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

Development of the model, Phase I

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delft hydraulics

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Contents

List of symbols

A_c	=	cross-sectional area of the channel	[m^2]
A_h	=	cross-sectional area of the high tidal flat	[m^2]
A_l	=	cross-sectional area of the low tidal flat	[m^2]
c	=	sediment concentration by volume at a node	[-]
c_c	=	sediment concentration by volume in the channel	[-]
c_{ce}	=	equilibrium concentration by volume in the channel	[-]
c_h	=	sediment concentration by volume in the high tidal flat part	[-]
c_{he}	=	equilibrium sediment concentration by volume in the high tidal flat part	[-]
c_l	=	sediment concentration by volume in the low tidal flat part	[-]
c_{le}	=	equilibrium sediment concentration by volume in the low tidal flat part	[-]
D_c	=	dispersion coefficient channels	[m^2/s]
D_h	=	diffusion coefficient high flats	[m^2/s]
D_l	=	diffusion coefficient low flats	[m^2/s]
F_{lc}	=	exchange rate of sediment between the channel the low tidal flat	[m^2/s]
h_h	=	effective water depth for the high tidal flat	[m]
h_l	=	effective water depth for the low tidal flat	[m]
j	=	index of the branch	[-]
k	=	index of the node	[-]
L	=	length of a branch	[m]
L_{hl}	=	distance between the centre of the high flat and that of the low flat	[m]
L_{lc}	=	distance between the centre of the channel and that of the low flat	[m]
$N_{br,k}$	=	number of branches connected to node k	[-]
Q	=	discharge	[m^3/s]
S	=	sediment transport	[m^3/s]
t	=	time	[s]
u	=	residual flow velocity	[m/s]
x	=	horizontal coordinate	[m]
W_c	=	width of the channel	[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]
w_s	=	coefficient having the dimension of velocity	[m/s]

The following conventions are used in this report:

- A parameter subscript *j* denotes that the value of this parameter is at a branch (*j*).
- A parameter subscript *k* denotes that the value of this parameter is at a node (*k*).
- A parameter superscript *n* denotes that the value of this parameter is at the old (previous) time step (*n*).
- A parameter superscript *n+1* denotes that the value of this parameter is at the new (present) time step (*n+1*).

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1 Introduction

The Directoraat-Generaal Rijkswaterstaat/Rijksinstituut voor Kust en Zee of the Ministry of Public Works and Transport (RWS/RIKZ) is interested in morphological models predicting the consequences of (human) interference (e.g. dredging, land reclamation) in the geometry of estuaries and tidal basins.

Two types of models are considered:

- a one-dimensional middle long-term model to predict the morphological development in estuaries and tidal basins for a period of 20 to 30 years.
- a one-dimensional long-term model to predict the morphological development in estuaries and tidal basins for a period of 50 to 100 years.

The middle long-term model (called EENDMORF) is studied in the project DYNASTAR, for which a study of the proper nodal relations to be applied in the model to be developed is just completed.

The long-term model (called ESTMORF), which is the subject of this report, is also studied in the project DYNASTAR. For the latter RWS/RIKZ 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). It was recommended to choose this combined concept for the development of the 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).

In November 1992, RWS/RIKZ commissioned DELFT HYDRAULICS to carry out a part of the development of the model. That part contained the verification of the choice of the model concept and the elaboration of the physical relations in the model in detail taking into account the work carried out in the ISOS*2-project (Eysink, 1992). The study was completed with a report (Karssen and Wang, 1993).

In view of the previous studies, the RWS decided to build the model. With letter AOE/936522 dated 29 July 1993, RWS/RIKZ commissioned DELFT HYDRAULICS to perform the following activities:

- Phase I:
  Development of the ESTMORF-software, preparation of a dedicated model of both the Westerschelde and the Friesche Zeegat and performance of first tests with the software.

- Phase II:
  Performance of extensive tests with the software, calibration of the models, sensitivity analyses and implementation of the software at the clients' office.

Two changes to the above list of activities were made in close concert with the client:

- During execution of Phase I it became clear that branches without tidal flats were present in the Westerschelde IMPLIC-model. Furthermore, these branches consisted of a channel with vertical walls. The physical relations described in (Karssen and Wang, 1993) did not foresee in such a geometry. It was therefore decided to extend the solution method of the concentration field and the changes in the cross-sectional area in order to make morphological computations using this channel geometry possible.

- The preparation of the dedicated models of the Westerschelde and the Friesche Zeegat already required comprehensive tests with the software. It was therefore decided to perform these tests during Phase I instead of during Phase II.

This report contains a description of the activities performed during Phase I and the results of these activities. In Chapter 2 the technical requirements of the software are worked out in detail. Chapter 3 contains a detailed description of the software (structure of the software and technical contents of its subroutines), whereas in Chapter 4 the results of the first tests are described, including the preparation of the dedicated models. Finally, in Chapter 5 the conclusions and recommendations are summarised.

This study was performed by R. Bruinsma, B. Karssen and Dr. Z.B. Wang under the guidance of A. Langerak from RWS. The report is drawn up by B. Karssen.

2 Technical requirements of the software

2.1 Introduction

In general, the requirements of software can be separated in functional and technical requirements. For the ESTMORF-software, the functional requirements describe the physical system ESTMORF should model, whereas the technical requirements describe the numerical and software-technical requirements of the software.

In (Karssen and Wang, 1993), the **functional** requirements of the ESTMORF-model were worked out. However, during execution of Phase I it became clear that branches without tidal flats were present in the Westerschelde and the Friesche Zeegat IMPLIC-model. Furthermore, these branches consisted of a channel with vertical walls. The presence of these branches were not foreseen during the definition of the functional requirements and therefore the physical relations described in (Karssen and Wang, 1993) were not applicable to such a geometry.

In view of the above, in close cooperation with the client it was decided that the following functional requirement should be added:

- the user can define for which branches the tidal flats should be taken into account during the computation of the sediment transport and of the change in cross-sectional area. Where the tidal flats are not taken into account, the sediment transport only takes place in the channel and the resulting sedimentation/erosion only leads to a change in the bed level of the channel part.

This additional requirement makes it possible to include branches with vertical walls in the model, provided the user indicates these branches as 'without tidal flats'.

This chapter gives an overview of the **technical** requirements of the software. The technical requirements are mainly based on the results of the previous studies performed in the framework of the ESTMORF-project and discussions with the client. The following items will be discussed in the next sections:

- General description
- Hardware requirements
- Input requirements
- Requirements with respect to the computational module
- Output requirements

A comprehensive description of the structure of the software can be found in Chapter 3.

2.2 General description and hardware requirements

The ESTMORF-software is a software system for research purposes that can be used to predict the long-term morphological development of estuaries. The software makes use of a dynamic model (IMPLIC) to compute the hydrodynamics in the estuary. Sediment transport/morphological equations based on empirical relations are used to compute the morphological changes in the estuary.

The fact that ESTMORF is a software system for research purposes, indicates that:

- it concerns a non-operational working prototype
- the code and the documentation of the software do not satisfy the standard RWS requirements for software development

The software is set up in a modular way, making it possible for RWS researchers to work with the model independently (i.e. without assistance of staff of DELFT HYDRAULICS) and to change the source, if needed. A description of the structure of the software as it is now, i.e. after the completion of Phase I of the project, can be found in Chapter 3. It is noted that during Phase II, it may appear to be necessary to change the software on some minor points, but it is very likely that the overall structure will remain unchanged.

The ESTMORF software is written in the standard FORTRAN 77 computer language.

The ESTMORF software runs on a PC with operating system DOS and on a workstation with operating system UNIX. It is not necessary to have more than 1 Mb internal memory available.

2.3 Input requirements

The input of model parameters for the ESTMORF software is very similar to the way the input in IMPLIC is handled. The input of the parameters is set up very flexible. The (calibration) parameters and initial values can be defined either space varying or constant over the area. Apart from the boundary conditions it is not possible to define time varying parameters.

The format of prescription of the boundary conditions is similar to the way IMPLIC boundary conditions should be defined. However, in view of the fact that for most applications the boundary conditions for both the hydrodynamic computation and the morphological computation will be periodical or constant (which is a special case of a periodical condition), a very useful feature is built in: after the last value of the boundary file is read on a certain time step, the file is rewind and the first value in the file is read again on the next time step. This means that it is not necessary to prescribe the boundary values for all time steps when a periodical signal is prescribed at the boundaries.

