concept version of this report of E. Allersma, W. Eysink, A. Langerak and H.J. De Vriend is sincerely acknowledged.

2 Assumptions

2.1 Introduction

The purpose of the development is to obtain a model that can predict rough changes in the geometry of the Western Scheldt and the Friesche Zeegat on a time scale of 50 to 100 years due to (human) interference. Examples of human interference are: dredging, dumping and mean sea level rise (also considered as human interference).

The model will be based on a combination of an already existing one-dimensional flow model and a morphological module using empirical relations, i.e. a dynamic/empirical model (Karssen and Wang, 1991b).

2.2 Assumptions

The alternative model concept is based on the following assumptions:

a. The changes in morphology in the estuary tend to reach an equilibrium on a long-term time scale. This equilibrium situation can be described by simple empirical formulae.
b. The time process of adjustment to the equilibrium is governed by an advection-diffusion equation for sediment in which source terms (due to erosion and sedimentation) depending on the difference between the equilibrium situation and the present situation are included.
c. Both advection and diffusion are incorporated in the sediment transport. This means that the disturbances are not only transported in the direction of the net flow, but also dispersed by concentration gradients.
d. The local cross-sectional area, the tidal flat height (divided into a low and a high tidal flat) and the area of the tidal flat characterize the morphology of the area of interest sufficiently.
   The hydraulic model though, will need a more elaborate description of the estuarine profile.
e. The advective transport of sediment in longitudinal direction only takes place in the channels. This means that there is no exchange between neighbouring tidal flats and that lateral transport is only possible between the channels and the adjacent tidal flats through dispersion.
f. The sediment in the estuary consists only of middle fine sand.
g. Availability of sediment is not a constraint. This means for instance that the ebb tidal delta will be considered as an unlimited source of sediment, i.e. separate modelling of the ebb tidal delta is not necessary.

2.3 Dependent parameters

The dependent variables of the model are the cross-sectional area of the channel part, the height of the low tidal flat and the height of the high tidal flat.

From these three variables the following dependent parameters that have to be used in the flow module can be derived:

- A(x,h), the cross-sectional area at spatial coordinate x as a function of the water elevation h.
- B(x,h), the storage area at spatial coordinate x as a function of the water elevation h.
- d(x,h), the average depth at spatial coordinate x as a function of the water elevation h.
- C(x,h), the bed resistance at spatial coordinate x as a function of the water elevation h.

The cross-sectional area A can be separated in the average cross-sectional area A_g over the channel section and the difference between the begin and end cross-sectional area of the channel section ΔA.

2.4 Functional requirements

The functional requirements are determined by the applications that are foreseen or the types of human interference that have to be modelled. The most important applications foreseen for the model are the study of the effects of sea level rise in the Wadden Sea and the study of an alternative management of the Western Scheldt.

The study of the Wadden Sea focuses on the consequences of an increase of sea level rise from 20 cm/century to 60 cm/century on the geometry of the tidal basin. Furthermore, the consequences of the increase of the tidal range at a rate of 15 cm/century and the consequences of the 18.5 year periodic tidal cycle on the geometry will be studied.
The Wadden Sea model will be calibrated on the situation of the closure of the Lauwerszee as a major human impact.

The study of the Western Scheldt focuses on the consequences of the dumping of sediment in the secondary channels, dredging and enlargement of the storage area.
The Western Scheldt model will be calibrated on the period of depth increase (1968-1980).

With respect to above applications, the model should be able to incorporate the following effects:
- gradual increase of the mean sea level;
- gradual increase of the tidal range;
- 18.5 years periodic tidal cycle;
- abrupt closure of channels;
- local withdrawal of sediment from the channel bed, tidal flat and channel bank (dredging);
- local dumping of sediment on the channel bed, tidal flat and channel bank;
- local fixing of the channel width;
- local fixing of the channel depth;
- abrupt change of the local storage area;
- land reclamation by a degression of the basin area at high water, to be given by user via initial schematisation.

3 Physical relations

3.1 Introduction

This chapter contains the physical relations of the model concept worked out in this report. It is noted that only the morphological module is worked out: the flow module of the model will consist of an already existing one-dimensional flow model.

A dynamic/empirical model for morphological development as the one described here can be characterised by three factors: the schematisation of the geometry, the empirical relations defining the equilibrium state and the formulation of the time process of the morphological development when the equilibrium is disturbed. The present model concept is based on a combination of the schematisation of the geometry suggested by Eysink (1992) and the concept of morphological development process suggested by Karssen and Wang (1992). The needed empirical equilibrium relations will be based on the available information in the literature.

