Prepared for:
RIKZ Rijkswaterstaat

A long-term morphological model for the whole Dutch Coast

Part I: Model formulation

Report
November, 2004
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1 Introduction

1.1 Background

National decisions regarding coastal management require understanding of the long-term (50-100 years) effects and large-scale (1-100 km) implications of both natural processes and major coastal engineering projects. Examples are the effects of climate change and sea-level rise on a sandy coast that is partly protected by groynes or sea-walls and, in relation to this, the long-term effects of coastline maintenance by on-going nourishment. Problems related to major coastal engineering projects are the far-field effects of large-scale land reclamation and the effects of the large-scale sand-mining necessary for such projects.

The national research program COAST*2005 focuses, amongst others, on understanding these long-term, large-scale morphological effects and on developing the tools to quantify them. Within this framework, a model is being developed, which should be capable of simulating the morphological evolution of the Dutch coast at the required spatial and temporal scales.

Morphological characteristics of complicated coastal systems can be described using different modelling approaches [De Vriend et al., 1993]. One such an approach is process-based modelling where the physical processes involved are described mathematically, combining a detailed fluid-flow model with a sediment-transport model. By successive iteration the dynamical evolution of an area can be simulated.

For the analysis of the dominant processes and circulation patterns, wave, current and sediment transport, process-based models appear to be useful. However, they are less suitable for simulating long time periods, as they require large computational effort and the numerous iterations and accumulation of rounding-off errors may lead to unrealistic results. Moreover, it is questionable whether such an up-scaling approach yields realistic and useful result for long-term applications, because processes that may be ignored at the small scale (hence are not included in the process models), may have large net effects on the large scale.

PONTOS and ASMITA use a different modelling approach, which is behaviour-oriented [Steetzel et al., 1998; Stive et al., 1998]. In PONTOS the physical processes (i.e. cross- and long-shore transport) are parameterised in simple relationships which respond to input conditions of wave and tidal climate and sea-level. The combined effects of the processes result in the morphological evolution of the coastal system. The resolution of simulations is coarser than would be available with a process-based model, but the results in terms of the distribution of erosion and sedimentation after, e.g. a 50 year-period, seem more realistic. In addition, because of its straightforward approach, these models are easier accessible and more user-friendly than most process-based models. Calculations with the previous version of the PONTOS model (version 1.0) indicated that it is a promising tool to simulate and quantify the morphological implications of the problems just described.
The basic concept in ASMITA is that a tidal inlet system can be schematised into a number of morphological elements and that for each element a morphological equilibrium exists depending on the hydrodynamic conditions and large-scale morphometric conditions (e.g. tidal basin area). When one or more elements are out of equilibrium morphological changes will take place tending to restore the system to (a possibly new) equilibrium. Erosion/sedimentation rates are assumed to be proportional to the difference between the local equilibrium concentration and the actual concentration.

1.2 Study objective

Within the framework of the Dutch national research program “COAST*2005”, a model has to be developed that is capable of quantifying the long-term (50 to 100 years) and large-scale (1-100 km) morphological evolution of the Dutch coast. This model will be used to determine the effects of sea level rise for a partly protected coastline, the far field effects of a large-scale land reclamation and the required extraction of large amounts of sand (sand mining), the long-term effects of ongoing nourishments and the long-term effects of a changing climate.

Within the framework of a preceding phase of the study (contract RKZ-370), the set-up of the PONTOS-model, the so-called pilot-version and the conceptual validation of its components were dealt with. Also a preliminary application for the Holland coast was addressed [Steetzel et al., 1998]. In the next phase of the study (contract RKZ-594), the existing pilot version has been updated and validated yielding a more complete and better applicable version of the model and the PONTOS-1.0 model has been applied to the Holland coast.

In the present phase of the study (contract RKZ-1257) the application is extended. In order to apply the model concept to the entire Dutch coast the impact of ebb-deltas and related tidal inlet systems has to be taken into account. Therefore an ‘inlet-extension’ of the PONTOS-concept, based on formulations used in the MOBIC-model (a multi-layer model for the interrupted coast which acted as the basis of the current PONTOS-model) has to be implemented. The ASMITA model will be used to provide input for this inlet extension.

1.3 Approach

The model developed is originally based on the multi-layer concept, in which the cross-shore profile is schematised as a number of mutually coupled layers, defined between fixed profile depths. These layers interact through cross-shore transport. In longshore direction the layers respond to gradients in the longshore transport generated at the profile regions they represent.

This type of models has been developed to describe the movement of selected depth contours in a similar way as one-line models. The cross-shore exchange of sand between the various cross-shore subsections and associated changes in the bed profile can to some extent be taken into account. This was first accomplished by Bakker, later by Perlin and Dean, by De Vriend and Bakker and Steetzel (see [Bakker, 1999]).
In spite of the additional detail given by the multi-line models, they have not been very successful so far, mainly because it has been difficult to specify realistic relations for cross-shore sediment transport and the distribution of the longshore transport. The initial result was a model that is more detailed than the one-line model, but also requires much more calibration and in the end does not provide significantly more new information than it requires for calibration.

Some recent developments have substantially increased the applicability of these models. Starting with the Bakker’s two-line model (1968), Steetzel (1995) extended the concept by incorporating the morphological behaviour of mixed tidal inlets based on work by De Vriend and Bakker (1993) and more recently by adding more layers and improving the way in which both the cross-shore and longshore interaction are taken into account [Steetzel et al., 1997].

Earlier versions of this kind of models, see e.g. [Bakker et al., 1988], had the drawback that the interaction between the layers and their response in the longshore direction was determined by a series of constants, which had to be pre-defined by the user based on mathematical process-based models or on empirical data. This put considerable restraints on the practical use of the concept. In the present set-up of the model these pre-defined constants have been replaced by formulations to compute cross-shore and longshore sediment transports directly within the model in terms of external conditions such as wave climate, tidal conditions, bathymetry and sediment characteristics.

1.4 Project team

The work has been carried out by a joint venture WL | Delft Hydraulics and Alkyon Hydraulic Consultancy & Research mainly by Dr. Ir. H.J. Steetzel (Alkyon) and Dr.Ir. Z.B. Wang (WL | Delft Hydraulics).

Dr. J.P.M. Mulder and Ir. J.G. de Ronde participated on behalf of the National Institute for Marine and Coastal Management of Rijkswaterstaat.

1.5 Set-up of the report

The final report of the study is divided into two parts, namely the model formulations and the application of this model to the Dutch coast.

This is part I of the report: model formulations. The theoretical background on the model concept is described, focusing on the way physical processes have been incorporated in the model. Within the framework of this study some of these processes have been significantly improved and validated more extensively. Attention is paid to:

- The model concept and operation (Chapter 2);
- Hydraulic climate schematization (Chapter 3);
- Basic sediment transport formulations (Chapter 4);
- Impact of structures (Chapter 5);
- Refraction, diffraction and contraction (Chapter 6);
- Implementation of tidal inlets (Chapter 7);
- Coastal management (Chapter 8);
Chapter 9 summarizes the most relevant improvements of the model.
2 Model concept and operation

2.1 Introduction

In this chapter, the general aspects of the model concept and application will be discussed. The following items are dealt with:

- The multi-layer concept;
- The definition of the basic layer;
- The governing equations used in the model;
- The model boundaries;
- The mathematical implementation;
- The output provided by the model;
- A brief guideline for model.

2.2 Multi-layer concept

2.2.1 Introduction

In a multi-layer or multi-line model, the cross-shore profile is schematised as a number of mutually coupled horizontal layers. The vertical interaction between these layers (i.e. the cross-shore transport) depends on the associated intermediate bottom slope (which is determined by the mutual distance between the layers), the related wave action and the characteristics of the bed material.

The local transport in longshore direction depends, amongst others, on the orientation of the layer relative to the equilibrium orientation (usually perpendicular to the direction of wave attack). Compared to the standard 1-line models, the advantage of this approach is that the effect of cross-shore movement of sediment can now be taken into account also. In some of the applications this seems a very welcome modification. Extension of the broadly applied GENESIS-model (a 1-line model [Hanson, 1989]) in cross-shore direction using some of the concepts introduced in the PONTOS-model is even considered [Hanson and Larson, 1999].

2.2.2 Coordinate system

The PONTOS-model uses a rectangular grid, with the x-axis in longshore direction. The y-axis refers to the seaward direction and the z-axis is directed upward with the zero level at the reference level. As a consequence of the definition of the y-axis, a positive cross-shore transport implies movement of material in seaward/downward direction.
2.3 Layer definition

2.3.1 Introduction

In the present version of the PONTOS-model, the cross-shore profile was schematised as five horizontal layers, ranging from the dune top down to the near-horizontal coastal shelf. Each individual layer is denoted with an index \( j \), ranging from \( j = 0 \) to \( j = 4 \).

The first layer, having index \( j = 0 \), refers to the dune layer. Subsequent layers refer to layers positioned further seaward.

Figure 2.1 shows the model concept and layer approach including the schematisation of the cross-shore profile.

2.3.2 Layer levels

In order to define individual layer positions, the accompanying levels have to be specified. The horizontal intersection between the five basic layers, is described by a longshore varying or fixed level.

The upper level of the dune layer \( Z_0 \) refers to the level of the dune top, which of course could vary in longshore direction.

For layer 1 to 4 a specific fixed level has to be assumed. These levels have to be based on the schematization of the processes involved. The following levels could be used:

- The intersection between beach and dune level at the average level of the dune foot (\( Z_1 \));
- The intersection between the surf zone and beach level, just below mean low water (\( Z_2 \));
- The intersection between middle shoreface and surfzone, just below the region where breaker bars are active (\( Z_3 \));
- The intersection between middle and lower foreshore (\( Z_4 \));
- The intersection between lower foreshore and (near-horizontal) sea bottom (\( Z_5 \)).