All input files are in ASCII-format, which makes editing of the files easy. The input files and formats will be described in detail in the report of Phase II of this project.

2.4 The computational module

The main requirement of the computational module is simple: the computational module should compute the new cross-sectional profiles in the area of interest (which is the model area, such as the Westerschelde and the Friesche Zeegat) based on the physical relations as described in (Karssen and Wang, 1992; Karssen and Wang, 1993).

An additional requirement is that the computational effort needed for a simulation should be as small as possible. This means that the numerical scheme should be stable for reasonably large time steps and thereby providing sufficient accuracy.

An implicit scheme looks very promising from the stability point of view, but will lead to the use of complicated one-dimensional network solvers. The gain on the magnitude of the time step may be compensated by the loss on computational time needed to solve the system of differential equations. Another disadvantage is the complexity of the software and the maintenance. An explicit scheme facilitates the testing of the software and will lead to less computational effort per simulation. However, using an explicit method leads to stability criteria that have to be met. One of the main problems with respect to this is due to the source terms in the transport equations. To reduce the stability problems, it was therefore decided to build in one semi-explicit:

- a central differences scheme, combined with implicit source terms to solve the concentration in the internal points of the branches,

and one explicit numerical scheme:

- Euler's method to solve the sedimentation/erosion field.

It is noted that the cross-sectional areas are assumed to remain unchanged during the computation of the concentration field: the proper concentration field is found by iteration (see also Section 3.4).

The software makes it possible to run an IMPLIC simulation first until the effect of the initial conditions have disappeared from the hydrodynamic parameters solved. After this 'spin-up period' the results of the hydrodynamic model can be used by the morphological module to determine the equilibrium values of the morphological parameters to be solved, followed by the morphological computation.

2.5 Output requirements

In order to calibrate a model, the software should provide the following (morphological) information:

- the final model configuration (i.e. of the whole model area) after a simulation and/or the model configuration at selected time steps during the simulation in IMPLIC model format
- time series of the cross-sectional profile and/or the concentrations (channel, low flats, high flats) at previously defined stations

During Phase II of the project, the exact output procedures will be defined in close concert with the client.

3 Description of the software

3.1 Introduction

In this chapter, the ESTMORF-software is described as it is developed during Phase I. It may appear that minor changes will be necessary during Phase II. The overall description of the software in this chapter, however, can be considered as final. In Section 3.2. the structure of the software is presented followed by a detailed description of the subroutines and executables in Section 3.3. Section 3.4 contains a description of the numerical methods applied.

3.2 Structure of the software

A morphological simulation with ESTMORF basically consists of the following steps:

1. A hydrodynamic simulation (using IMPLIC) is performed to determine:
   - the inflowing and outflowing volumes of water during a tidal cycle, and
   - the mean high water level (MHW), mean sea level (MSL) and the mean low water level (MLW)

   at the beginning and at the end of each branch.
   Above values are used in empirical relations to determine the equilibrium values of several parameters.

2. Based on the new equilibrium values, the sediment transport is computed, followed by the computation of the change in cross-sectional area. This is repeated until the morphological change is large enough to have effect on the hydrodynamics.

The period during which the hydrodynamics are assumed to be constant is to be given by the user. When this period has elapsed, the whole cycle consisting of Step 1 followed by Step 2 is repeated. This whole cycle is repeated until the simulation end time is reached.

The above rough description of the structure of the computations leads to the structure of the main program depicted on the next page. It is noted that the names refer to subroutine calls in the program, except where the extension '.exe' is added: in those cases, an external program is executed. The main advantage of calling external programs is that the amount of internal memory needed to run the software is less than in the case that the other programs are integrated in ESTMORF as subroutines.

```
| Subroutines                                   | Files

PROGRAM ESTMORF

   Initialization:

      NodeSize                            <--     Model.inp
                                                  (IMPLIC
                                                   schematization)

      GetNodes                            <--     Model.inp

      GetRand                             <--     MorfRand.inp
                                                  (morphological
                                                   boundary conditions)

      GetUser                             <--     EstMorf.inp
                                                  (input parameters
                                                   Estmorf)

      InitNode

  ┌──Loop until end of simulation
  │   Implic.exe                          <--     Model.inp
  │                                       <--     IMPLIC input-files
  │                                       -->     Implic.out
  │                                               (tidal volumes,
  │                                               water levels)
  │                                       -->     IMPLIC output-files
  │
  │   IF first IMPLIC run THEN
  │       Imp2Morf.exe                    -->     Morf.dat
  │                                               (ESTMORF profiles)
  │   ENDIF
  │
  │   Morf (see next page)                <--     Morf.dat
  │                                       <--     Implic.out
  │                                       <--     MorfRand.inp
  │                                       -->     Morf.dat
  │
  │   Morf2Imp.exe                        -->     Model.inp
  │        │
  └────────┘

END
```

The core of the morphological computations is formed by the subroutine Morf, in which the following structure is adapted:

1. Compute the present cross-sectional areas from the present ESTMORF-profiles.
2. Read in the tidal volumes and the water levels from the output of IMPLIC.
3. Compute the new ESTMORF-profiles due to a possible change in water levels and land subsidence (no transport; see Karssen and Wang, 1993).
4. Compute the new cross-sectional areas and widths.
5. Compute the new equilibrium values for the heights of the tidal flats, the cross-sectional area below MSL and the concentration field.
6. Read in the new boundary conditions for the concentration.
7. Compute the sediment transport and the new concentration field.
8. Compute the sedimentation/erosion.
9. Compute the new cross-sectional areas and the new ESTMORF-profiles.
10. Repeat steps 4. through 9. until a new hydrodynamic computation is necessary.

The above rough description of the structure of the morphological computation leads to the structure of the Morf subroutine depicted below.

```
    |  Subroutines                          |     Files

SUBROUTINE Morf

   Initialization:

      InitVerA                              <--- Morf.dat

      Volumes                               <--- Implic.out

      DeltaZ

 ┌──Loop until new IMPLIC-run is necessary
 │
 │    Areas
 │
 │    InitHorA
 │
 │    Heq
 │
 │    Aeq
 │
 │    Ceq
 │
 │    GetRand                               <--- MorfRand.inp
 │
 │    Conc
 │
 │    SedEro
 │
 │    DeltaA
 │                                          --> Morf.dat
 │          │
 └──────────┘
END
```

3.3 Description of the subroutines and executables

Areas

Function: Computation of the cross-sectional area of the channel part, the low tidal flats and the high tidal flats, using the ESTMORF profiles stored in the file Morf.dat.

It is noted that the cross-sectional profiles are symmetric by definition. From a software development point of view it is convenient to use in the FORTRAN source code half of the symmetric profile only. The input and output values all concern whole cross-sectional areas, so the user is not aware of this internal transformation.

Aeq

Function: Computation of the equilibrium areas below MSL, using the user-defined constants of the empirical relations.

Ceq

Function: Computation of the equilibrium concentrations (channel, low flats, high flats), using the present and equilibrium heights of the flats and the present and equilibrium areas below MSL.

Conc

Function: Computation of the sediment transport and the new concentration field.

This is the core routine of the morphological part of ESTMORF. The transport equations as described in (Karssen and Wang, 1992; Karssen and Wang, 1993) are solved. A detailed description of the solution method of the transport equations can be found in Section 3.4.

DeltaA

Function: Computation of the new ESTMORF profile due to sedimentation/erosion.

DeltaZ

Function: Computation of the new ESTMORF profile due to the change of the water levels and land subsidence.

GetNodes

Function: Read IMPLIC-schematisation from the file Model.inp and prepare ESTMORF model-information in the form of a nodal array and a branch array.

The nodal array contains:

- 1st dimension; index of the node in the nodal array

- Index of 2nd dimension:

1:	number of the node in the IMPLIC-schematisation
2:	type of node, filled in GetRand
3 t/m 2+maxtak+1:	numbers of the branches connected to the node: • value > 0 : incoming branch • value < 0 : outgoing branch • -10000 < value or value > 10000: a structure (Dutch: vervalsektie) is connected to this node. The absolute value minus 10000 gives the index of the node at the opposite side of the structure. The sign again indicates if it concerns an incoming branch of outgoing branch.