The morphological development in the estuary is described by the change of the cross-sectional area of the channel, the area of the tidal flat and the height of the tidal flat.

The tidal basin is assumed to have fixed geometrical boundaries during the whole simulation. In reality this assumption not always holds. In view of the type of model to be developed this assumption is, however, essential. Non-fixed boundaries would change the model concept drastically and would require extra study. It is therefore decided to use a fixed tidal basin area in the alternative model, similar to the concept of Van Dongeren (1992). The tidal basin area is divided in the channel area, the low and the high tidal flat area, which are all subdivided in sections with lengths that remain fixed during the computation (see Figure 1).

3.2 Geometry schematisation

The model will use an existing 1D network flow model as flow module. Therefore the modelling area will be schematised into a network consisting of branches.

The cross-sections of the branches are schematised as shown in Figure 2. (Note that in the figure the tidal flat is shown only on 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 shape. The two parts of the tidal flat are described by their widths as well as their heights. Each part is schematised into two straight lines as shown in Figure 2 and the joint point of the two lines (C for the low tidal flat and E for the high tidal flat) is defined such that it has the height of the tidal flat part as vertical coordinate. The cross-sections is thus defined by the coordinates of six points (A-F), leading to 12 parameters.

The morphological module of the model uses three variables: the cross-sectional area under the mean water level, the height of the low tidal flat and the height of the high tidal flat. For these three variables there exist empirical relations for the equilibrium situation (Eysink, 1992). It is noted that to use these empirical relations, the cross-sectional area under the mean water level also includes the low part of the tidal flat.

The total change of a cross-section can be divided into two parts:

- a change due to sedimentation/erosion,
- a change due to modification of the relative water level (sea level rise/land subsidence).

These changes will have to be translated into a change in the 12 parameters determining the shape of the cross-section. Therefore, a "profile module" has to be developed that describes the new values of the 12 parameters after a morphological time step. In this module the two parts of the changes are treated separately.

Sedimentation/Erosion

The needed 12 relations for determining the 12 parameters consist of definitions, mass-conservation laws and assumptions.

The following definitions are relevant for adjusting the cross-sectional profile due to sedimentation and erosion:

- Point B is defined at MLW, which implies that the vertical coordinate of B does not change.

- Point D is defined at MSL, which implies that the vertical coordinate of D does not change.

- Point F is defined at MHW, which implies that the vertical coordinate of F does not change.

- Point C is defined such that its vertical coordinate represents the average height of the low tidal flat. This gives a relation between the horizontal coordinate and the vertical coordinate of C.

- Point E is defined such that its vertical coordinate represents the average height of the high part of the tidal flat. This gives a relation between the horizontal coordinate and the vertical coordinate of E.

The following mass-conservation laws have to be satisfied:

- The change of the cross-sectional area of the channel part (under MLW) is given, yielding one of the relations from which the new coordinates of point A can be determined.

- The total sedimentation or erosion at the low tidal flat is given, yielding a relation from which the new vertical coordinate of C can be determined.

- The total sedimentation or erosion at the high tidal flat is given, yielding a relation from which the new vertical coordinate of E can be determined.

The definitions supply 5 and the mass-conservation laws supply 3 relations. Thus 4 more relations have to follow from assumptions. For the time being the following assumptions are chosen:

- No morphological change occurs above MHW, thus the horizontal position of point F does not change.

- The side slope (AB) of the channel part does not change.

- The horizontal coordinate of B is equally influenced by the change of the channel part and the change of the low tidal flat part. The horizontal position of B is thus determined as follows: First both the channel part and the low tidal flat part move vertically due to the determined sedimentation/erosion. Two points can then be determined at the low water line (see Figure 3). The new position of B is exactly in between these two points.

- The horizontal coordinate of D is equally influenced by the change of the change of the low tidal flat part and the change of the high tidal flat part. The horizontal position of D is thus determined as follows: First both the high and the low tidal flat part move vertically due to the determined sedimentation/erosion. Two points can then be determined at the mean water line. The new position of D is exactly in between these two points.

Water level change/Land subsidence

For the case of the change of the water levels again the following definitions are relevant:

- Point B is defined at MLW, which implies that the change of the vertical coordinate of B is equal to the change of the low water level.

- Point D is defined at MSL, which implies that the change of the vertical coordinate of D is equal to the change of the mean water level.

- Point F is defined at MHW, which implies that the change of the vertical coordinate of F is equal to the change of the mean high water.

- Point C is defined such that its vertical coordinate represents the average height of the low tidal flat. This gives a relation between the horizontal coordinate and the vertical coordinate of C.