2.3.3 Layer positions

The actual position of a layer has to be assessed from the sediment balance in the cross-shore profile. Assuming that at a certain location \( x \) in longshore direction, this profile can be defined by some general function, according to:

\[
    z = F(y) \tag{2.3.1}
\]

The characteristic layer position \( y_i \) for a layer with thickness \( d_j \) between lower level \( Z_{j+1} \) and upper level \( Z_j \) is the average position computed from:

\[
    y_j = \frac{1}{d_j} \int_{z_{j+1}}^{z_j} y(z) \, dz \tag{2.3.2}
\]

Depending on the actual shape of the local cross-shore profile, the characteristic layer position is located somewhere in between the position of the depth contours of the boundary levels.
It should be noted that the user of the PONTOS-model has to define the various initial positions of the individual layers, since a general mathematical tool to transfer a specific cross-shore profile e.g. a JARKUS-profile, to a series of cross-shore layer positions is not implemented in the model.

### 2.3.4 Reciprocal modelling

To define the actual input for the layer-model, the actual position of local layers can be assessed from simple balance equations as presented in the previous section.

The PONTOS-model basically uses a schematic cross-shore profile consisting of several layers and associated positions, which proofs to be adequate for the assessment of both global and detailed balance properties. In some cases however, additional information on the actual shape of the cross-shore profile is needed in order to implement specific processes in a more sound way.

An example of a process which asks for more detail on the actual cross-shore profile is the bypass of material along a groyne in case of wave-induced sediment transport. Depending on the actual cross-shore profile just updrift of the structure, a part of the sediment transport will pass the seaward tip of the groyne. The estimated level of the cross-shore profile at this tip location forms the basic parameter.

Another example is the incorporation of the effect of a contracted tidal flow due to partial blockage of the surfzone. In order to take the continuity of the tide-induced flow into account, a transition from adjusted horizontal flow patterns to layer related transports has to be made.

The original idea was to compute the settings (constants and powers) of a polynomial profile shape according to:

\[
z(y) = \sum_{p=0}^{n} A_p \ y^p
\]

or:

\[
y(z) = \sum_{p=0}^{n} B_p \ z^p
\]

taking in account the balance restrictions from Eq.(2.3.1). In spite of numerous efforts the procedure based on these assumptions yielding unacceptable profile shapes in case of steep cross-shore profiles.

In order to obtain a reliable result, a rather pragmatic, though robust procedure has been implemented in order to assess a continuous cross-shore profile \(y_p(z)\) from layer level and position information, yielding either a depth contour for a specific cross-shore position (for the groyne problem) or a cross-shore position for a specific depth contour (for the contraction problem).
This procedure is based on the following assumptions:

- The continuous profile in between the two layer boundaries consists of two straight lines, connecting three specific points;
- The position of these lines at these boundary levels is located in the middle between the adjacent layer positions, yielding the two outer points;
- The level of the middle point is based on the balance equation per layer.

The second condition yields a cross-shore position of this profile at level \( Z = Z_j \) according to:

\[
y_{c,j}(z = Z_j) = \left( Y_{j-1} + Y_j \right) / 2 \quad \text{for } j > 1
\]

and:

\[
y_{c,j}(z = Z_j) = Y_0 \quad \text{for } j \leq 1
\]

The last condition yields the level of the continuous cross-shore profile \( y_p(z) \) at the location of the related layer \( Y_j \).

From the balance equation (and using the positions \( y_{c,j} \) at \( z = Z_i \) and \( y_{c,j+1} \) at \( z = Z_{j+1} \)) according to:

\[
(Y_j - y_{c,j})(Z_j - z_{c,j}) / 2 = (y_{c,j+1} - Y_j)(z_{c,j} - Z_{j+1}) / 2
\]

the \( z_{c,j} \) level can be determined. The result is a continuous cross-shore profile.

### 2.3.5 Shelf extension

In order to be able to incorporate the effects of offshore withdrawal of material, a part of the (near horizontal) shelf should be incorporated in the model.

In order to do this, the most favourable approach would be to position the outer limit of the model say 50 km’s seaward of the reference line, that is far seaward of the \( Z_5 \)-depth contour. In that case the internal exchange between this 5\(^{th}\) layer (or in fact 5\(^{th}\) zone) and the 4\(^{th}\) layer should be taken into account in the model, whereas no net transport across the seaward boundary of the 5\(^{th}\) layer might be assumed.

In that case, the longshore exchange of sediment in the shelf zone will be governed by the tide-induced sediment transport pattern. Since the rate of transport depends on the water depth to a large extent, the effect of a longshore variation in the shelf level will yield a sediment transport pattern, which aims at a gradual elimination of these discontinuities.

With respect to the actual sediment transport rate it might be assumed that the effect of wave-induced transport can be ignored on this depth. However, the effect of wave-induced stirring is taken into account in the tide-induced transport formulation.

As a consequence, the actual longshore transport (expressed in m\(^3\)/yr) across the boundary of two adjoining grid cells depends to a large extent on two parameters, namely, the characteristic depth used in the transport formulation and the characteristic width of the transport path.
Special attention should be given to the procedure to assess the longshore transport rate (expressed in m$^3$/m$^1$/yr) at the intersection between two grid cells with different bottom level.

An extraction of material from the shelf zone yields a lowering of the shelf layer. The amount of lowering will depend on the actual geometry.

In the present version of the model the actual evolution of the shelf layer is not yet taken into account, although the set-up of the model has been modified such that the actual incorporation of this extension seems relatively simple.

An additional advantage of this extra layer would be that the cross-shore transport rate across the 20m depth contour (the interface between layers moving in horizontal direction and the shelf moving in vertical direction) can be modelled more elegant, in order to take the effects of deep water extractions and profile steepening into account [Mulder, 1998; Stam, 1999].

### 2.4 Governing equations

#### 2.4.1 Balance equations per cell

For a specific computational cell with width $\Delta X_i (= X_i - X_{i-1})$ the increase of volume $\Delta V_{ol_{i,i}}$ is computed from:

$$\frac{D V_{ol_{i,i}}}{D t} = (Q_{x_{i-1},i} - Q_{x_{i},i}) + (Q_{y_{i},i} - Q_{y_{i+1},i}) + \frac{D S_{i,i}}{D t} \] (2.4.1)$$

in which $Q_{x,i}$ refers to the longshore transport in layer $j$ at position $X_i$, $Q_{y,i}$ refers to the cross-shore transport at level $Z_j$ in the interval $X_{j-1} ... X_j$ and $S_{i,i}$ corresponds to a source or sink term in cell $(j,i)$.

#### 2.4.2 Balance equations per layer

Using the concept of a layer-approach, the volume in a specific cell or layer is represented by the specific position of the layer in cross-shore direction. A mutation in a cell’s volume, $\Delta V_{ol_{j,i}}$ in layer $j$ and cell with index $i$ yields a cross-shore shift in the characteristic position of layer $j$, denoted as $\Delta y_{j,i}$ according to:

$$\Delta y_{j,i} = \frac{\Delta V_{ol_{j,i}}}{\Delta X_i d_{j,i}} \] (2.4.2)$$

in which $d_{j,i}$ denotes the thickness of layer $j$ in the interval $X_{j-1} ... X_j$.

Substitution of this translation yields:

$$\frac{\Delta y_{j,i}}{\Delta t} = \frac{(Q_{x_{j,i-1},i} - Q_{x_{j,i},i})}{d_{j,i} \Delta X_i} + \frac{(Q_{y_{j,i},i} - Q_{y_{j,i+1,i}})}{d_{j,i} \Delta X_i} + \frac{\Delta S_{j,i}}{d_{j,i} \Delta X_i \Delta t} \] (2.4.3)$$
In this equation \( Q \) refers to the longshore integrated magnitude, viz. taken into account the width of the cell \( \Delta X_j \). Using \( q_y \) (expressed in \( m^3/m^1/yr \)) instead of \( Q \) (expressed in \( m^3/yr \)) yields:

\[
\frac{\Delta y_{j,i}}{\Delta t} = \frac{(Q_{x,j,i} - Q_{x,j,i-1})}{d_{j,i} \Delta X_i} + \frac{(q_{x,j,i} - q_{x,j,i+1})}{d_{j,i} \Delta X_i \Delta t} + \frac{\Delta S_{j,i}}{d_{j,i} \Delta X_i \Delta t} \tag{2.4.4}
\]

The assessment of the longshore transport \( Q \), for each individual layer is elaborated in Chapter 4, whereas the cross-shore transport \( q_y \), rate at each intersection is studied in Chapter 5. Sources and sinks related to the last term in this equation are elaborated in Chapter 7 dealing with nourishments.

### 2.4.3 Longshore exchanges

The longshore exchange between the individual cells is denoted by \( Q_{x,j,i} \) (expressed in \( m^3/yr \)), in which \( j \) refers to the layer-index and \( i \) refers to the index of the cells in longshore direction. This longshore transport has to be defined for every individual layer, that is for \( j = 0 \) to 4 at every gridpoint along the coastal stretch.

A more detailed elaboration of the formulations for this longshore exchange is presented in Chapter 4.

### 2.4.4 Cross-shore exchanges

The cross-shore exchange between the layers is denoted by \( q_{y,j,i} \) (expressed in \( m^3/m^1/yr \)), in which \( j \) refers to the layer-index and \( i \) refers to the cell-index in longshore direction. This cross-shore transport rate has to be defined for every layer transition, that is for \( j = 0 \) to 5, in which the index refers to the importing layer.

A more detailed elaboration of the formulations for this cross-shore exchange is presented in Chapter 5.