The branch array contains:

- 1st dimension: index of the branch in the branch array

- Index of 2nd dimension:

1:	index of the node at the begin of the branch
2:	index of the node at the end of the branch

GetRand

Function: Read the boundary information from the file MorfRand.inp and fill Index 2 of the 2nd dimension of the nodal array with the type of boundary of the nodes:

0: no boundary
1: concentration boundary
2: transport boundary
3: dispersive transport boundary (van Dongeren, 1992)
4: closed boundary

The prescribed boundary value is read in every morphological time step and stored in an array.

GetUser

Function: Read the User input information from the file EstMorf.inp:

- Length of the simulation
- Morphological time step
- Number of morphological time steps before new IMPLIC run is necessary
- Time step for iteration in a morphological loop
- Diffusion coefficients (channel, low flats, high flats)
- Initial concentrations per branch
- Fall velocity of the sediment
- Constants for empirical relations
- Overall equilibrium concentration

Heq

Function: Computation of the equilibrium heights of the flats using empirical relations and the mean water levels.

Implic.exe

Function: Standard software for hydrodynamic computations. A subroutine has been added to the standard IMPLIC software to compute the tidal volume through and the mean water levels at each end of all branches. The computed values are written to a file (Implic.out).

Input (among other standard IMPLIC input-files):
- Model.inp: model schematisation which changes due to the previous morphological time step

Output (among other standard IMPLIC output-files):
- Implic.out: MLW, MSL and MHW
  Incoming and outgoing volume

Imp2Morf.exe

Function: Transformation of an IMPLIC profile to an ESTMORF profile, which is only necessary after the first IMPLIC run. For the next steps, the ESTMORF profile is stored in a file after the morphological step.

Input:
- Model.inp: IMPLIC model schematisation

Output:
- Morf.dat: ESTMORF profile

InitHorA

Function: Computation of the horizontal areas (basin area and flat area for van Dongeren boundary) and the widths (half).

InitNode

Function: Initialization of information at the nodes:

- weight factors for interpolation of the dispersion coefficients and the initial concentrations in the branches
- initial concentration in the nodes

InitVerA

Function: Initialization of the cross-sectional areas (half!), using the estmorf profiles stored in the morf.dat file.

Input: Morf.dat

Morf

Function: Main morphological subroutine in which the concentration field and the new cross-sectional (ESTMORF) profiles are computed.

A detailed description of the structure of the computation can be found in Section 3.4.

Morf2Imp.exe

Function: Transformation of an ESTMORF profile to an IMPLIC profile

Input:

- Morf.dat: ESTMORF profile

Output:

- Model.out (= Model.inp): IMPLIC model schematisation

Nodesize

Function: Read the IMPLIC-schematisation from the file Model.inp and determine the dimension of the several multi-dimensional arrays.

SedEro

Function: Computation of the sedimentation/erosion of the channel part (half), low flats and high flats.

A detailed numerical description of the solution method of the sedimentation/erosion can be found in Section 3.4.

Volumes

Function: Read in the volume and water level information from the Implic.out file.
Input: Implic.out

3.4 Description of the numerical solution method

In this section, the ESTMORF-model is described from a numerical point of view. The following items can be found below:

- the grid (see Section 3.4.1)
- the numerical solution method for the concentration field (step 7 on page 3 — 3; see Section 3.4.2)

The computation of the new concentration field is decoupled from the solution of the new cross-sectional areas. This means that the cross-sectional area is assumed to remain unchanged during the computation of the concentration field.

It is noted that the equilibrium values for the concentrations and the cross-sectional areas are described in (Karssen and Wang, 1993).

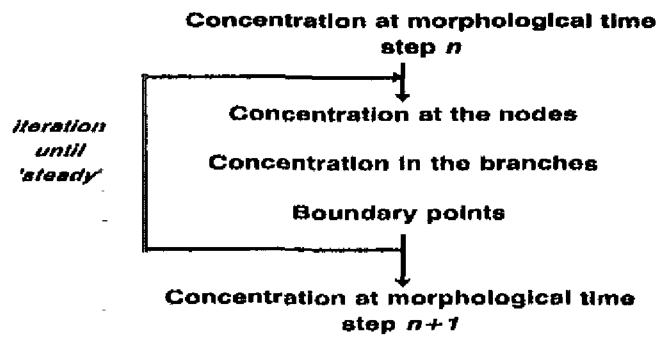
3.4.1 The grid

The topology of the ESTMORF model can be characterized as follows:
The model consists of branches which are interconnected by nodes. In each branch, the concentration and the cross-sectional area are computed in the centre of that branch. At that location, the tidal flat area is connected to the branch. Transport of sediment is possible between the high tidal flat area and the low tidal flat area, between the low tidal flat area and the channel part, and between the channel parts of the different connected branches through the nodes.
The topology of the ESTMORF model is depicted in Figure 3.4.1.

3.4.2 The concentration field

The computation of the concentration field is an iterative process, which leads to a (quasi-) steady concentration field, i.e. a concentration field which is steady during one morphological time step, but (of course) not steady during the whole morphological computation. The time step of the iterative solution method for the (quasi-)steady concentration field is small (minutes) compared with the morphological time step (days/months/years).

Graphically, the iterative process can be presented as follows:



The computation of the concentration field within the iterative process is described below.

Nodes

First, the concentration in the nodes is computed. In the nodes the continuity equation for the sediment must hold, i.e. the incoming sediment transport must equal the outgoing sediment transport:

$$\sum_{j=1}^{N_{br,k}} S_j = \sum_{j=1}^{N_{br,k}} \left(Q_j \, c_k - A_{c,j} \, D_{c,j} \frac{\partial c_{c,j}}{\partial x} \right) = 0 \qquad \textbf{(3.1)}$$

where:

A_c	=	cross-sectional area of the channel	[m^2]
c_c	=	sediment concentration by volume in the channel	[-]
c	=	sediment concentration by volume in a node	[-]
D_c	=	dispersion coefficient for the channel	[m^2/s]
j	=	index of a branch	[-]
k	=	index of a node	[-]
$N_{br,k}$	=	number of branches connected to node k	[-]
Q	=	discharge	[m^3/s]
S	=	sediment transport	[m^3/s]
x	=	horizontal coordinate	[m]

In view of the fact that the continuity equation for the water is already satisfied (the discharges originate from an IMPLIC-run), this leads to the following numerical relation for the concentration in the nodes that are not boundary points:

$$c_k^{n+1} = \frac{\sum_{j=1}^{N_{br,k}} \left(\frac{A_j D_j}{L_j} c_{c,j}^{n} \right)}{\sum_{j=1}^{N_{br,k}} \left(\frac{A_j D_j}{L_j} \right)} \tag{3.2}$$

where:

L_j	=	length of branch j	[m]

It is noted that the superscript $n+1$ denotes the new time step, whereas the superscript n denotes the previous time step.

Branches

Then the concentration in the branches is computed. Two cases must be distinguished:
- the branches for which sediment transport from and to the tidal flats should be included (case A)
- the branches for which no sediment transport from and to the tidal flats takes place (case B)

The user should specify the above status of the branches in the model schematization before running the ESTMORF-model.

Case A: Tidal flats included

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

$$\frac{\partial A_c c_c}{\partial t} + \frac{\partial A_c u c_c}{\partial x} - \frac{\partial}{\partial x}\left(A_c D_c \frac{\partial c_c}{\partial x}\right) = W_c w_s (c_{ce} - c_c) + F_{lc} \tag{3.3}$$

where:

c_{ce}	=	equilibrium concentration by volume in the channel	[-]
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	[m²/s]
t	=	time	[s]
u	=	residual flow velocity	[m/s]
W_c	=	width of the channel	[m]
w_s	=	coefficient having the dimension of velocity	[m/s]

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

$$F_{lc} = D_l \, h_l \, \frac{c_l - c_c}{L_{lc}} \tag{3.4}$$

where:

c_l	=	sediment concentration by volume in the low tidal flat part	[-]
D_l	=	diffusion coefficient low flats	[m²/s]
L_{lc}	=	distance between the centre of the channel and that of the low flat	[m]
h_l	=	effective water depth for the low tidal flat	[m]

By the use of a central differences scheme, combining Equations (3.3) and (3.4) and by taking the source terms (the right hand side of Equation (3.3)) implicit, the following expression is found:

$$\left(A_c^n + W_c \, w_s \, \Delta t + \frac{D_l \, h_l}{L_{lc}} \Delta t \right) c_c^{n+1} - \frac{D_l \, h_l}{L_{lc}} \Delta t \; c_l^{n+1} = A_c^n \, c_c^n + W_c \, w_s \, \Delta t \; c_{ce} - \frac{S_2 - S_1}{L} \Delta t \tag{3.5}$$

where:

$$\begin{aligned} S_2 &= A_{c,2}^n \, u_2 \, c_{k,2} - \frac{A_{c,2}^n \, D_c}{0.5 \, L} \left(c_{k,2}^{n+1} - c_c^n \right) \\ S_1 &= A_{c,1}^n \, u_1 \, c_{k,1} - \frac{A_{c,1}^n \, D_c}{0.5 \, L} \left(c_c^n - c_{k,1}^{n+1} \right) \end{aligned} \tag{3.6}$$

It is noted that the subscript 2 refers to the end of the branch, whereas subscript 1 refers to the beginning of the branch.