- Point E is defined such that its vertical coordinate represents the average height of the high part of the tidal flat. This gives a relation between the horizontal coordinate and the vertical coordinate of E.

The mass-conservation law supplies the following relations:

- The total amount of sediment below the new MLW does not change.
- The total amount of the sediment between the MLW and the new MSL does not change.
- The total amount of the sediment between the new MSL and the new MHW does not change.

Further the following 4 assumptions are added:

- The horizontal coordinate of A does not change.
- The vertical coordinate of A does not change.
- The new horizontal coordinate of D is determined by the intersection point of the new MSL and the old cross-sectional profile.
- The new horizontal coordinate of F is determined by the intersection point of the new MHW and the old cross-sectional profile (The part above the old MHW has a fixed slope).

Land subsidence can be first treated as increase of water levels (MLW, MSL and MHW) with the same magnitude. Then the vertical coordinates of all the six points are lowered with the subsidence value.

The present schematisation differs from the one described by Karssen and Wang (1992) in two aspects. First the schematisation gives more detail about the cross-sections. Second, no more explicit relations are needed for the width of the channel and that of the tidal flat. The widths follow automatically from the procedures described above. This may be an improvement because the empirical relations describing the equilibrium widths usually have a poor accuracy (Eysink and Biegel, 1992). However, the suggested "profile" module needs some assumptions as described above. If the formulated assumptions differ too much from reality an unrealistic development of the shape of the cross-section may be obtained from the model. If necessary these assumptions can be modified during the calibration of the model.

3.3 The equilibrium state

As the morphological module works with three variables, three empirical relations are required in order to define the equilibrium state of the system: one for the cross-sectional area (under mean water level), one for the height of the low part of the tidal flat and one for the height of the high part of the flat.

The equilibrium cross-sectional area of the channel (under MSL) is related to the tidal volume. For the Wadden Sea Eysink (1992) recommends the following relations:

$$
\begin{aligned}
A_{MSLe} &= 448.10^{-6} P_v^{0.9} - 157 \quad \mathit{for}\ P_v > 5.10^6\ m^3 \\
A_{MSLe} &= 64.4\ 10^{-6} P_v \qquad\qquad \mathit{for}\ P_v < 5.10^6\ m^3
\end{aligned}
\tag{1}
$$

Herein				
	A_{MSLe}	=	equilibrium cross-sectional area under MSL	[m^2]
	P_v	=	virtual tidal volume.	[m^3]

The equilibrium heights of the two parts of the tidal flat are related to the total area of the basin. Eysink (1992) recommends the following relations for the Wadden Sea:

$$H_{he} = \Delta h_l + \frac{0.165}{1+10^{-8} A_b} \Delta h_h \tag{2}$$

$$H_{le} = 0.347\ \Delta h_l \left(1 + \frac{1}{1+10^{-8} A_b}\right) \tag{3}$$

In these two equations

H_{he}	=	equilibrium height of the high flat measured from mean low water,	[m]
H_{le}	=	equilibrium height of the low flat measured from mean low water,	[m]
Δh_l	=	difference between MSL and MLW	[m]
Δh_h	=	difference between MHW and MSL	[m]
A_b	=	total area of the basin.	[m^2]

In equations (1) through (3) specific relations with specific coefficients are defined for the equilibrium value of the three variables. However, these coefficients only apply for the Wadden Sea. For another area, e.g. the Western Scheldt, other values (or even the form of the relations) have to be chosen based on the field data. This part of the model will be kept as flexible as possible in order to guarantee a wide applicability of the model. The coefficients in the equations will also be allowed to vary in the area such that an existing equilibrium state can be represented in the model.

3.4 Morphological development

When the system is not in equilibrium, morphological changes will occur. The morphological development is described by a concentration model in the present concept. The sedimentation and/or erosion rate is described by the following simple formulation:

$$\frac{\partial z}{\partial t} = w_s \left(c - c_e\right) \tag{4}$$

Herein z = bed level, [m]
w_s = coefficient having the dimension of velocity [$\mathrm{ms^{-1}}$]
t = morphological time, [s]
c = sediment concentration, [-]
c_e = local and instantaneous equilibrium sediment concentration. [-]

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

$$\frac{\partial A_c}{\partial t} = W_c w_s \left(c_{ce} - c_c\right) \tag{5}$$

$$\frac{\partial A_l}{\partial t} = W_l w_s \left(c_{le} - c_l\right) \tag{6}$$

$$\frac{\partial A_h}{\partial t} = W_h w_s \left(c_{he} - c_h\right) \tag{7}$$

In these three equations (see Figure 2):