Special attention will be given to the net transport across the first dune row, viz. a source or sink for the dune layer with index \( j = 0 \), and the exchange between the lowest layer, viz. the lower shoreface \( j = 4 \) and the sea bottom denoted as \( q_{y,5,I}(x) \).

### 2.5 Model boundaries

#### 2.5.1 Introduction

The overall schematization basically refers to the position of the left- and right-hand boundary of the coastal area of interest. This overall schematization (including the specification of individual coastal sections) forms the starting point for the large-scale interpretation of the models results and links PONTOS-results to other large-scale box-like models (e.g. the ASMITA-model).
2.5.2 Left- and right-hand boundary

Exchange through both the left- and right-hand boundary of the model is restricted to the actual basic layers of the scheme, viz. the layers with index \( j = 0 \) to 4.

To be more specific the actual transport across the boundary cells can be pre-defined using a time-series \( Q_{jd}(t) \) in which \( j \) refers to the layer index and the index \( i = 0 \) or \( i = n \) refers to the first, left-hand gridpoint and the last, right-hand gridpoint respectively.

2.5.3 Landward boundary

The first dune row, viz. layer with index \( j = 0 \) acts as the landward boundary. Exchange across the landward boundary due to a yearly net transport can be taken into account using a pre-defined longshore distribution of the net transport \( q_{l}(x) \). A negative magnitude implies a landward loss of sediment.

In the present version of the model (PONTOS-1.0), the landward boundary consist of an uninterrupted dune row.

2.5.4 Seaward boundary

In the initial set-up of the model (the pilot version) the lower boundary of the most seaward layer was positioned at the transition between the (relative steep) shoreface and the relative flat shelf and acts as the seaward boundary. Exchange across this boundary, due to a yearly net transport, was taken into account by a pre-defined longshore distribution of the net transport rate, denoted as \( q_{s}(x) \). According to the coordinate system a positive magnitude implies a seaward loss of sediment. This definition holds also for the present version of the model (PONTOS-1.0).

In a next version of the model in which the so-called shelf-extension is incorporated, this boundary will be positioned at the seaward side of the modelled part of the shelf, located at a fixed distance from the reference line (the so-called \( Y_b \)-contour).

As a result of this the longshore distribution of the net transport rate from the fourth layer to the shelf across the \( Z_b \)-level, denoted as \( q_{b}(x) \), becomes an internal transport rate to be assessed from the cross-shore transport formulation as elaborated in Chapter 5.

The seaward loss across the seaward border of the model, the \( Y_b \)-contour, denoted as \( q_{b}(x) \) and has to be treated as an external boundary.

2.5.5 Tidal inlets

In the framework of the present study, the PONTOS-model has been coupled to the ASMITA model so that also an interrupted coastline can be modelled. An off-line as well as an on-line coupling have been implemented.

In the off-line coupling the net transport through the tidal inlet has been based on external computations with the AsMiTA-model, whereas a conceptual basin model based on ASMITA has been incorporated for the on-line coupling.

Detailed description of the model formulations concerning tidal inlets is given in Chapter 7.
2.6 Software implementation

2.6.1 Set-up of the model

The computational model PONTOS basically consists of three parts:

- A pre-processor which helps the user to generate the model input files (the EDIT-menu),
- The actual processor (RUN-menu) that performs the computations using the so-called MMLM.DLL-module and generates an output file comprising the model results and
- A post-processor (the VIEW-menu) which allows the user to investigate the results of the computations performed.

The actual computations are performed using a FORTRAN-based model which is linked to the VISUAL BASIC-environment using a dynamic link library, a so-called DLL-file. The FORTRAN program called ‘Modified Multi Layer Model’ is used to assess the development of a coastal stretch during one single time step and is repeatedly called by the PONTOS-model itself.

2.6.2 Data-flow

The data-flow used in the model is rather simple, since basically only two types of data files are used, namely:

- Input files with the extension ‘.DAT’, describing the input for the PONTOS-model for a specific case;
- Output files with the extension ‘.MAT’, summarising the models results.

The core of the model, viz. the processor (or in fact the MMLM-routine) adds an output file with extension ‘.MAT’ to the corresponding DAT input file. Depending on the specifications in the input file and the general specifications in the settings-file, information is transferred and stored in a related result-file with a MAT-extension. The contents of this MAT-file can be inspected and visualised using the post-processor.

2.6.3 Basic menus

The present version of the PONTOS-model has six main menu items:

- File-options menu (the FILE-menu);
- Pre-processor (the EDIT-menu);
- Processor (the RUN-menu);
- Post-processor (the VIEW-menu);
- Parameter settings (the SETTINGS-menu);
- Help (the HELP-menu).

More details on these items can be found using the online help information.
2.6.4 Model settings

The PONTOS model uses several constants of which a part of them is stored in the so-called PONTOS.PAR-file. These general settings of the model can be inspected and modified using the SETTINGS-menu. Several groups of parameters can be distinguished, namely:

- Numerical parameters;
- Physical parameters;
- Transport parameters.

Furthermore the actual output of the model can be influenced by specification of so-called:

- Output options.

The 'physical processes' considered in the present version of the model are:

- Equilibrium profile shape;
- Wave-driven transport distribution;
- Tide-induced current distribution;
- Refraction and shoaling model;
- Diffraction model;
- Contraction model.

The actual sediment transport is due to both wave and currents. In the formulations used in the model three types of transport are distinguished:

- Wave-forced cross-shore transport;
- Wave-driven longshore transport;
- Tide-driven longshore transport.

The contents of an output-file, a CASE.MAT-file is affected by the actual setting of the output options. In the PONTOS.PAR-file these settings are present as a series of 0's or 1's. No specific output is obtained for a zero-setting.

2.6.5 Help information

The information provided in the help-file is accessible in an effective way, using a summary, an index and a search option. Some of the topics are directly accessible from the related window in the PONTOS-program.

The advantage of this method of program documentation is that modifications in the set-up and capabilities of the program can be directly added to the online help, keeping the documentation always up-to-date.

2.6.6 Environment and installation

The PONTOS-model uses a WINDOWS-orientated user-interface, developed using MICROSOFT VISUAL BASIC for WINDOWS version 6.0 (SP5) and a mutually linked dynamic link library, developed using COMPAQ Visual FORTRAN Version 6.1.0 (Professional edition), for the actual computational routines.

The online documentation of the model has been developed using the EASYHELP/WEB for WORD 6/7, Version 2.82i (32 bit-release).

Running the PONTOS-model requires a 32-bit WINDOWS environment.
The PONTOS-model must be installed using the set-up-program SET-UP.EXE (provided on the first diskette or CD-ROM). The installation wizard will guide the user through the complete process. At the end a PONTOS-program group will be installed consisting of a number of files in a PONTOS-program-directory. This PONTOS-program directory (e.g. C:\Program Files\PonTos) comprises the following files:

- PONTOS.EXE (the actual overall program);
- PONTOS.HLP (the help-information);
- MMLM.DLL (the computational procedure assessed by PONTOS.EXE);
- MMLM.EXE (a standalone computational routine);
- PONTOS.PAR (a file containing parameter settings).

After running the model for the first time, a sub directory PONTOS/TMP will be present in which the PONTOS-program (both PONTOS.EXE, MMLM.DLL) stores temporary files.

After running the model four more files will be present:

- PONTOS.LOG (a file containing session information);
- MMLM.LOG (a file containing information on the most recent computation);
- PONTOS.CAL (an input file containing data used for calibration purposes);
- PONTOS.VAL (an output file containing validation data).

The so-called PONTOS.LOG-file keeps track of each individual PONTOS-session, while the MMLM.LOG-file contains information on the most recent computation only. The calibration and validation file will be present on the program directory as well.

2.7 Model output

2.7.1 Introduction

The output of the model consists of both specific array’s (as specified in the settings-file) and case-related output information. The latter refers to:

- The evolution per coastal section;
- The evolution of specific profiles;
- The evolution of depth contour positions;
- The bottom evolution on a horizontal grid.

Last option provides the opportunity to compare the results of the PONTOS-model with other morphological models. The results can be visualised using the VIEW-option of the PONTOS-model and can be used directly by the TEKAGX-drawing package.

2.7.2 Specific array’s

In the PONTOS.PAR-file these settings are present as a series of 0's or 1's. No specific output is obtained for a zero-setting.

Potentially a large number of arrays can be generated. Amongst these are:
• The detailed initial longshore distribution of the hydraulic conditions per individual combination of waves and tide;
• The detailed initial distribution of both the cross-shore transport rate, the wave-induced and tide-induced sediment transport rate per individual combination of waves and tide;
• The net cross-shore and longshore transport rates at every required output interval;
• The position of the individual layers at every required output interval, both planform as cross-shore;
• The longshore distribution of the absolute and relative change in the layer positions, both per individual grid cell as averaged per section;
• In case of nourishments, the longshore distribution and temporal evolution of nourishment volumes;
• The time evolution of the cross-shore profiles in specific location;
• The time evolution of the volume changes in specific coastal sections.

More detailed information on the model output is provided in the output file itself.

2.7.3 Coastal sections

The overall schematization (specification of individual coastal sections) forms the starting point for the large-scale interpretation of the model's results and links PONTOS-results to other large-scale box-like models). At this level of schematization a distinction is made between longshore coastal cells.

Based on a pre-defined position of boundaries the model provides two kinds of output namely:
• The longshore distribution of the absolute and relative change in the section-averaged layer position;
• The time evolution of the cross-shore distribution of the net longshore transport rate for every individual section boundary;
• The time evolution of the volume changes in these individual coastal sections.

Especially the interpretation of these results will provide to be very useful in comparing with observed long-term coastal evolution.

2.7.4 Specific profiles

Using this option the development of specific cross-shore profiles, or in fact the evolution of the positions of the various layers at specific locations can be studied.