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

$$\frac{\partial (A_l c_l)}{\partial t} = W_l w_s \left(c_{le} - c_l \right) - F_{lc} + F_{hl} \tag{3.7}$$

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

$$\frac{\partial (A_h c_h)}{\partial t} = W_h w_s \left(c_{he} - c_h \right) - F_{hl} \tag{3.8}$$

The exchange rate F_{hl} between the two parts of the tidal flat is formulated as

$$F_{hl} = D_h \frac{h_h}{4} \frac{c_h - c_l}{L_{hl}} \tag{3.9}$$

where:

A_h	=	cross-sectional area of the high tidal flat	[m²]
A_l	=	cross-sectional area of the low tidal flat	[m²]
c_h	=	sediment concentration by volume in the high tidal flat part	[-]
c_{he}	=	equilibrium sediment concentration by volume in the high tidal flat part	[-]
c_{le}	=	equilibrium sediment concentration by volume in the low tidal flat part	[-]
D_h	=	diffusion coefficient high flats	[m²/s]
L_{hl}	=	distance between the centre of the high flat and that of the low flat	[m]
h_h	=	effective water depth for the high tidal flat	[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 combination of Equations (3.4), (3.7) and (3.9) and taking the source terms (the right hand side of Equation (3.7)) implicit, leads to the following expression:

$$\left(A_l^n + W_l\, w_s\, \Delta t + \frac{D_l\, h_l}{L_{lc}}\, \Delta t + \frac{D_h\, h_h}{L_{hl}}\, \Delta t \right) c_l^{n+1} - \frac{D_l\, h_l}{L_{lc}}\, \Delta t\, c_c^{n+1} - \frac{D_h\, h_h}{L_{hl}}\, \Delta t\, c_h^{n+1}$$

$$=$$

$$A_l^n\, c_l^n + W_l\, w_s\, \Delta t\, c_{le} \tag{3.10}$$

The combination of Equations (3.8) and (3.9) and taking the source terms (the right hand side of Equation (3.8)) implicit, leads to the following expression:

$$\left(A_h^n + W_h\, w_s\, \Delta t + \frac{D_h\, h_h}{L_{hl}}\, \Delta t \right) c_h^{n+1} - \frac{D_h\, h_h}{L_{hl}}\, \Delta t\, c_l^{n+1} \tag{3.11}$$

$$=$$

$$A_h^n\, c_h^n + W_h\, w_s\, \Delta t\, c_{he}$$

The system of three linear equations ((3.5), (3.10) and (3.11)) is now solved for the concentrations in the channel and the tidal flats.

Case B: Tidal flats are not included

In the case that tidal flats are not included, sediment transport between the low flat and the high flat and between the low flat and the channel does not take place. In fact, because the flats are not included, the concentration at the flats is not defined.

From Equation (3.3) with $F_{lc} = 0$, the following numerical equation for the concentration in the channel can be deduced:

$$c_c^{n+1} = \frac{A_c^n \, c_c^n + W_c \, w_s \, \Delta t \, c_{ce} - \dfrac{S_2 - S_1}{L} \Delta t}{A_c^n + W_c \, w_s \, \Delta t} \tag{3.12}$$

Boundary conditions

Four types of boundary conditions can be defined by the user:

- a closed boundary
- a concentration boundary
- a transport boundary
- a dispersive transport boundary

The boundary conditions are described in the nodes.

Closed boundary

At a closed boundary, the sediment transport through the node is zero:

$$A_c \, u \, c_k - A_c \, D_c \, \frac{\partial c_c}{\partial x} = 0 \tag{3.13}$$

Numerically, this leads to the following equation, assuming that the node is located at the beginning of a branch (if not, a similar equation holds).

$$c_k^{n+1} = \frac{D_{c,j} \, c_{c,j}^{n+1}}{0.5 \, u_j \, L_j + D_{c,j}} \tag{3.14}$$

Concentration boundary

At a concentration boundary, the concentration at the node is prescribed by the concentration which is given by the user.

Transport boundary

At a transport boundary, the sediment transport is given by the user. This leads to the following numerical equation for the concentration at the node:

$$c_k^{n+1} = \frac{A_c\, D_{c,j}\, c_{c,j}^{n+1} + 0.5\, S_k\, L_j}{0.5\, A_c\, u\, L_j + A_c\, D_{c,j}} \tag{3.15}$$

Dispersive transport boundary

In the dispersive transport concept of van Dongeren, the sediment enters the model by dispersive transport and is proportional to the sediment demand of the system (see Van Dongeren, 1992). This sediment demand is computed by using an empirical relation with the area of the tidal flats and the total basin area as parameters. The resulting equation for the concentration at the boundary is as follows:

$$c_k^{n+1} = c_j^{n+1} + \frac{0.5\, L_j\, S_k}{A_c\, D_{c,j}} \tag{3.16}$$

3.4.3 The cross-sectional area

The change of the cross-sectional areas of the channel, the low tidal flats and the high tidal flats satisfy the following equations:

$$\frac{\partial A_c}{\partial t} = W_c\, w_s\, (c_{ce} - c_c) \tag{3.17}$$

$$\frac{\partial A_l}{\partial t} = W_l\, w_s\, (c_{le} - c_l) \tag{3.18}$$

$$\frac{\partial A_h}{\partial t} = W_h\, w_s\, (c_{he} - c_h) \tag{3.19}$$

Using Euler's method yields the following numerical relations:

$$A_c^{n+1} = A_c^n + \Delta t \; W_c \; w_s \left(c_{ce} - c_c^{n+1}\right) \tag{3.20}$$

$$A_l^{n+1} = A_l^n + \Delta t \; W_l \; w_s \left(c_{le} - c_l^{n+1}\right) \tag{3.21}$$

$$A_h^{n+1} = A_h^n + \Delta t \; W_h \; w_s \left(c_{he} - c_h^{n+1}\right) \tag{3.22}$$

Remarks:
1. The sediment concentration at the new time step (with superscript $n+1$) is already computed, using the formulae described in Section 3.4.2.
2. For the case that the tidal flats are not included (case B, see Section 3.4.2), Equations (3.18), (3.19), (3.21) and (3.22) are not used.

4 First tests

4.1 Introduction

For each computer program or software package, the testing phase is essential in the process of software development. In most cases, the testing effort is proportional to the complexity of the software concerned. The ESTMORF-software, including the IMPLIC-program and the communication modules, is rather complex, both from a physical and a programming point of view (time frame, the solution of the concentration field, geometry transformations).

In view of the above, the following testing phases were defined for Phase I of the project:

- *Debugging*
  The debugging concerns tests on source code level without looking at the physical results, in order to detect programming errors in the source code.
- *Prototype testing*
  During the prototype testing, morphological computations are performed with models of a simple geometry (such as a closed basin) for which the physical results of a morphological simulation are known beforehand, in order to determine both errors not found during the debugging and possible physical shortcomings.
- *Real model testing*
  The real model testing concerns the performance of morphological computations with the Westerschelde model and the Friesche Zeegat model. The objective of Phase I, which is described in this report, was to perform an ESTMORF-computation with both models, without looking at the physical results. The calibration of the models should then take place during Phase II of the study.

This chapter contains an overview of the testing phases above. The debugging, prototype testing and the real model testing are described in Sections 4.2, 4.3 and 4.4, respectively.

During Phase II additional tests will be performed, especially with respect to land subsidence and sea level rise.