A_c = cross-sectional area of the channel part (below MSL) [$\mathrm{m^2}$]
A_h = cross-sectional area of the high tidal flat [$\mathrm{m^2}$]
A_l = cross-sectional area of the low tidal flat [$\mathrm{m^2}$]
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, [m]
W_h = width of the high part of the tidal flat, [m]
W_l = width of the low part of the tidal flat, [m]

The equilibrium concentrations are determined as follows:

$$c_{le} = C_E \left(\frac{H_l}{H_{le}}\right)^{n_l} \tag{8}$$

$$c_{he} = C_E \left(\frac{H_h}{H_{he}}\right)^{n_h} \tag{9}$$

$$c_{ce} = \frac{c_{MSLe}\, A_{MSL} + c_{le} A_l}{A_c} \tag{10}$$

where:

$$c_{MSLe} = C_E \left(\frac{A_{MSLe}}{A_{MSL}} \right)^{n_{MSL}} \tag{11}$$

In these equations:

A_{MSL} = cross-sectional area below MSL =
= $A_c + A_l$ =
= $A_c + W_l(\Delta h_l - H_l)$ [m^2]
C_E = overall equilibrium sediment concentration [-]
Δh_l = difference between mean water level and low water level, [m]
H_h = height of the high tidal flat measured from MLW [m]
H_l = height of the low tidal flat measured from MLW [m]
n_l = constant coefficient [-]
n_h = constant coefficient [-]
n_{msl} = constant coefficient [-]

When the whole system is in equilibrium the sediment concentration will be equal to this overall equilibrium value.

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 in the tidal flat part of the cross-sections.

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

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

where:

A_c = cross-sectional area of the channel [m^2]
c_c = sediment concentration by volume in the channel [-]
D_c = horizontal dispersion coefficient in the channel [m^2/s]
F_{lc} = exchange rate of sediment between the channel the low tidal flat, which is defined positive if transport occurs from the tidal flat to the channel [m^2/s]
t = time [s]
u = residual flow velocity [m/s]

Remark: The velocity u in the advection term is in fact not equal to the residual flow velocity due to two reasons. First, the vertical distribution of the velocity and the sediment concentration makes the advection velocity smaller. Second, the tidal asymmetry has influence on the net sediment transport, which may be taken into account via the advection term. However, taking these two effects into account is not very easy, because the corrected advection velocity field has to satisfy the mass balance. Therefore the residual flow velocity will be used for the time being. In the future the model may be improved by taking the two effects into account.

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

$$F_{lc} = D_l \, \overline{\Delta h_l} \, \frac{c_l - c_c}{L_{lc}} \tag{13}$$

Herein:

D_l = diffusion coefficient [m^2/s]
L_{lc} = distance between the centre of the channel and that of the low flat [m]
$\overline{\Delta h_l}$ = effective water depth for low tidal flat [m]

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

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

At the high part of the tidal flat the mass-balance reads

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

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

$$F_{hl} = D_h \, \overline{\Delta h_h} \, \frac{c_h - c_l}{L_{hl}} \tag{16}$$

Herein:

D_h = diffusion coefficient [m^2/s]
L_{hl} = distance between the centre of the high flat and that of the low flat [m]
$\overline{\Delta h_h}$ = effective water depth for high tidal flat [m]

3.5 Physical parameters

All parameters in the equations worked out in this report are expressed in SI-units. It is noted that the time steps for the morphological computations will be large, and will therefore in practice be in (for example) years. This will not affect the character of the physical relations.

The definition of most of the parameters is clear and they can be determined quite easily. In this section the parameters that need some extra attention are described.

3.5.1 The equilibrium concentration

The equilibrium concentration in each element of the model area depends on two constants, the overall equilibrium concentration C_E and the constant n. Both will be used as calibration parameters. The constant n will be about 4. The overall equilibrium concentration C_E should be approximately equal to the (long-term) average sediment concentration in the whole model area.

Further it should be noted that C_E does not have any influence on the final equilibrium state of the system but it is an important parameter determining the time scale of the morphological development together with the dispersion coefficients and the fall velocity. Therefore C_E may be used as one of the calibration parameters in the model.

3.5.2 The horizontal dispersion coefficient

The determination of the horizontal dispersion coefficient D_c may play an important role in the development of the model. Di Silvio (1989) states that the dispersion coefficient in his model is determined by using a formulation described by Dronkers et al. (1981). He does, however, not describe the calculation of the dispersion coefficient in detail. In Dronkers et al. (1981) the calculation of the dispersion coefficient is worked out, but this is done for the case of transport of (dissolved) salt and not for suspended sediment transport.