2.7.5 Depth contours

In order to provide a more usual 2DH-view, the model is provided with the option to generate a 2DH-model like visualization of the bottom contours. The assessment of the position of individual depth contours is based on this procedure.

2.7.6 Horizontal boxes

In order to be able to compare the characteristic results generated by the PONTOS-model with other box-like models (e.g. the ASMITA-model) an additional output option has been
defined. In order to ‘map’ the results of the ‘vertical plane-oriented’ (using horizontal layers!) PONTOS-model on ‘horizontal plane-oriented’ model results, a procedure for this ‘plane-conversion’ should be derived. In the present version of the model, this option is not yet incorporated in the model, although the set-up of the model is modified in such a way that this option can be implemented easily.

2.8 Application guideline

2.8.1 Introduction

The objective of this section is to describe a basic outline of a general applicable step-by-step procedure concerning the way the PONTOS-model should (or better must) be used for specific applications.

In order to apply the PONTOS-model, four successive phases can be distinguished, namely:

- Phase 1) The overall schematization of the coastal problem to be modelled;
- Phase 2) The more detailed definition of the required input for the model;
- Phase 3) The calibration and verification of the model behaviour (hindcast);
- Phase 4) The actual model application (forecast).

These principal steps are discussed hereafter.

2.8.2 Phase 1 - Problem schematization

With respect to the overall schematization of the coastal area under study the following subjects have to be elaborated:

- **Reference line**
  - The definition of the global coastline contour and the location and orientation of the so-called reference line to schematise the coastal area under study;

- **Boundaries**
  - The definition of the approximate location of the longshore boundaries;
  - The definition of a longshore-oriented reference line (the \( X_m \)-axis), to be used for the definition of both cross-shore and longshore positions;

- **Geometry (overall)**
  - The (fixed) position of the left-hand and right-hand boundary on this \( X \)-grid as the outer limits of the computational grid;
  - The position of the seaward boundary along this reference line: \( Y_b(x) \).

2.8.3 Phase 2 - Input definition

After the overall set-up of the model application, the input of the model must be defined in more detail. For each of the 9 parameter groups

- **1 – Geometry (detailed)**
  - The definition of the layer levels including the longshore distribution of the upper dune level \( Z_0 \);
The assessment of the longshore distribution of the characteristic layer positions;

2 - Material
- The longshore and cross-shore distribution of the characteristic sediment diameter;

3 - Structures
- Schematization and definition of revetments and groynes (Note: offshore breakwaters are not yet incorporated);

4 - Inlets
- Schematization and definition of the location and parameterisation of the tidal inlets;

5 - Hydraulic conditions
- Definition of position and index of both tidal and wave climate stations;
- Definition of the discrete tidal and wave climate in each of the stations (Note: the number of individual conditions for each of the related stations should match);
- Definition of global trends such as sea level rise and wave climate change;

6 - Boundary handling
- Definition of the time series or free boundary behaviour for every individual layer at both the left and right-hand boundary;
- Definition of the longshore distribution of the year-averaged cross-shore transport rate at both the dune boundary as the seaward boundary;
- Definition of the net transport rate for each individual tidal inlet;

7 - Management
- Definition of pre-defined sources or sinks in terms of volumes, positions and execution interval;
- Definition of critical layer positions in order to steer the models auto layer-nourishment mode (the temporal and spatial nourishment need will be the result of the computation);
- Definition of critical cells in order to steer the models auto cell-nourishment mode (the temporal and spatial nourishment need will be the result of the computation);

8 - Runinfo
- Definition of the computational grid;
- Definition of the time interval, including the moments at which additional momentary output should be generated;
- Definition of the time stepping constraints;
- In addition to the basic output of the model additional output can be defined regarding specific profiles, coastal sections and depth contours;

9 - Calibration
- Initially, the default setting of the various calibration coefficients can be used.

2.8.4 Phase 3 - Calibration and verification

For calibration and verification purposes it is strongly recommended to use separate time intervals (so temporal subdivision instead of spatial).
In order to obtain a calibrated model a number of case-related calibration coefficients can be defined, namely:
For calibration purposes a number of overall calibration parameters are available, referring to:

**Longshore transport processes**
- Wave-induced longshore transport capacity;
- A correction of the wave direction;
- Tide-driven longshore transport capacity;

**Cross-shore transport processes**
- Cross-shore transport capacity;
- Equilibrium profile steepness;
- Equilibrium profile shape;
- Equilibrium layer distances.

These parameters refer to a longshore distribution of a correction coefficient which (apart from the wave angle correction) basically equals 1.0.

If possible, the more general model settings (present in the PONTOS-PAR-file) should be unaltered. The idea is that the modification of the four individual case-related calibration factors should be enough in order to achieve a satisfactory resemblance between observed and computed trends.

### 2.8.5 Phase 4 - Final model application

The calibrated and verified model application can now be used for the actual application. Aggregated results can be obtained using the section and time-averaged output of the model.
3 Hydraulic climate schematization

3.1 Introduction

3.1.1 Approach

In the PonTos-model, the hydraulic conditions acting on the area of interest, act as the actual driving force. For the definition of these hydraulic conditions the yearly-averaged hydraulic climates (including global trends) are used.

This method provides the opportunity to specify the spatial variation of both yearly averaged wave and tidal climates as well as the relative or absolute change of global conditions in time (i.e. sea level rise).

In the standard climate approach the actual hydraulic conditions (wave attack and currents) can be specified using a description of both two types of climates, namely:

- Wave climates;
- Tidal climates.

In both descriptions, two types of variation have been taken into account, namely:

- Spatial climate variation;
- Temporal climate variation.

The spatial variation is incorporated in the model by applying different climate stations, whereas the long-term, temporal changes can be specified by defining long-term trends in the governing parameters, this using the yearly-averaged wave and tidal climates as starting-point.

Examples of these governing parameters are the mean water level (sea level rise), the wave height (wave climate change), the wave direction, the tidal range and the tidal velocities.

Use of reference depths

It should be noted that in the present version of the model, climate information is both related to a specific longshore position (the location of the ‘climate station’) and a specific water depth.

The addition of latter specification for both the wave condition (wave height and direction at a specific water depth) and the tidal condition (tidal current velocity and direction at a specific water depth) provides the opportunity to define the hydraulic conditions at arbitrary positions in the area of interest. As a consequence, there are hardly any restrictions with respect to the use of available hydraulic climate data.
Translation to offshore climates

Both the formulations for cross-shore and longshore sediment transport (as discussed in the next sections) are based on the actual offshore climates. In the PONTOS-model this ‘offshore’-location is defined as the position of the NAP-20m depth contour. For the actual computations, the local conditions as specified in the individual climate files (and thus valid specific reference depths) are transferred to this 20m depth contour using the refraction and shoaling model. Even in case of modified wave conditions (e.g. due to diffraction processes) an (virtual) offshore wave condition will be used as a starting point.

Individual combinations

In earlier versions of the PonTos-model the net effect of wave and current conditions was computed for every individual grid cell not taken into account the spatial distribution of the individual conditions. In the present model set-up, the combined effect of waves and currents is taken into account for every individual condition. The individual wave- and currents fields (for $N_w$ wave conditions and $N_t$ tidal conditions $N_w, N_t$ hydraulic conditions have to be addressed) form the starting point for structure-induced corrections.

3.2 Wave climates

3.2.1 Introduction

The basic version of the PONTOS-model uses time-averaged, mean wave climates, specified by the user of the model, as input. Whereas in the pilot-version these wave conditions had to be described on the $Z_r$-depth contour by definition (say at NAP-20m for the Dutch coast), in the present version a so-called wave reference depth can be specified per individual condition. Since the transport formulations use offshore climate properties as an input, a translation of wave parameters such as wave height and wave direction to characteristic deep water conditions has to be taken into account.

The actual wave climate schematization is elaborated in the following. Related spatial and temporal variations will be discussed also.

3.2.2 Wave climate schematization

A local wave climate is schematised as a set of individual conditions, described by a number of input parameters, namely:

- The significant wave height $H_s$ (at the wave reference depth);
- The accompanying peak wave period $T_p$;
- The angle of wave approach $\theta$ (at the wave reference depth);
- The storm-related set-up $h_s$;
- The wave reference depth $d_w$;
- The fraction of occurrence of the combination of previous five parameters.
The wave climate consists of a distinct number individual wave conditions \(N_w\) for which the total fraction of occurrence equals 1.00. Some remarks on the individual parameters are presented hereafter.

### Wave height

The significant wave height \(H_s\), expressed in m, describes the main property of the individual waves. Since due to both shoaling and breaking processes the actual wave height varies in cross-shore direction and the defined wave height is related to a specific water depth, the so-called wave reference depth.

### Wave period

The peak wave period \(T_p\) is related to the offshore wave height \(H_{s0}\). The actual magnitude might be assessed from the deep water steepness of the waves \(S_w\).

### Angle of wave attack

The offshore angle of wave attack depends on the actual meteorological conditions.

In the previous version of the model (PONTOS-1.0) perpendicular wave attack is denoted as the zero-angle \(\theta = 0^\circ\), whereas a positive angle \(\theta > 0^\circ\) refers to a situation with a wave-drive current in positive x-direction. The angle specified in the model input-file refers to the wave direction as present at the specified reference depth.

In the present version of the model (PONTOS-1.4) the orientation of the reference line is taken into account also. In this case the wave directions in the wave climate table should be related to the North. The computational model takes care of the translation of the North-related wave direction towards a wave direction relative to the local coastal orientation.

For the computation of the wave-induced sediment transport, the wave condition is translated to the default 20m depth contour to obtain a standard reference.