4.2 Debugging

Subroutine testing

Each subroutine has been tested independent from the other routines by comparing the computed values after the completion of the routine with 'hand-computed' results. Typing mistakes, syntax errors, etc. were found and the source code was corrected.

Integral testing

After the subroutines were checked independently, the complete source code was compiled in order to detect errors in the communication between subroutines, inconsistent definition and use of parameters, arguments, etc. For this purpose, a compiler with very good debug facilities was used: the SALFORD FTN77/x86™ compiler. The software has been compiled using the most stringent options for definition and debugging, which has led to a software package in the standard FORTRAN 77 language, without extensions. This makes sure that the software can easily be transferred to hardware using the UNIX-operating system.

4.3 Prototype testing

4.3.1 A semi-closed basin without tidal flats

The first prototype considered is a semi-closed tidal basin without flats. This semi-closed basin consists of a channel, which is open at one end and closed at the other end. At the open boundary, the tidal level is prescribed. The initial geometry of this prototype is characterized as follows:

length of the basin	:	15000	m
width of the channel	:	1000	m
depth of the channel (below MSL)	:	10	m
amplitude of the tide	:	1	m

The parameters for the sediment transport were chosen as follows:

'fall velocity' of the sediment	:	0.001	m/s
concentration at the open boundary	:	0.0015	
overall equilibrium concentration (c_E)	:	0.0015	

The basin was divided into 15 IMPLIC-branches, each with a length of 1000 m.

The computations were performed with a range of dispersion coefficients. The time steps for the solution of the concentration field were chosen such that the following stability criterion - which is only valid for the case without tidal flats - is fulfilled:

$$\lambda \leq \frac{1}{4} \left(\frac{A + W_c \, w_s \, \Delta t}{A} + 1 \right) \tag{4.1}$$

where:

$$\lambda = \frac{2 \, D_c \, \Delta t}{L^2}$$

The time step for the computation of the change of the cross-sectional area was set at one month.

Concentration field

The quasi-steady concentration field after one morphological time step (so with the initial geometry) can be computed analytically for this case.
In a closed basin such as described above, the residual currents are zero at each location in the basin. Furthermore, because tidal flats are not included, there is no sediment transport between the channel part and the low tidal flat part. Thus $u \equiv 0$ and $F_{lc} \equiv 0$ in Equation (3.3), which yields:

$$\frac{\partial A_c c_c}{\partial t} - \frac{\partial}{\partial x}\left(A_c D_c \frac{\partial c_c}{\partial x}\right) = W_c w_s (c_{ce} - c_c) \tag{4.2}$$

with boundary conditions $c_c(0) = c_E$ and $\frac{\partial c_c}{\partial x}\Big|_{x=L} = 0$.

During the computation of the concentration field, the cross-sectional areas are assumed to be constant. Furthermore, a quasi-steady concentration field is obtained after the iterative process for the computation of the concentration field. With a constant dispersion coefficient this gives:

$$\frac{\partial^2 c_c}{\partial x^2} - \frac{W_c\, w_s}{A_c\, D_c}\, c_c = -\frac{W_c\, w_s}{A_c\, D_c}\, c_{ce} \tag{4.3}$$

Using a linear relation between the equilibrium concentration and the equilibrium cross-sectional area below MSL for this basin, it can be deduced that:

$$c_{ce} = c_E\, \frac{L - x}{L} \tag{4.4}$$

The general solution of Equation (4.3) is then:

$$c_c(x) = a\, \exp(x\, \sqrt{r}) + b\, \exp(-x\, \sqrt{r}) + c_E \left(1 - \frac{x}{L}\right) \tag{4.5}$$

where:

$$r = \frac{W_c\, w_s}{A_c\, D_c} \qquad [m^{-2}]$$

By applying the boundary conditions, a and b in Equation (4.5) can be computed:

$$\begin{aligned} a &= \frac{c_E}{L\, \sqrt{r}\, (\exp(L\, \sqrt{r}) + \exp(-L\, \sqrt{r}))} \\ b &= \frac{-c_E}{L\, \sqrt{r}\, (\exp(L\, \sqrt{r}) + \exp(-L\, \sqrt{r}))} \end{aligned} \tag{4.6}$$

A computation with the ESTMORF model should yield above concentration field. Figures 4.3.1 and 4.3.2 show the analytically computed concentration field using Equations (4.5) and (4.6) and the concentration field computed with the ESTMORF model after one morphological time step for dispersion coefficients varying from 10 - 10000 m^2/s. The analytical solution and the numerical solution are almost identical, which shows that the numerical solution method that is implemented is correct. It can also be seen that for D_c = 10 m^2/s and D_c = 100 m^2/s, the concentration field is very close to the equilibrium concentration field (Equation (4.4)). For these values of D_c, the concentration is higher than the equilibrium concentration at the closed side of the basin only, where sedimentation will occur. The deviation between the concentration field and the equilibrium concentration field is much larger for D_c = 1000 m^2/s and D_c = 10000 m^2/s which results in higher sedimentation rates in the whole basin.

Bed level changes

The time frame of the morphological changes is determined by the choice of the dispersion coefficient and the 'fall velocity'. A sensitivity analysis during Phase II will make clear what influence the choice of the values of these parameters has on the time scales. Therefore, the exact time scale is not yet important during Phase I. However, the morphological computation should produce results which are in line with the physics in a qualitative sense.

Previous studies (van Dongeren, 1992; Wang, 1992; Fokkink, 1992; Fokkink, 1993) have shown that the morphological changes for a closed basin should lead to a bed with constant slope, with maximum depth at the tidal basin entrance and zero depth at the closed boundary. To check whether the ESTMORF model yields such a morphological development, a 5 years morphological computation was performed with the same coefficients as described above. After each year a new IMPLIC run was performed to incorporate any possible effects of the bed level changes on the hydrodynamic behaviour.

Figure 4.3.3 shows the bed level after 5 years for runs with dispersion coefficient varying from 10 - 10000 m^2/s and the equilibrium bed level with constant slope. The computed bed level of the run with D_c = 10000 m^2/s is already very close to equilibrium, whereas the bed level of the run with D_c = 10 m^2/s is far from equilibrium. It can be seen that sedimentation at first only takes place at the closed side of the basin, which is in line with the results of the analytical (and numerical) computation of the concentration field.

Note: Above computations have been carried out using a linear relation between the equilibrium concentration and the equilibrium cross-sectional area. This is done because for this case the analytical solution can be found very easily, while it proves that the solution method is correct. A power relation between the equilibrium concentration and the equilibrium cross-sectional area will lead to other differences between the concentration field and the equilibrium concentration and thus to another sedimentation/erosion pattern. In the next sections, the power of this empirical relation is set to 4.

Conclusions

The behaviour of the model is as was expected for the semi-closed basin prototype. As was stated before, the time scales involved are not yet important. In fact, by changing the values of the time determining parameters, it is possible to obtain any time scale.

4.3.2 A semi-closed basin including tidal flats

This prototype is very much similar to the one described in the previous section. However, there is one main difference: tidal flats are now part of the tidal basin.
The initial geometry of this prototype is characterized as follows:

length of the basin	:	15000	m	
width of the channel part	:	500	m	
width of the low tidal flat part (sum of the two sides adjacent to the channel part)	:	300	m	
width of the high tidal flat part (sum of the two sides adjacent to the low tidal flat part)	:	200	m	
depth of the channel part (below MSL)	:	10	m	(see upper part of Fig. 4.3.5)
height of the low tidal flat (above MLW)	:	0.5	m	(see upper part of Fig. 4.3.5)
height of the high tidal flat (above MSL)	:	0.5	m	(see upper part of Fig. 4.3.5)
amplitude of the tide	:	1	m	

The parameters for the sediment transport were chosen as follows:

'fall velocity' of the sediment	:	0.001	m/s
concentration at the open boundary	:	0.0015	
overall equilibrium concentration	:	0.0015	
dispersion coefficient channel transport	:	100.	m^2/s
dispersion coefficient channel-low flat	:	0.1	m^2/s
dispersion coefficient low flat-high flat	:	0.1	m^2/s

The power for the relation between the equilibrium concentration below MSL and the cross-sectional area below MSL was chosen 4, whereas the power for the relation between the equilibrium concentration on the flats and the equilibrium heights was chosen 3.

The time parameters were:

time step for area change	:	1	month
time step for solution concentration field	:	250	s
number of iterations	:	500	
time step until new IMPLIC run	:	1	year

A morphological computation was performed for a 5 years period, with a new IMPLIC run every year.