The formulation that will be used to calculate the dispersion coefficient depends on the area involved and the schematisation. At this stage of the project an exact description of the (calculation of the) dispersion coefficient cannot yet be given. Depending on the sensitivity of the model for the value(s) of the dispersion coefficient, time has to be reserved during the calibration phase of the project to find a proper formulation.

3.6 Boundary conditions

In order to ensure that the equilibrium state according to the empirical relations is reached, at least at one of the boundaries the overall equilibrium sediment concentration C_E has to be prescribed.

Closed Boundary:

At a closed boundary the sediment flux is set to zero.

Open boundary:

At an open boundary one of the following conditions has to be applied:

- Prescription of the sediment concentration, e.g. equal to the overall equilibrium concentration

$$c_{boundary} = c_E \tag{17}$$

- prescription of the sediment transport. This can e.g. be applied at the upstream boundary when a river flows into the estuary.

- specification of the dispersive sediment transport. One of the possibilities is to set the dispersive sediment transport at the downstream boundary proportional to the sediment demand by the whole system, similar to the formulation of Van Dongeren (1992).

4 Comparison with other formulations

In this chapter three model concepts will be compared with each other:

- The formulation of Van Dongeren (1992) (1992, see also Langerak 1992). Further on this will be called formulation I;

- The formulation described by Karssen and Wang (1992), formulation II;

- The formulation described in this report, formulation III.

Formulation III may be considered as an improved version of formulation II. The major improvements concern the schematisation of the geometry. A more detailed schematisation of the cross-sections has been introduced after Eysink (1992). The cross-section is divided into three parts (instead of two in formulation II), viz. the channel, the low tidal flat and the high tidal flat. A new formulation has been added for the change of the cross-sectional profile due to sedimentation/erosion in the three parts and due to changes of water level and/or land subsidence. As a consequence no more special assumptions are needed for the width of the channel and that of the tidal flat as in formulation II.

Another consequence of the detailed schematisation of the cross-section in formulation III is that the connection to the flow module is improved.

The formulations I and II have already been compared with each other by Karssen and Wang (1992). The main features of formulation III are similar to those of formulation II. Therefore many of the conclusions drawn by Karssen and Wang (1992) can now be extended to the comparison with formulation I on one side and with formulations II and III on the other side.

The three formulations have the following common features:
- All three formulations are aimed for the same type of problems. The model of Van Dongeren is originally developed for tidal basins in the Wadden Sea. The present model is aimed for tidal basins in the Wadden Sea as well as in the Western Scheldt estuary.
- All three formulations are based on the same basic assumptions (see Section ?).
- The three formulations use similar empirical relations describing the equilibrium morphological state. Applied to a particular situation all three models will give the same equilibrium state after a long time.

The three formulations also clearly have a number of different features:
- The major difference between formulation I and formulations II and III lies in the description of the time variation processes. In formulation I the time process is governed by a number of exponential functions (the deviation from the equilibrium decreases exponentially in time). The continuity equation is fulfilled through additional requirements. In the formulations II and III the time process is mainly described by the advection-diffusion equation governing the sediment concentration. This equation also automatically gives the sediment distribution. The priority for the distribution of sediment to the different elements can only be influenced by the model parameters.
- The most important calibration parameters in the formulation I are the time scales τ, τ_f

and the constant coefficients α, μ, γ, etc. In the formulations II and III the most important calibration parameters will be: the overall equilibrium sediment concentration C_E, the settling velocity w_s, the diffusion coefficients D_c and D_l and D_h. The parameters C_E and w_s mainly determine the morphological time scale of the system.

- The tidal flat is treated differently in the three formulations. In formulation I only the total tidal flat area is calculated and a triangular distribution of the flat along the channel is assumed. In formulation II the tidal flat in each section is modelled. In formulation III the tidal flat is modelled in even more detail by dividing it into a low part and a high part. Human interferences in the tidal flat area e.g. land reclamation can easily be modelled with the formulations II and III, whereas formulation I will need some modifications to deal with such interferences and a non-triangular shape.
- In formulation I the residual flow is not explicitly taken into account. In the formulations II and III the residual flow is taken into account via the advection term.
- The mathematical character of the formulations II and III is similar to that of the model of Di Silvio (1989; Di Silvio and Gambolati, 1990) whereas formulation I (van Dongeren, 1992) may be considered as an improved version of the model of Allersma (1988). Karssen and Wang (1991b) have shown that the description of the time process in the model of Di Silvio is preferable to that in the model of Allersma.