### Storm-induced set-up

Since large waves are related to extreme meteorological conditions, the storm-induced set-up of the water level \(h_s\) is related to the offshore wave height \(H_{s0}\).

### Wave reference depth

The wave reference depth refers to the depth contour for which an individual wave condition is specified. Using this reference depth as a starting point the cross-shore translation of the local wave conditions is computed.
**Fraction of occurrence**

The fraction of occurrence refers to the part of the year that an individual wave condition (the combination of wave height, wave period, wave direction, storm set-up active on a specific reference depth) is active. The total of all fractions (added up for all individual wave conditions) should be 1.00 (100%).

### 3.2.3 Cross-shore climate translation

Since the transport formulations use offshore climate properties as an input, a translation of some of the wave parameters to characteristic deep water conditions has been taken into account for every individual condition. It should be noted that the cross-shore variation of the wave period is not taken into account in the model.

### 3.2.4 Spatial wave climate variation

The longshore variation of the yearly wave climate is taken into account by relating a specific wave climate to a specific longshore position. The so-called ‘wave climate reference table’ (WCR) provides the validity of each individual wave climate as a function of the longshore $X$-position.

It should be noted that the PONTOS-model computes the longshore distribution of the ‘offshore’ wave conditions for each individual combination of wave and tidal conditions. From this the individual transport fields are computed and (after eventually pragmatic corrections) are subsequently used to assess the year-averaged transport patterns and bottom evolution. As a consequence of this approach, the number of wave conditions for every individual wave climate station used should be the same.

Thus a longshore variation in the wave climate in case of two climate stations can be obtained by applying a different wave condition for each of the stations (yielding a longshore distribution of the wave height) or by applying two different wave conditions for each station in combination with a different fraction of occurrence.

### 3.2.5 Temporal wave climate variation

Using the yearly-mean wave climates as starting-point, the effect of long-term changes in the governing parameters such as:

- Wave heights and
- Wave direction,

can be taken into account by a specific correction of some of the parameters.

A gradual (relative) change in wave height is taken into account by multiplying each individual significant wave height $H_i$ with a factor, denoted as $P_H(t)$.

$$H_i(t) = P_H(t) \cdot H_i$$  \hspace{1cm} (3.2.1)
A gradual (absolute) change in wave direction is taken into account by adding the absolute change in the direction, denoted as $\Delta \theta_o$ to the basic value of $\theta_o$.

$$\theta_q(t) = \theta_o + \Delta \theta_q(t) \quad (3.2.2)$$

It should be noted that these global modifications are valid for the complete coastal stretch.

### 3.3 Tidal climates

#### 3.3.1 Introduction

The astronomical conditions are schematised using the mean features of the astronomical climate, viz. the vertical (water levels) and horizontal tide (tidal currents). A new improved method is introduced in which the longshore continuity of the tidal discharge is taken into account also.

#### 3.3.2 Tidal climate schematization

A local tidal climate is, comparable to the wave climate schematization, schematised as a (limited) number of individual tidal conditions ($N_t$), each having a specific percentage of occurrence.

A specific tidal climate is characterised by a set of individual conditions. These individual conditions are described by:

- The astronomical water level elevation $h_a$ (vertical tide)
- The accompanying longshore tidal velocity $v_a$ (sign and magnitude);
- The tide reference depth $d_a$ for which $v_a$ is specified;
- The fraction of occurrence of the combination of former three parameters.

The tidal climate consists of a number individual conditions for which the total fraction of occurrence equals 1.00.

**Vertical tide**

The local vertical tide is described by an overall fluctuation of the water level, denoted as $h_a(t)$ with respect of the reference level. During a year, a large range of individual $h_a$-values will be present. For schematization purposes however, only a limited number of them will be used.

**Horizontal tide**

The local horizontal tide can, at a certain position, be described by fluctuating longshore current, denoted as $v_a(t)$. During a year, a large range of individual $v_a$-values will occur, this related to the fluctuation of the water level $h_a(t)$. For schematization purposes however, comparable to the description of the vertical tide, only a limited number of them will be used.
Tide reference depth

Using the reference depth $d_c$ as a starting point the cross-shore distribution of the tidal current velocity is computed.

Fraction of occurrence

The fraction of occurrence refers to the part of the year that an individual tidal condition (the combination of water level and current velocity on a specific reference depth) is active. The total of all fractions (added up for all individual tidal conditions) should be 1.00 (100%).

3.3.3 Cross-shore current distribution

The cross-shore distribution of the tidal current is elaborated using the basic approach (according to the pilot-version of the model) as well as an improved method which takes into account the longshore continuity of the tidal discharge.

Basic approach

Since the actual longshore current depends on the local water depth, the velocity used in the schematization is related to a certain reference depth $d_c$. Based on both the velocity at this depth, the local longshore gradient in the water level $i_a$ ($= - dh/dx$) is computed from the basic Chézy-equation, according to:

$$ v_a = - C \sqrt{(d_c + h_a)} i_a $$  \hspace{1cm} (3.3.1)

in which $C$ refers to the so-called Chézy-coefficient and a positive velocity (in $x$-direction) is related to a negative water level gradient. Further elaboration of this longshore gradient yields:

$$ i_a = \frac{-1}{(d_c + h_a)} \frac{|v_a|}{C^2} $$  \hspace{1cm} (3.3.2)

taking into account the effect of negative velocities also.

The cross-shore distribution of the longshore current $v(y)$ for other water depths $d(y)$ can consequently be assessed from:

$$ v(y) = - C \sqrt{(d(y) + h_a)} i_a \text{ for } i_a \geq 0 $$  \hspace{1cm} (3.3.3a)

and:

$$ v(y) = + C \sqrt{(d(y) + h_a)} |i_a| \text{ for } i_a < 0 $$  \hspace{1cm} (3.3.3b)
If no cross-shore variation in the water level gradient is taken into account (and thus $i_a$ does not vary across the profile), the cross-shore distribution of the tidal velocity can be assessed from:

$$v(y) = \sqrt{\frac{d(y) + h_a}{d_c + h_a}} v_a$$  \hfill (3.3.4)

yielding increasing tidal velocities at deeper water.

In the present version of the program, the Chézy-coefficient related square root is extended to a more general form:

$$v(y) = \left(\frac{d(y) + h_a}{d_a + h_a}\right)^c v_a$$  \hfill (3.3.5)

in which the coefficient $c$ equals 0.50 for the Chézy-case.

Based on the elaboration presented in Volume 4 of [Steetzel et al., 1998], a magnitude of 0.25 seems more appropriate.

**Improved method**

It should be noted that former basic procedure for the assessment of the longshore flow distribution does not take the continuity of the tide-driven flow (in terms of the cross-shore integrated discharge) into account. The characteristic longshore current velocity is computed locally for every individual layer and directly and unconditionally used to compute the related local tide-driven sediment transport.

In the next the consequences of this simple approach are discussed and a pragmatic method to take the longshore continuity of the tide-driven flow into account is presented. The original objective of this improvement was to take the effects of contraction of the tide-driven flow in case of a large cross-shore structure into account.

3.3.4 Spatial tidal climate variation

The longshore variation of these time-averaged climates is taken into account by relating a specific tidal climate (viz. a tidal climate table with a specific index as discussed further on) to a specific longshore position. Use will be made of a so-called ‘tidal climate reference table’ (TCR) describing the validity of each tidal climate table as a function of the longshore $X$-position.

This procedure is comparable to the procedure described for the wave climates. The PONTOS-model computes the longshore distribution of the ‘offshore’ tidal conditions for each individual combination of wave and tidal conditions. From this the individual flow fields and transport fields are computed and (after eventually pragmatic corrections to take into account the continuity of the tidal current) are subsequently used to assess the year-averaged transport patterns and bottom evolution. As a consequence of this approach, the number of tidal conditions for every tidal climate station used should be the same.
3.3.5 Temporal tidal climate variation

Using the yearly-mean tidal climates as starting-point, the effect of long-term changes in the governing parameters such as:

- Mean water level,
- Tidal range and
- Tidal velocities,

are taken into account by a specific correction of some of the parameters.

A gradual sea level rise is taken into account by adding the absolute change in the mean water level, denoted as $\Delta h_o(t)$, to the astronomical elevation $h_o$, according to:

$$h_a(t) = h_o + \Delta h_o(t)$$  \hspace{1cm} (3.3.6)

A long-term gradual (relative) change in tidal amplitude is taken into account by multiplying each individual astronomical variation $h_o$ with a factor, denoted as $P_h(t)$.

$$h_a(t) = P_h(t) \cdot h_o$$  \hspace{1cm} (3.3.6)

Combined with sea level rise this yields:

$$h_a(t) = P_h(t) \cdot h_o + \Delta h_o(t)$$  \hspace{1cm} (3.3.7)

A long-term gradual (relative) change in tidal velocities is taken into account by multiplying the astronomical tidal current $v_a$ with a factor, denoted as $P_v(t)$.

$$v_a(t) = P_v(t) \cdot v_a$$  \hspace{1cm} (3.3.7)

Consequently, the temporal variation of the astronomical parameters is controlled by three parameters, namely, $\Delta h_o(t)$, $P_h(t)$ and $P_v(t)$.
Basic transport formulations

Wave-induced longshore transport

Introduction

The wave-induced longshore transport, denoted as \( q_{l,w} \), expressed in \( \text{m}^3/\text{m}^1/\text{yr} \) is generated by oblique incident waves which generate a longshore current mainly in the breaker zone. The wave action itself stirs up the sediment, while the wave-driven current acts as the transport agent yielding the actual sediment transport. The wave-induced transport rate mainly depends on the incoming wave energy (wave height and period) and the direction of wave propagation relative to the coastline.

The basic idea is that the cross-shore distribution of the wave-driven longshore transport is transferred to a vertical distribution (the upper right panel) which provides the opportunity to derive relatively simple though powerful descriptions.