In Figure 4.3.4 the bed level in the channel part along the basin length is presented. It shows that the basin is filling slowly, with the highest sedimentation in the middle of the basin.

Figure 4.3.5 shows the development of the cross-sectional profile. The upper figure presents the uniformly distributed cross-sectional profile at the start of the morphological computation. The lower figure presents the same profiles after 5 years of simulation at distances 0, 8500 and 14500 m from the mouth of the basin. Examination of intermediate results showed that the heights of the flats were almost in equilibrium. The channel area, however, was still not stable, which is in line with the expected equilibrium cross-sectional areas. These should be similar to the test described in the previous section.

Conclusions

The test shows that the computed morphological changes for this case are qualitatively correct. As was stated before, the correct time scales should be determined by performing sensitivity tests on the parameters concerned. Such a sensitivity analysis is part of Phase II of the project.

4.3.3 An estuary including river input

The geometry for this case is similar to the geometry described in Section 4.3.1. However, there are now two open boundaries: at one of these boundaries (the sea side) the tide is prescribed, whereas at the other open boundary (the river side) a constant discharge is prescribed.

The initial geometry of this prototype is characterized as follows:

length of the basin	:	15000 m
width of the channel	:	1000 m
depth of the channel (below MSL)	:	10 m
amplitude of the tide	:	1 m
river discharge	:	4500 m^3/s

The parameters for the sediment transport were chosen as follows:

'fall velocity' of the sediment	:	0.001 m/s
concentration at the open boundary	:	0.0015
overall equilibrium concentration (c_E)	:	0.0015
dispersion coefficient	:	10000 m^2/s

The power for the relation between the equilibrium concentration below MSL and the cross-sectional area below MSL was chosen 4.

The time parameters were:

time step for area change	:	1	month
time step for solution concentration field	:	25	s
number of iterations	:	1000	
time step until new IMPLIC run	:	1	year

The basin was divided into 15 IMPLIC-branches, each with a length of 1000 m.

Previous study (Fokkink, 1993) has shown that the morphological changes for this case should lead to a bed with exponential slope, with maximum depth at the tidal basin entrance and minimum depth at the river boundary. To check whether the ESTMORF model yields such a morphological development, a 5 years morphological computation was performed with the same coefficients as described above.

In Figure 4.3.6 the bed level after 5 years is shown. The exponential bed profile is obvious.

Conclusion

The ESTMORF model simulates the morphological behaviour of a tidal river qualitatively correct.

4.4 Real model testing

4.4.1 Westerschelde model

The ESTMORF model has been run for the Westerschelde model. For branches with vertical or almost vertical channel sides it was necessary to adapt the software with respect to the input, the solution method and the communication between the routines in order to compute morphological changes in the channel only (so without tidal flat change). Morphological computations and hydrodynamic computations have been performed alternately without problems.

At this moment, it does not make sense to present results of the morphological computations for the Westerschelde. The values of parameters that strongly determine the morphological behaviour such as the dispersion coefficient, the equilibrium concentration, 'fall velocity' and the constants in the empirical relations should be determined during the calibration phase.

Furthermore, it is not yet clear whether the model geometry is suitable to perform proper morphological computations. Allersma (1993) concludes that the present one-dimensional models are calibrated with respect to the hydrodynamics, but not with respect to sediment transports and morphology. During the calibration phase of the project, it should become clear whether proper morphological computations can be performed with the existing Westerschelde schematization.

Conclusions

A Westerschelde ESTMORF model has been built. Morphological computations have been performed, which show that the ESTMORF software can handle the present Westerschelde model. The calibration of the model during Phase II should show whether the present model is suitable for morphological computations or that adaptations are necessary.

4.4.2 Friesche Zeegat model

A Friesche Zeegat model has been built based on a preliminary DUFLOW schematization provided by the client. During the test phase, it became clear that it was not sufficiently detailed to perform a proper IMPLIC run. Furthermore, it appeared that there is a bug in the IMPLIC software provided by the client. From discussions with the client it was concluded that further runs would be postponed until the new schematization of the Friesche Zeegat model was available. The IMPLIC software provided by the client will be analyzed at the clients' offices.

5 Conclusions

- A first version of the ESTMORF-software has been developed according to the functional requirements laid down in Karssen and Wang (1993) and to the technical requirements described in Chapter 2 of this report.

- Comprehensive tests have been performed with the software, in the form of debugging, prototype testing and real model testing.

- The test have shown that:
  - the software is correct from a programming point of view.
  - the numerical solution method is correct and correctly implemented.
  - the results of morphological computations with the software for prototype models are exactly in line with results of theoretical analyses

- A model for the Westerschelde has been built and morphological computations have been performed.

- A Friesche Zeegat model is built based on an existing DUFLOW schematization, which does not yet run with the IMPLIC software. A proper working model will be provided by the client during Phase II of the project.

The following activities still have to be performed during Phase II of the project:

- A brief sensitivity analysis for the three prototypes described in this report (a semi-closed basin without tidal flats, a semi-closed basin with tidal flats and an estuary) in order to get a feeling for the values of the parameters.

- Tests will have to be done for sea level rise and land subsidence.

- The calibration of the Westerschelde model and the Friesche Zeegat model. The calibration should be started after the sensitivity analysis. During the calibration it should become clear whether the present schematization is suitable for morphological computations.

- Preparation of a report.

- Delivery of the software to the client.

In close concert with the client it was decided to perform the comprehensive tests during Phase I of the project. This activity is therefore dropped from the scope of work for Phase II.

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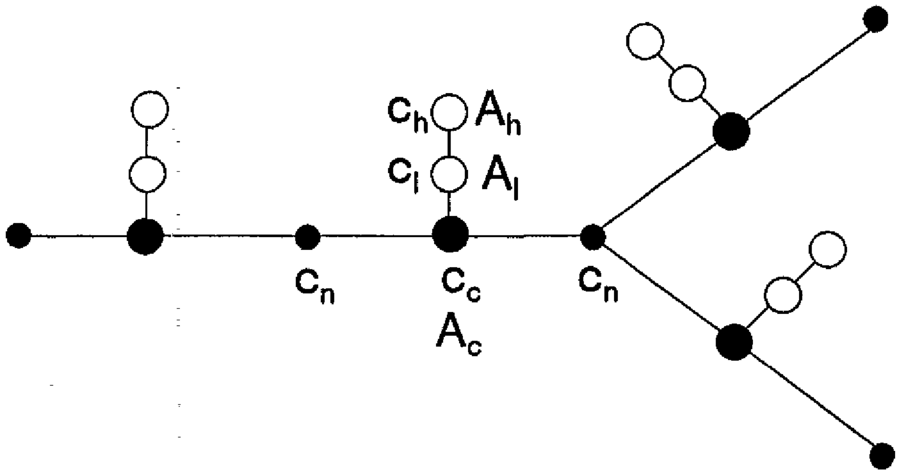
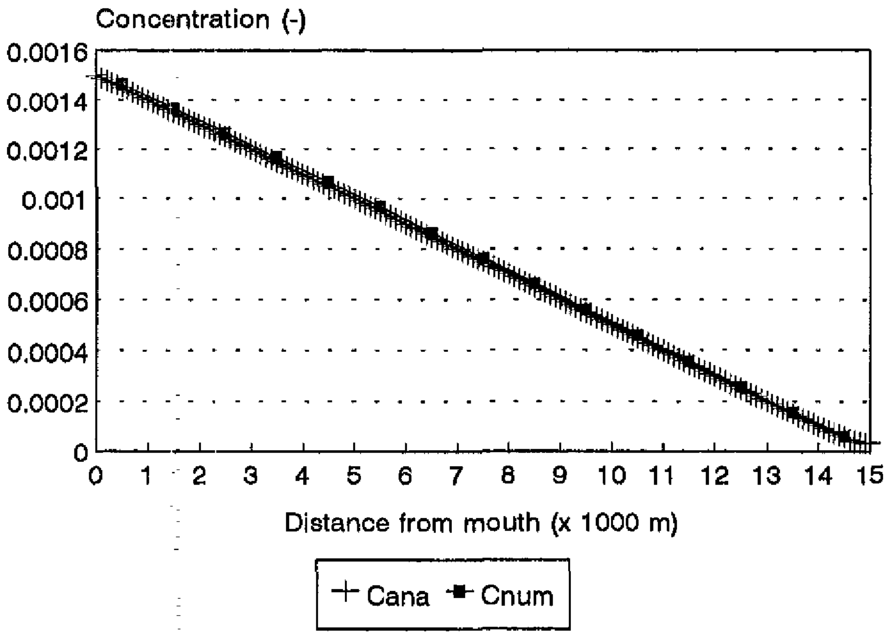