Furthermore, the following general remarks concerning the models were made:
- Formulation I will need a complete rebuilding in order to satisfy the specified requirements of the model to be developed:
  * The residual flow should be included in order to express flood and ebb dominance in the Western Scheldt.
  * The formulation for the flat distribution has to be expressed in all three models to be able to combine the tidal flow model with the morphological module and to be able to describe in the model the consequences of the human interferences to the tidal flat.
- Formulation I has already been successfully applied to the tidal basin 'Het Friesche Zeegat' (van Dongeren, 1992). However, the application only concerns sedimentation in the tidal basin.

- No experience with formulation II and III exists in the Netherlands. Only some restricted experience is present abroad (Di Silvio, 1989, Di Silvio and Gambolati, 1990) about similar formulations.

Karssen and Wang (1992) already made the conclusion that formulation II is preferable to formulation I. Compared to the two other formulations the main disadvantage of formulation I is its restricted applicability.

In summary the major characteristics of the three formulations are compared with each other in the following table.

characteristic	formulation I	formulation II	formulation III
schematisation	-	+	++
equilibrium	o	o	o
time process	o	+	+
assumptions	o	o	o
experience	+	o	o
link with flow model	-	o	+
applicability	-	o	o

Based on the conclusions above it is recommended to choose the formulation described in the this report for building the model.

5 Summary and conclusions

A concept for a long-term morphological model for estuaries and tidal basins is formulated in this report (Chapter). The formulation is based on the same basic assumptions (Chapter) as in the concept described by Langerak (1992, Van Dongeren, 1992).

The present formulation is mainly based on the formulation described by Karssen and Wang (1992). The main features of the formulation remain the same. The improvements mainly concern the schematisation of the geometry. The more detailed schematisation presented by Eysink (1992) is used in the present formulation.

The present formulation has been compared with other two concepts in Chapter. The conclusion is that the present formulation is the best one of the three. Therefore it is recommended to choose the present formulation for building the model.

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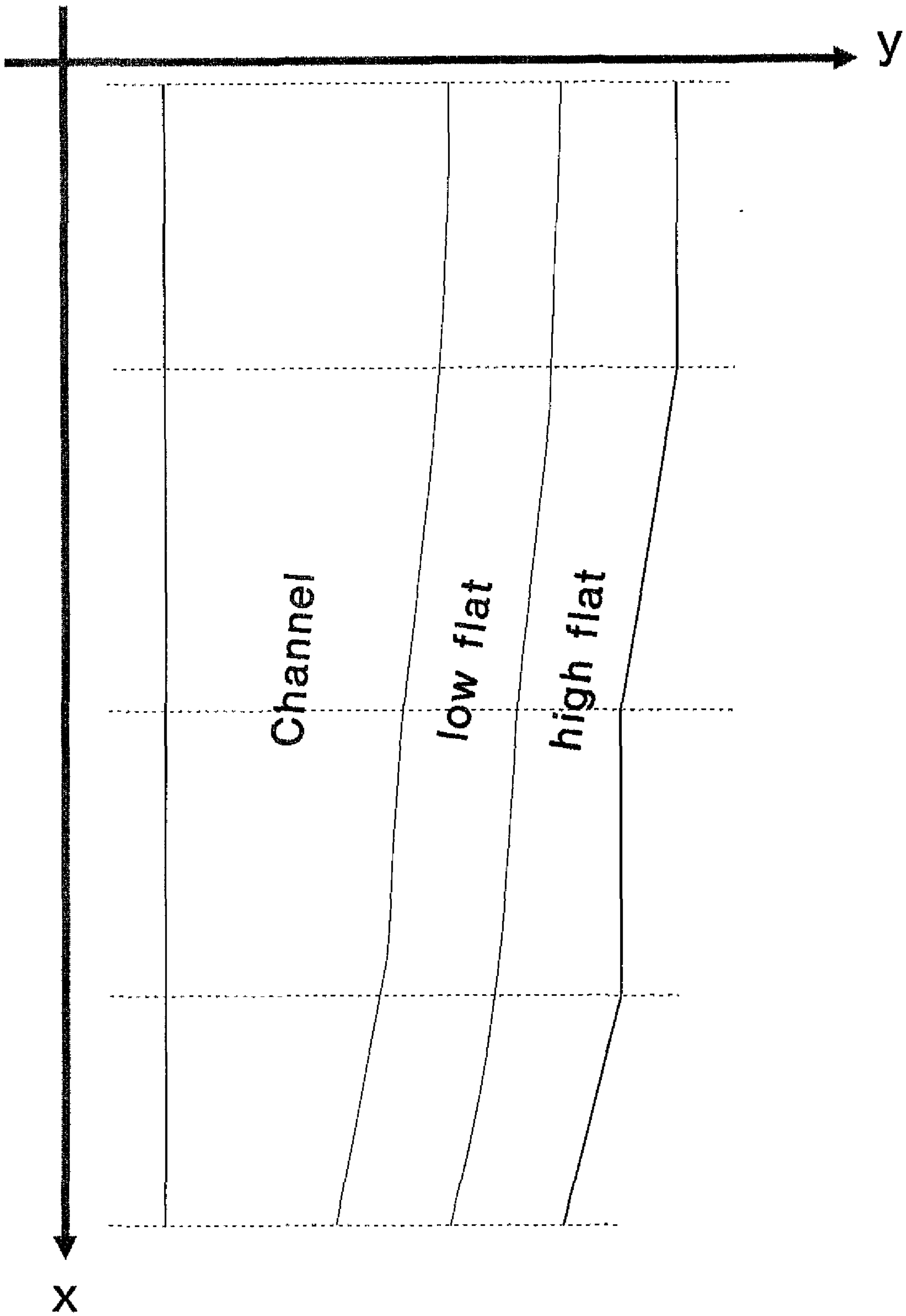