Cross-shore integrated transport rate

The total, viz. cross-shore integrated wave-induced longshore transport \( Q_{c,w} \) for a specific wave condition (the area below the \( q_{w} \)-contour), is computed from:

\[
Q_{c,w} = c_{w,0} \left( \frac{H_{s}^{2.8}}{D_{s}} \right) (\theta_{c} - \theta_{w}) \exp \left( - (c_{2} (\theta_{c} - \theta_{w}))^{2} \right) \tag{4.1.1}
\]

in which \( \theta_{c} \) denotes the orientation of the coast (assuming parallel depth contours), \( \theta_{w} \) the (virtual) direction of the incoming waves at the offshore boundary and \( c_{2} \) a constant describing the shape of the function.

The coefficient \( c_{w,0} \) (the so-called basic constant) was used for calibration. This holds also for the \( c_{2} \)-coefficient.

It should be noted that this equation contains a number of dimensional parameters. No attempts have been made to yield an expression with non-dimensional parameters, since the initial objective of this kind of formulations was only to derive a relatively simple formulation which was able to ‘map’ the results of more complicated models.

Modification for large relative angles

The dependency of the relative angle \( \Delta \theta \) using Eq.(4.1.1) can be described by:

\[
Q_{c,w} \propto \Delta \theta \exp \left( - (c_{2} \Delta \theta)^{2} \right) \tag{4.1.2}
\]
The angle at which the maximum transport rate is present, denoted as $\Delta \theta_{\text{max}}$, can be shown to be equal to:

$$\Delta \theta_{\text{max}} = 1 / \left( \sqrt{2} c_2 \right)$$  \hspace{1cm} (4.1.3)

For $c_2 = 0.019$ this yields $\Delta \theta_{\text{max}} = 37.2^\circ$.

Beyond this angle the transport rate reduces only gradually, yielding even non-zero values for coast-parallel wave attack (denoted as basic relation).

In the current version of the PONTOS-model, the outer reaches of this function are modified in order to:

- Achieve a zero transport contribution for $|\Delta \theta| > 90^\circ$;
- To yield a gradual transition from towards this ‘boundary’.

This effect is obtained by multiplying the basic transport rate from Eq.(4.1.1) with a correction factor $C_\theta$ for $45^\circ < |\Delta \theta| < 90^\circ$; according to:

$$C_\theta = 1 - \left( \frac{\Delta \theta - 45}{45} \right)^2$$  \hspace{1cm} (4.1.4)

Outside this interval $C_\theta = 1$ for $|\Delta \theta| < 45^\circ$ and $C_\theta = 0$ for $|\Delta \theta| > 90^\circ$.

The modified formulation for the total wave-induced transport rate is now:

$$Q_{cw} = C_\theta c_{w,0} \left( H_s^{2.8} / D_i \right) \Delta \theta \exp\left( - (c_2 \Delta \theta)^2 \right)$$  \hspace{1cm} (4.1.5)

### Additional option

Based on the experience with some of the applications using these formulations it was found that due to the decrease of the transport capacity for increasing angles an undesired transport blocking might occur. Especially in case of groynes under oblique wave attack the spatial shift in the layer position just downdrift of the structure, may result in extreme $\Delta \theta$ - magnitudes and thus transport blocking whereas a significant bypass of sediment would be expected.

In order to cope with this problem an additional (non default) option has been implemented in the PONTOS-model for which the transport rate is kept at the maximum rate for relative angles above $\Delta \theta_{\text{max}}$.

### 4.1.3 Calibration coefficients

In the basic formulation a number of calibration coefficients is present. Based on the work described in [Steezel et al., 1998], the initial settings of the $c_{w,0}$ and $c_2$-coefficient are available. These coefficients have been based on an extensive series of UNIBEST_LT-computations (see [Delft Hydraulics, 1994]) in which the total longshore transport has been computed for a range of wave conditions (wave heights, wave periods and wave directions all present at 7 m water depth) and sediment characteristics.
Improved calibration

The introduction of a variable wave reference depth (see Section 3.2) has required an adaptation of the original settings of Eq. (4.4.1). The original wave conditions of the calibration set as present at a water depth of 7 m had to be translated in seaward direction to the basic offshore location (at the 20m depth contour) and the coefficients in the governing equation had to be re-calibrated to derive the most appropriate fit. The most appropriate setting of the two model coefficients has now been defined as $c_{w,0} = 4.0 \, \text{m}^{1.2}/\text{degr/yr}$ and $c_2 = 0.019 \, \text{degr}^2$. As a result of this backward transition the modified magnitude of the $c_{w,0}$-coefficient is smaller than the original magnitude (as derived in [Steetzel et al., 1998]).

4.1.4 Vertical distribution

This basic cross-shore integrated transport rate $Q_{vw,i}$ is computed for a specific grid cell, using the coast orientation and local sediment characteristics. The fraction of this total transport present in a specific layer is defined by an additional $F_z$-factor, with $0 \leq F_z \leq 1$ by definition:

$$Q_{vw,i,j} = F_z Q_{vw,i} \quad \text{(4.1.6)}$$

The distribution of this transport over the various layers is (in accordance with the formulation in the pilot-model) schematised as a triangle in the present version of the model. The maximum transport contribution is present at a $d/H_s$-ratio of 1.4, whereas the lower boundary of the triangle is positioned at $d/H_s = 3.0$.

Depending on the level of the upper and lower boundary of the layer relative to the water level, the magnitude of the fraction $F_z$ can be assessed and thus the actual wave-driven transport rate at the borders of an individual grid cell can be determined.

For non-parallel depth contours, the transport rate for an individual layer is computed from the basic cross-shore integrated transport rate $Q_{vw,i}$ taking the related layer orientation as input for $\theta_i$. Next the actual fraction of this rate is computed using Eq. (4.1.6). The total transport rate for non-parallel depth contours (the sum of the contributions per individual layer) might differ from the rate computed directly from the value which would be obtained using a characteristic orientation of the coast.

4.2 Tide-induced longshore transport

4.2.1 Introduction

The tide-induced transport, denoted as $q_{x,t}$, depends on the relative importance of the tidal currents, and is affected by the water depth and sediment characteristics. Moreover, the presence of waves will lead to an increase of the transport rate (see Section 4.3).
4.2.2 General formulation

In the PONTOS-model, the tide-induced longshore transport \( q_{lt} \) for a specific hydraulic condition (water level, wave and tidal current) is computed from:

\[
q_{lt} = c_{t,0} \left( D_s \right)^{-2.2} \left( v_a \right)^4 \left[ 1 + C_w \frac{H_s^{15} T_p^3}{d v_a^2} \right]
\]  

(4.2.1)

in which the term in between squared brackets takes account of the effect of additional stirring due to the presence of waves (\( C_w \)-factor) and the coefficient \( c_{t,0} \) was used for calibration. This holds also for the other numbers present in this formula. A detailed elaboration and validation of the formulations used in the model is presented in Annex C of the background documents [Steetzel et al., 1998].

It should be noted that, comparable to the formulation for the total wave-drive transport rate (Eq. (4.1.1)), this equation contains a number of dimensional parameters also. No attempts have been made to yield an expression with non-dimensional parameters, since the initial objective of this kind of formulations was to derive a relatively simple formulation capable of ‘mapping’ the results of more complicated models.

In the original expression in [Steetzel et al., 1998] a \( \Delta y / \Delta z \)-term on the right-hand side was added to transform the transport rate per m\(^3\) in cross-shore direction to a rate per m\(^3\) in vertical direction as required for the layer-concept. In the current version, this has been solved in the following way.

To assess the transport in a specific layer, the computed rate has to be multiplied by the actual width of the layer in cross-shore direction, according to:

\[
Q_{st,j,i} = B_{j,i} q_{st,j,i}
\]  

(4.2.2)

where \( B_{j,i} \) refers to the characteristic width of layer \( j \) in grid cell \( i \). The latter is assessed from the continuous profile from:

\[
B_{j,i} = y_{c,j+i,i} - y_{c,j,i}
\]  

(4.2.3)

The current-related longshore transport rate (expressed in m\(^3\)/yr per m\(^1\)), is defined according to:

\[
q_{tr,c} = c_{t,0} \left( D_s \right)^{-2.2} \left( v_a \right)^4
\]  

(4.2.4)

The current-related longshore transport is a linear function of the water depth (see Eq. (4.2.4) and Eq. (3.3.5) in which the relation between the water depth and the currents is given). The stirring-up effect of the waves yields a contribution to the total transport rate according to:

\[
q_{tr,w} = c_{t,0} \left( D_s \right)^{-2.2} \left( v_a \right)^4 C_w \frac{H_s^{15} T_p^3}{d v_a^2}
\]  

(4.2.5)
which basically decreases with increasing water depth.

Near the water line and in the breaker zone, with a very high $H_s/d$-ratio, this formulation provides unrealistic results by definition.

### 4.2.3 Calibration coefficients

In the basic formulation a number of calibration coefficients is present. Based on the work described in [Steetzel et al., 1998], the initial settings of the $c_{t,0}$ and $C_w$-coefficient are available. These coefficients have been based on an extensive series of UNIBEST_LT-computations in which the total longshore transport has been computed for a range of current and local wave conditions (wave heights and wave periods), sediment characteristics and water depths (see [Steetzel et al., 1998]).

In the current version of the model the original settings have been somewhat adapted due to the introduction of a variable wave reference depth. The most appropriate setting of the two model coefficients has been defined as $c_{t,0} = 16.0 \times 10^{-6} \text{ m}^{0.2} \text{s}^4 \text{yr}^{-1}$ for the basic coefficient and $C_w = 2.0 \text{ m}^{1.5} \text{s}^3$ for the wave stirring factor.