Numerical grid Locations of computational points		January 1994
	ESTMORF	
D E L F T H Y D R A U L I C S	Proj: Z-715	Fig. 3.4.1



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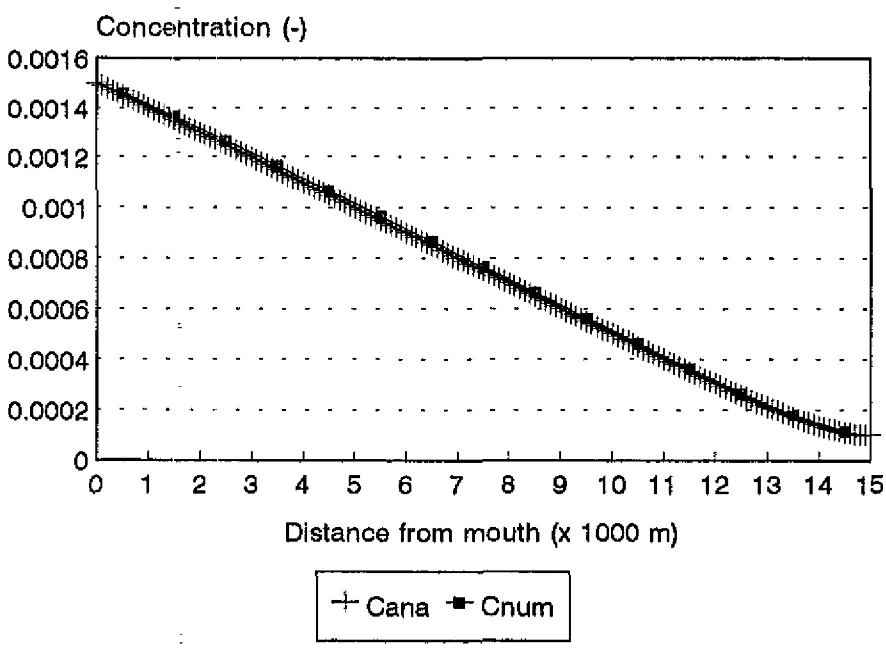
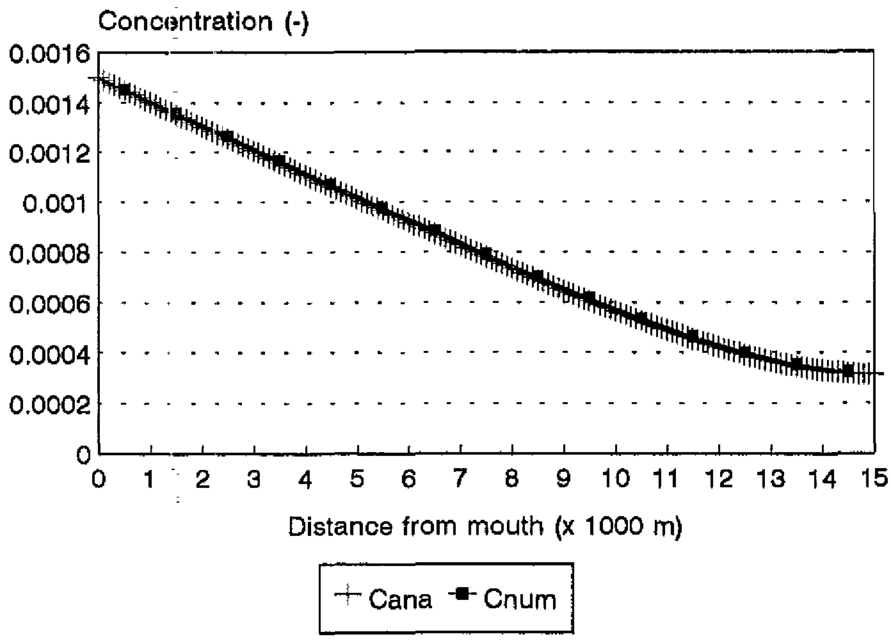


D = 100

Analytical and numerical concentration field Closed basin without flats D = 10, D = 100		January 1994
	ESTMORF	
DELFT HYDRAULICS	Proj: Z-715	Fig. 4.3.1



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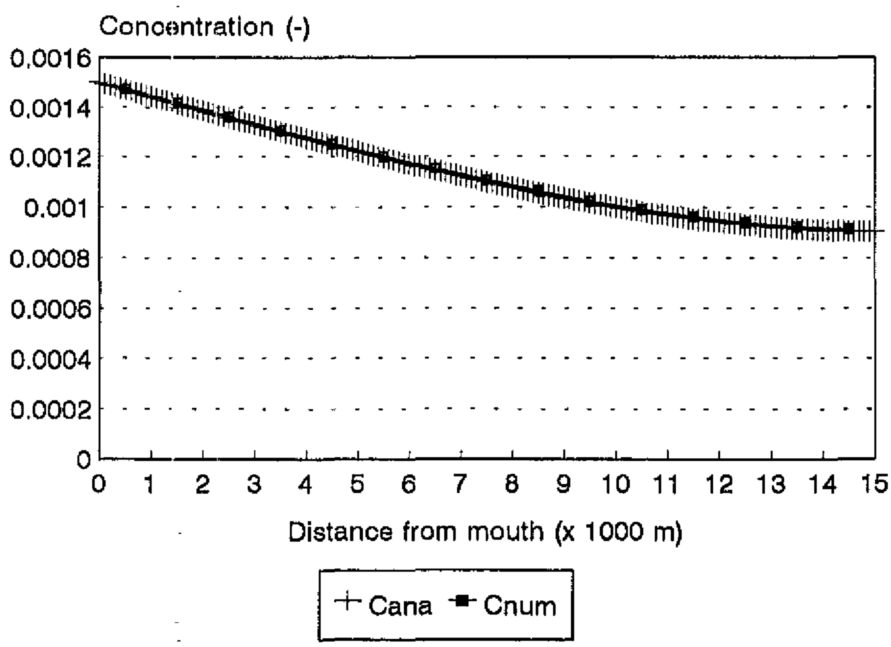
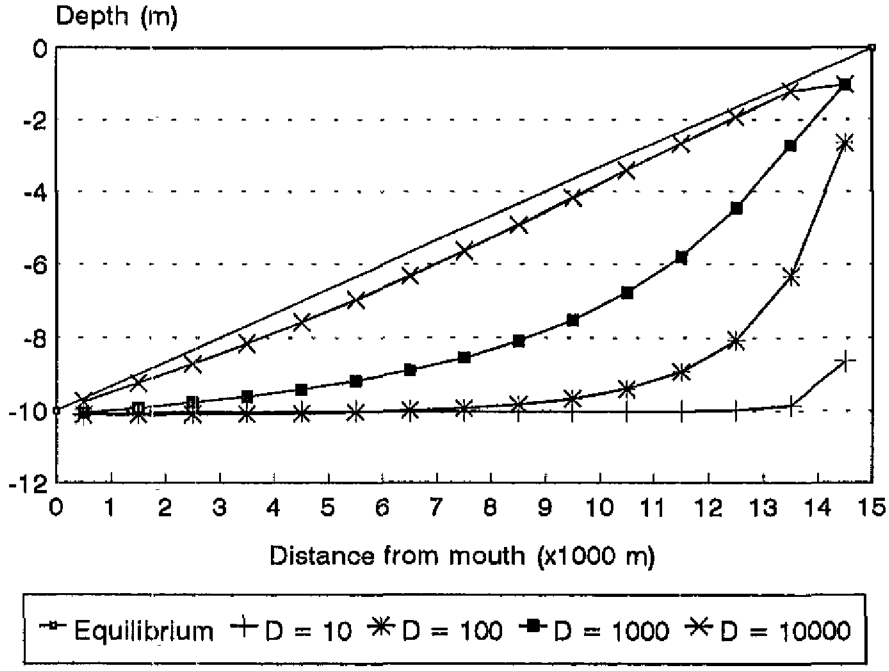
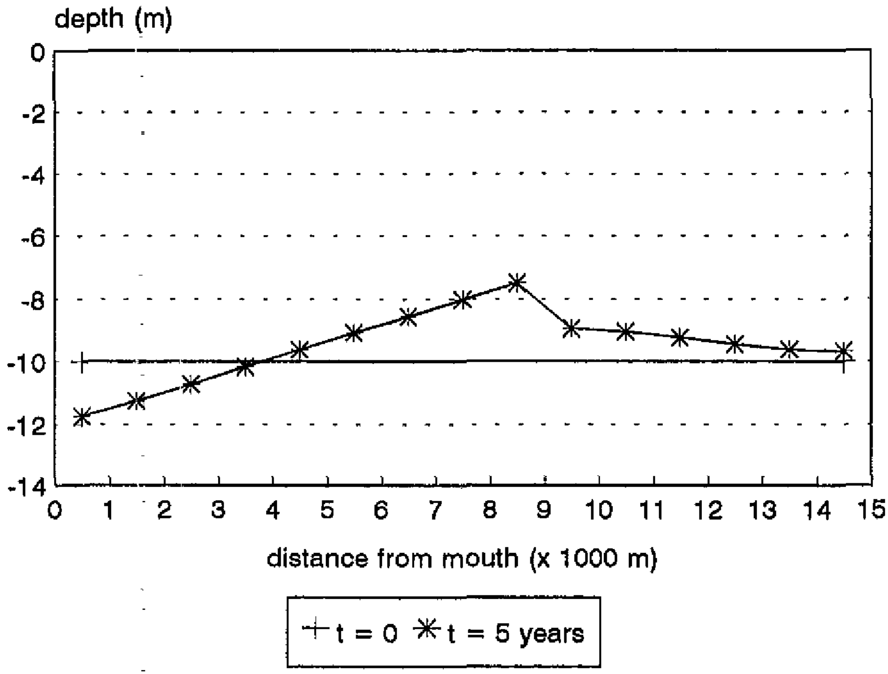