Schematisation

Top view

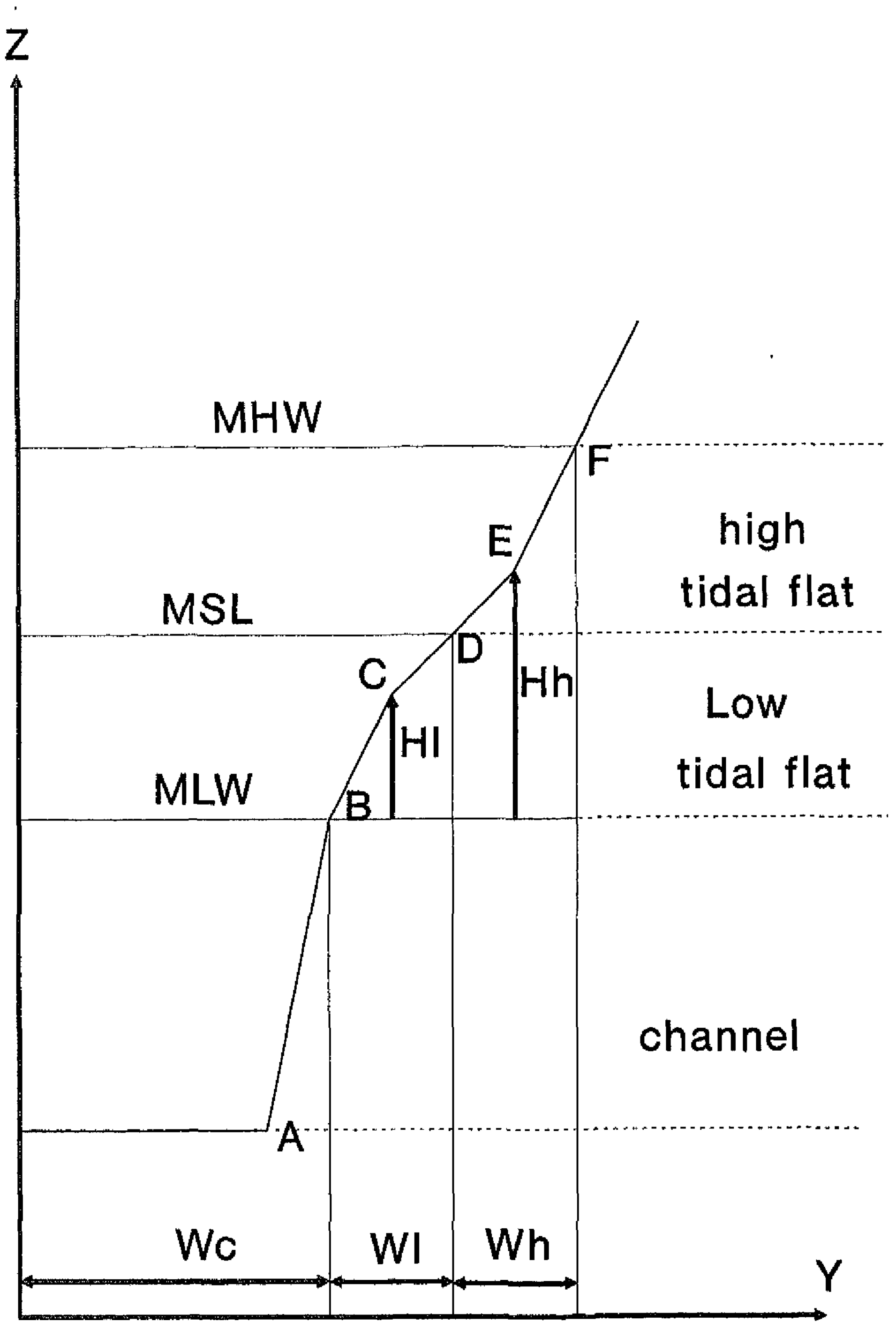
February 1993

DYNASTAR-ESTMORF

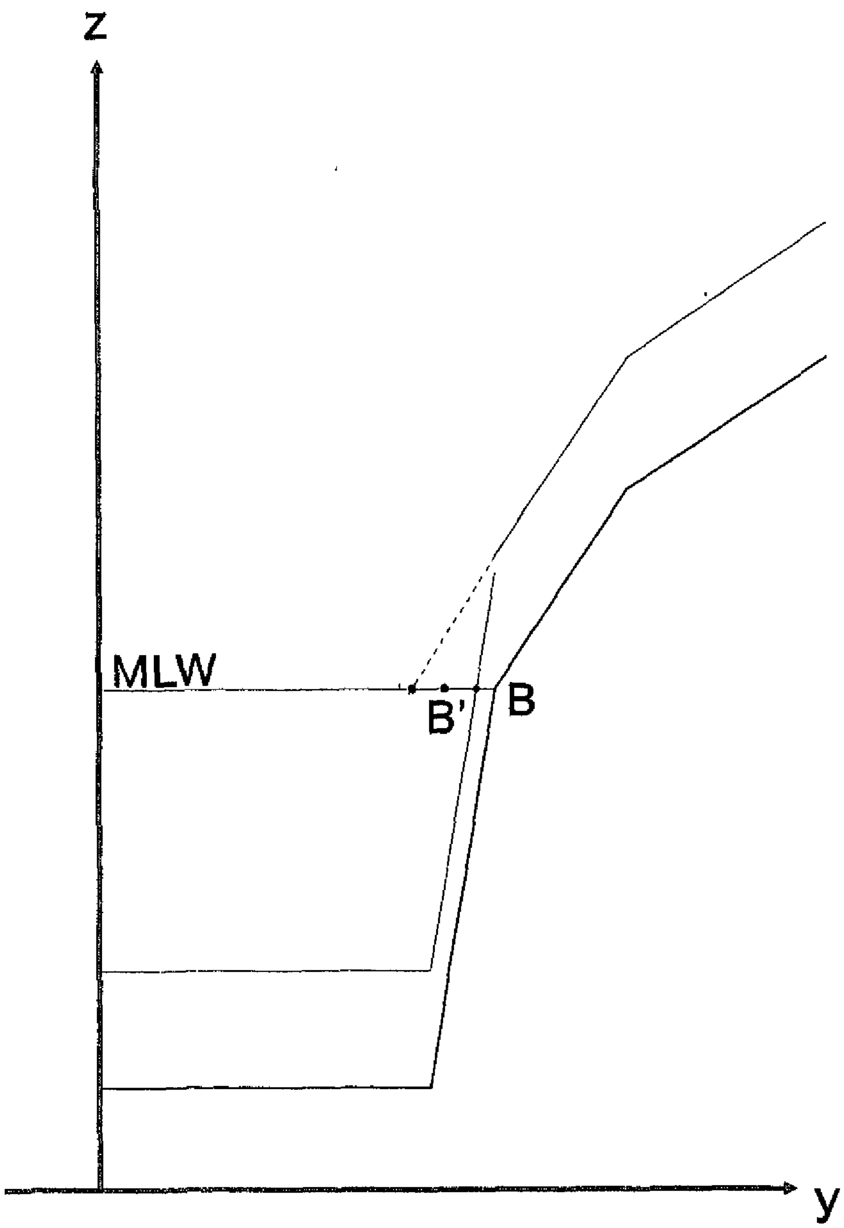
DELFT HYDRAULICS

Proj: Z-622

Figure 1



Schematisation Cross-section	February 1993	
	DYNASTAR-ESTMORF	
DELFT HYDRAULICS	Proj: Z-622	Figure 2



Displacement of point B (at low water level) Due to sedimentation	February 1993 DYNASTAR-ESTMORF
DELFT HYDRAULICS	Proj: Z-622 / Figure 3