In the present formulation the wave-related contribution is related to the characteristic offshore wave height instead of the local wave height. This approach is consistent with the methodology used for the wave-driven longshore transport rate.

### 4.2.4 Improved schematization in breaker zone

In the pilot version of the model the longshore transport was unrealistically high in the breaker zone. This has been corrected in the current version by adding an additional correction factor $C_b$ which equals 1 for relatively deep water conditions $(d/H_s > 3)$ and a value between 0 and 1 for $d/H_s < 3$.

$$C_b = \min\left(1, \frac{d}{3H_s}\right) \quad (4.2.6)$$

The factor ’3’ in this equation refers to the lower limit of the wave-impact. The corrected equation for the wave-related contribution equals:

$$q_{w,w} = c_{t,0} \left(D_s\right)^{-2.2} \left(v_a\right)^4 C_w C_b \frac{H_s^{1.5} T_p}{d v_a^2} \quad (4.2.7)$$

As a consequence, the final equation applied in the PONTOS-1.0 model reads:

$$q = c_{t,0} \left(D_s\right)^{-2.2} \left(v_a\right)^4 \left[1 + C_w C_b \frac{H_s^{1.5} T_p}{d v_a^2}\right] \quad (4.2.8)$$
4.2.5 Translating to layers

In order to assess the total transport rate in a specific (vertical) layer, all the individual transports contribution should be translated to a vertical plane. Since the wave-induced longshore transport rate is already based on such a vertical approach, only the tide-driven transport must be transformed from a rate expressed in m³/yr per m of cross-shore (according to Eq. (4.2.1)) to a characteristic rate valid for a (vertical) layer.

This is achieved by the computation of the basic transport rate for a characteristic water depth \( d_c \) (by applying Eq. (4.2.2)) and multiplying this with the estimated width of the layer in cross-shore direction (according to Eq. (4.2.2)). In the model, the balance-based \( z_{c,j} \)-level for the assessment of the characteristic water depth.

4.3 Wave-induced cross-shore transport

4.3.1 Model definition

Cross-shore transport across a coastal profile is mainly generated by the incoming waves. The principal processes determining the cross-shore transport rate are wave asymmetry, gravity and the undertow compensating for the mass-flux above the wave troughs.

For the use in the PONTOS-model a rather simple approach is used in which the transport rate is related to the deviation of the local bed slope from the equilibrium slope [Steetzel, 1997a, 1997b]. The latter slope is expressed in terms of the offshore hydraulic conditions and the characteristics of the bed material, whereas the rate of change is, amongst others, related to the relative water depth. As discussed in [Steetzel et al., 1998], this approach is based on the elaboration of an extensive series of process-based UNIBEST-TC computations [Delft Hydraulics, 1994].

The wave-induced cross-shore transport \( q_{yw} \), for a specific hydraulic condition (water level and waves) at a certain depth is computed from:

\[
q_{yw} = q_o \cdot F_b \left( \frac{s}{s_e} - 1 \right) \left( \frac{s}{s_e} - 1 \right)^{\beta - 1}
\]

in which the \( s \) denotes the actual local bed slope and \( s_e \) refers to the local equilibrium slope. The first term on the right-hand side of the equation, \( q_o \), refers to reference magnitude of the transport capacity.

The power \( \beta \) takes into account the rate in which the impact of the actual slope is taken into account (for \( \beta = 0 \) no effect is taken into account whereas \( \beta = 1 \) yields a linear model). For \( \beta > 0 \), a relatively too steep slope, viz. \( s > s_e \), yields an offshore directed, positive transport rate.
The vertical variation of the transport rate, or in fact the dependency of the water depth, is described using a function $F_b(d)$ which yields $F_b(d=0) = 1.0$ by definition.

In Eq. (4.3.1), only two constants are present, namely the:
- The reference transport capacity $q_o$
- The slope-related power $\beta$

The basic settings used in the present model (see Table 4.1) are equivalent to the settings in the original model (see [Steetzel et al., 1998]).

<table>
<thead>
<tr>
<th>Table 4.1: Default settings for the cross-shore transport model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic parameters</strong></td>
</tr>
<tr>
<td>Reference transport capacity $q_o$</td>
</tr>
<tr>
<td>Slope-related power $\beta$</td>
</tr>
</tbody>
</table>

Figure 4.1 presents the basic relation between the relative slope and the relative transport rate using the default $\beta$-value.

Two items need to be defined, namely:
- The definition of the equilibrium beach slope $s_e$;
- The definition of the transport capacity distribution $F_b$.

These items will be discussed in the following.

### 4.3.2 Equilibrium profile definition

#### Introduction

The incorporation of the equilibrium slope formulation in the model is a good example of a behaviour-oriented element of the PONTOS-model. In this approach, the vertical distribution of the equilibrium slope $s_e$ is described by a pragmatic and relatively simple function based on only a limited number of parameters.

This function, assuming a concave cross-shore profile, is given by:

$$s_e(d) = s_o F_s$$

(4.3.2)

in which $s_o$ refers to the bottom slope at the water level which is denoted as the ‘beach slope’ and $F_s(d)$ describes the relative vertical variation.

For the vertical variation three different zones are being distinguished, namely:
- The dune face having a fixed slope;
- The dry beach with an upward increasing bottom slope;
- The under water profile with downward decreasing bottom slope.

Following Eq. (4.3.2) the beach slope $s_o$ is used as a reference magnitude.

This approach differs from the so-called panel model as originally proposed to describe large-scale coastal profile evolution [Stive and De Vriend, 1999; De Vriend and Stive,
A summary of the various approaches for large-scale coastal evolution is provided in [Stive et al., 1999].

**Equilibrium beach slope definition**

In the present version of the model, the equilibrium beach slope, denoted as $s_o$, is computed from:

$$s_o = C_s \left( \frac{H_s}{L_o} \right)^{\gamma_s} \left( \frac{D_s}{H_s} \right)^{\gamma_D}$$

and depends on the relative wave steepness ($H/L_o$) and the relative sediment diameter ($D_s/H_s$). The basic settings are summarized in Table 4.2.

**Table 4.2:** Default settings for the equilibrium beach slope definition

<table>
<thead>
<tr>
<th>Basic parameters equilibrium slope</th>
<th>Magnitude (default)</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic constant $C_s$</td>
<td>0.46</td>
<td>-</td>
</tr>
<tr>
<td>Wave steepness-related power $\gamma_s$</td>
<td>- 0.25</td>
<td>-</td>
</tr>
<tr>
<td>Relative sediment size-related power $\gamma_D$</td>
<td>0.265</td>
<td>-</td>
</tr>
</tbody>
</table>

These constants have been based on the work described in [Steezel et al., 1998]. The present negative value of $\gamma_s$ yields more gentle slopes for steeper waves, whereas the positive $\gamma_D$ value results in a steeper slope for coarser material.

Figure 4.2 provides the magnitude of the equilibrium beach slope as a function of the sediment size for a number of combinations of wave height and wave steepness.

**Equilibrium slope distribution formulation**

For the equilibrium slope distribution a distinction between the region below and above the water line is made.

**Below the water line**

As derived in [Steezel et al., 1998] the vertical distribution of the equilibrium bottom slope $F_s(d)$ is schematised as a negative exponential function for $d/H_s > 0$, according to:

$$F_s = \exp \left[ - \alpha_s \left( \frac{d}{H_s} \right) \right]$$

in which $\alpha_s$ is a calibration factor (see Table 4.3).

**Table 4.3:** Default settings the distribution of the relative slope

<table>
<thead>
<tr>
<th>Basic parameters slope distribution</th>
<th>Magnitude (default)</th>
<th>Dimension</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic constant $\alpha_s$</td>
<td>2.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Default dune slope $s_e$</td>
<td>0.25</td>
<td>-</td>
<td>for $d &gt; -H_s$</td>
</tr>
<tr>
<td>Minimum shelf slope $S_{min}$</td>
<td>0.001</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
It should be noted that this formulation yields $F_s = 1.0$ at the water level ($d = 0$) by definition.

**Above the water line**
Above the water level a transient formulation is applied in which the slope increases linearly with the (relative) level (in stead of exponential) according to:

$$ F_s = 1 - \alpha_s \left( \frac{d}{H_s} \right) $$

(4.3.5)

The actual vertical distribution of the equilibrium profile slope can be computed from Eq. (4.3.2) using the beach slope from Eq.(4.3.3) and the appropriate distribution function Eq. (4.3.4/5).

The ‘boundary problems’ at both the dune and the shelf are discussed hereafter.

**Dune slope**
In order to take into account the distinct transition of between the beach slope and the slope of the dune face, the slope of the dune face is added as an additional parameter. Above the ‘dune foot level’ at $d/H_s = -1$, the equilibrium slope is fixed at a constant level of $s_e = s_d = 0.25$ (see Table 4.3).

**Shelf slope**
Comparable to the incorporation of the slope of the dune face, the slope of the deeper sea floor can be defined also.
In the present version of the model a minimum value of $s_{min} = 0.001$ is used as the default setting (see Table 4.3).

The left-hand and middle panel of Figure 4.3 show the magnitude of the $F_s$-factor as a function of the relative water depth, respectively on a linear and a logarithmic scale.
The right-hand panel shows the related equilibrium slope including the results of the boundary conditions for dune and shelf slope.

### 4.3.3 Transport capacity distribution

**Introduction**
The $F_b$-function in Eq.(4.3.1) describes the relative transport rate as a function of the water depth. The actual shape of this function is based on the elaboration as presented in [Steetzel et al., 1998].
A distinction is made between the part below and above the waterline.