D = 10000

Analytical and numerical concentration field Closed basin without flats D = 1000, D = 10000		January 1994
	ESTMORF	
DELFT HYDRAULICS	Proj: Z-715	Fig. 4.3.2

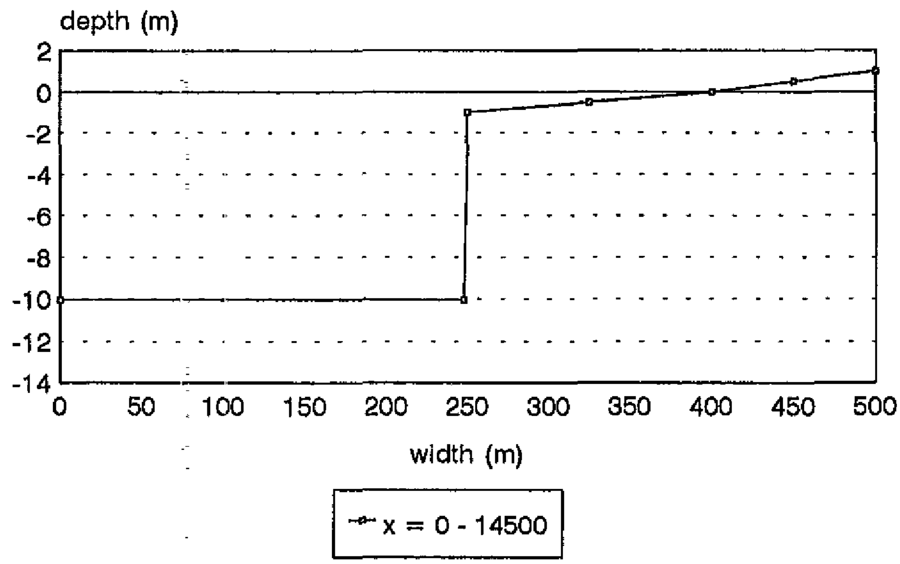


Bed level after 5 years Closed basin without flats D = 10 - 10000		January 1994
	ESTMORF	
D E L F T H Y D R A U L I C S	Proj: Z-715	Fig. 4.3.3

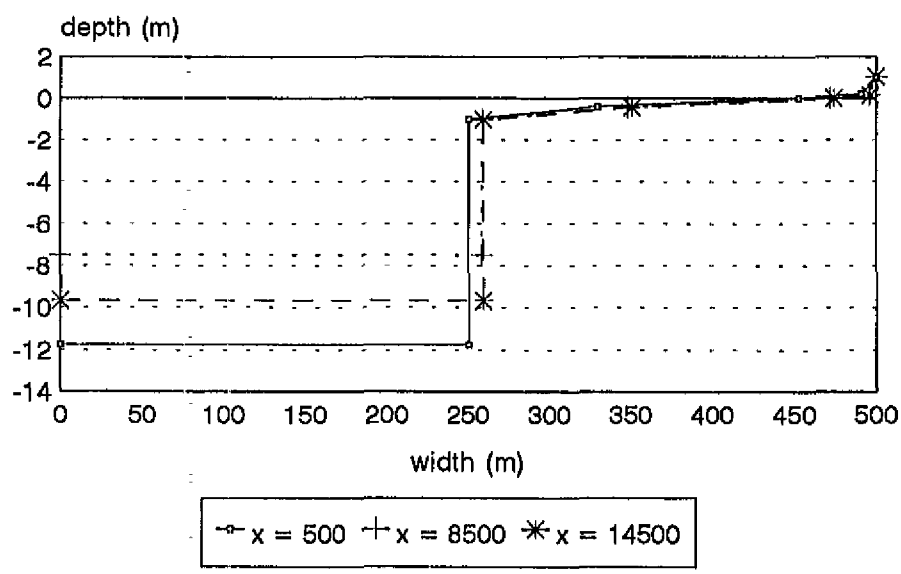


Bed level after 5 years Closed basin with flats		January 1994
	ESTMORF	
DELFT HYDRAULICS	Proj: Z-715	Fig. 4.3.4

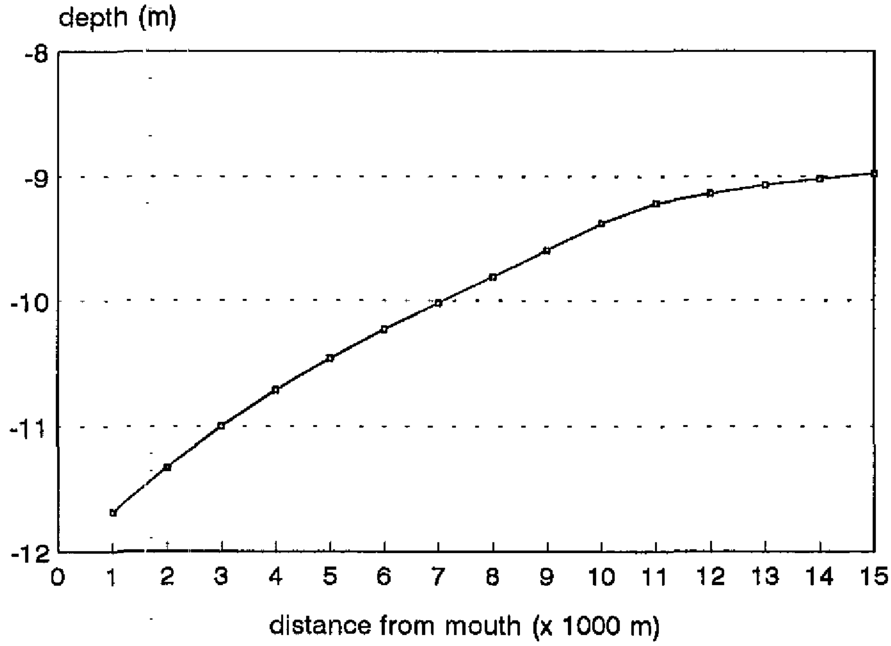
t = 0 years



t = 5 years



Morphological development of the cross-section Closed basin with flats t = 0, t = 5 years		January 1994
	ESTMORF	
DELFT HYDRAULICS	Proj: Z-715	Fig. 4.3.5



Bed level after 5 years **Tidal river**		January 1994
	ESTMORF	
D E L F T H Y D R A U L I C S	Proj: Z-715	Fig. 4.3.6

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