**Below the waterline**
The $F_b$-function describes the relative transport rate as a function of the $d/H_s$-ratio according to:
Based on the results of the UNIBEST-TC-model the default setting of the $\alpha_b$-parameter is defined (see [Steetzel et al., 1998]): see Table 4.4.

<table>
<thead>
<tr>
<th>Basic parameters transport distribution</th>
<th>Magnitude (default)</th>
<th>Dimension</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic constant $\alpha_b$</td>
<td>1.5</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4: Default settings of the vertical distribution of the relative transport rate

It should be noted that this basic expression yields a non-zero transport rate for underwater only.

**Above the waterline**

Just above the water level the transport capacity was zero by definition in the original formulation.

In order to deal with the numerical problems related to this discontinuity and moreover to add some behaviour-oriented aspects, a transition zone in which the transport capacity at the water level decreases to the zero level at some wave run-up related measure.

In the model, a linear reduction function is assumed up to the dune face transition level of at $d/H_s = -1$ (default model setting).

Figure 4.4 shows the magnitude of the $F_b$-factor as a function of the relative water depth on both a linear and a logarithmic scale.

4.3.4 **Implementation in the layer model**

**Introduction**

The former derived formulations can be used for normal continuous cross-shore profiles directly. In order to apply them in the multi-layer the actual characteristic bottom slope at the interface between adjacent layers must be defined.

**Formulation**

In the present version of the model, the actual bottom slope in the model at layer boundary $Z_j$ denoted as $s_j$ is assessed using the mutual distances between the two neighbouring layers, according to:

$$s_j = \frac{(d_{j+1} + d_j)/2}{Y_j - Y_{j+1}} \quad (4.3.7)$$

in which $d$ denotes the layer thickness.
If for the equilibrium profile this mutual distance is denoted as $W_j$ the characteristic equilibrium slope $s_{e,j}$ can be assessed from:

$$ s_{e,j} = \frac{(d_{j-1} + d_j)}{2W_j} \quad (4.3.8) $$

Consequently, the relative slope in the transport formulation is computed from:

$$ \frac{s_j}{s_{e,j}} = \frac{W_j}{Y_j - Y_{j-1}} \quad (4.3.9) $$

yielding the actual source term for the assessment of the cross-shore transport rate $q_{ij}$.

**Boundary conditions**

Exchange across the landward boundary due to a yearly net transport can be taken into account using a pre-defined longshore distribution of the net transport $q_0(x)$. A negative magnitude implies a loss of sediment in landward direction.

Exchange across the seaward boundary (say across the NAP-20m depth contour), due to a yearly net transport, can be taken into account by a pre-defined longshore distribution of the net transport rate, denoted as $q_b(x)$. A positive magnitude implies a seaward loss of sediment (seaward is positive by definition).

**4.3.5 Cross-shore profile evolution**

In the next a basic application of the cross-shore transport model is presented in which the time development of an initial cross-shore profile is computed for a combined wave and tidal climate. In such a climate case, the net transport rate across a specific layer transition is computed for each individual condition taking into account its individual fraction of occurrence.

The upper panel of Figure 4.5 shows both the initial and final cross-shore profile. In this case the initial profile is too steep (according to the default model settings).

The time evolution of the layer positions is shown in the lower panel. As can be observed ‘in the end’ a final equilibrium profile (with zero net cross-shore transport across the boundaries) is obtained.

More details on the time evolution and related processes are given in Figure 4.6 and 4.7. In addition to the layer positions, also the cross-shore transport rate and the mutual layer distances are presented.

As can be observed, the morphological adoption time scale increases for deeper water.
4.3.6 Cross-shore transport calibration

Introduction

For the calibration of the cross-shore transport model, two types of calibration factors can be applied, namely:

- A factor on the transport rate;
- A correction of the default settings for the equilibrium cross-shore profile.

The first factor only affects the rate and intensity of the cross-shore transport and has no (direct) effect on the final equilibrium shape of the profile.

In the second case, the equilibrium shape is modified and as a result both the magnitude and direction of the cross-shore transport rate will be affected.

In the latter case two types of calibration factors are being distinguished, namely:

- Modifications of the basic shape of the equilibrium profile (for a single hydraulic condition);
- A more pragmatic correction of the climate-based equilibrium layer distances.

More details on these calibration factors are presented in the following.

Cross-shore transport rate modification

In order to calibrate the cross-shore transport rate, an additional factor is applied in Eq. (4.3.1); the so-called CC-factor (Calibration for the Cross-shore transport). In this way, the reference magnitude of the transport capacity \( q_o \), and as a consequence, the morphological time scale is modified.

Default, the correction on the wave-induced cross-shore sediment transport equals 1.0.

Equilibrium profile modification

For the calibration of the equilibrium profile, two calibration factors can be applied, namely:

- A profile steepness correction;
- A profile shape correction.

In addition also the default setting of the dune slope and the minimum shelf slope may be modified also.

Figure 4.8 shows the basic equilibrium slope distribution and the related equilibrium cross-shore profile.

The CS-coefficient, the Calibration factor for the equilibrium profile Steepness, refers to a multiplier for the basic equilibrium beach slope (at the water line; see Eq.(4.3.3)).

A CS-value less than 1 yields a flatter slope, whereas \( CS > 1 \) results in a steeper profile.
The $CP$-coefficient, a calibration factor for the concavity of the equilibrium profile, is implemented as a multiplier on the $\alpha_s$-factor in Eq.\((4.3.4)\). A $CP$-value less than 1 yields a relative flatter slope, whereas $CP > 1$ results in more curvature.

**Cross-shore layer width**

The direction and rate of the cross-shore transport rate depends primarily on the ratio between the actual layer distance $Y_j - Y_{j-1}$ and the equilibrium layer distance $W_j$ (see Eq.\((4.3.1)\)).

The latter equilibrium layer distance $W_j$ can be computed using the PONTOS-model by running it for a very long time (see Figure 4.5 and 4.6). It should be noted that the $W_j$ depends on the local wave and tidal climate as well as on the local sediment characteristics.

In most cases this results will differ significantly from the observed distance; the initial value of $Y_j - Y_{j-1}$ based on measurements in the field. For the example presented in Figure 4.5/4.6, the computed distance shown in the right-hand panel of Figure 4.6/4.7 is probably far too large.

The magnitude of the equilibrium layer distances can also be assessed by the model by using a recently implemented computational routine. As a result the initial ratio between the actual (initial) layer distance $Y_j - Y_{j-1}$ and the equilibrium layer distance $W_j$ can be computed also. The computed equilibrium distance is provided in the right-hand plot of Figure 4.6/4.7 also.

In order to calibrate the cross-shore processes in a very pragmatic way, a correction has been defined on the (uncorrected) equilibrium layer distance. The latter reduction factor is used as a multiplier in Eq.\((4.3.10)\).

As a result, for a specific location, this procedure will result in four different calibration factors, namely $CW_1$, $CW_2$, $CW_3$ and $CW_4$.

It should be noted that these results can be used to define the basic calibration factors $CS$ and $CP$. For example if $CW_j$ equals 0.5 (and thus the computed equilibrium shows a too flat profile), the same calibration result may in principle be obtained for an increased equilibrium slope and thus for $CS = 2.0$. Since extensive wave climates instead of single wave attack are used, the latter approach is not successful.
5 Impact of structures

5.1 Introduction

5.1.1 Types of structures

The natural behaviour of the coastal zone is affected by the presence of human-made structures. Three types of basic structures exist:

- Cross-shore oriented structures like dams and groynes;
- Longshore oriented structures in the dune face like dikes and revetments;
- Longshore oriented structures positioned further seaward (offshore breakwaters).

In the following, the effects of these structures on the wave and current field is discussed and the way two of them are taken into account in the model is addressed. The effect of offshore breakwaters is not elaborated in this study.

5.1.2 Effect on hydraulic conditions

The basic impact of these structures on the coastal behaviour is elaborated by describing the structure’s impact on the hydraulic conditions. These effects (diffraction of the wave field and the contraction of the tidal flow) will be discussed in Chapter 6.

It should be noted that the effect of offshore breakwaters is not yet included in the model although the formulations needed to model them are available to a large extent.

5.2 Cross-shore groynes

5.2.1 Introduction

A groyne or dam is a cross-shore oriented structure basically used to affect the large-scale longshore sediment transport gradient.

5.2.2 Structure schematization

In the PONTOS-model a groyne is schematised as a coastline perpendicular vertical wall, characterised by its location in longshore direction $X$ and its landward and seaward extent denoted as $Y_l$ and $Y_s$, respectively. For further characterization the upper level $Z_g$ of the groyne is required as well as the blocking effectiveness $E$ for longshore transport, ranging from $E = 0$ for a situation without blocking and $E = 1.0$ for 100% blocking.
5.2.3 Effects on hydraulic conditions

A groyne or dam yields wave diffraction on the lee side of the structure. Moreover, if the tip of the groyne penetrates in the tidal flow zone, contraction effects have to be taken into account also. Both processes as well as the way they have been incorporated in the PONTOS-model, are discussed in Chapter 7.

5.2.4 Effect on cross-shore transport

Since the groyne is schematised as a cross-shore wall having a infinitely small size in longshore direction, no direct effect on the cross-shore transport rate is present.

5.2.5 Effect on longshore transport

Since the wall-like structure is non-erodable, no transport through the structure is allowed. In the case of $E < 1$, this only holds for a specific fraction of the transport only. If a groyne extends in a specific layer with index $j$ and the groyne level $Z_g$ is higher than the lower boundary of the layer $Z_{j+1}$ the modified longshore transport $Q_{x,j}$ is computed from:

$$Q_{x,j} = (1 - E) \left( 1 - \frac{Z_g - Z_{j+1}}{Z_j - Z_{j+1}} \right) Q_{x,j}$$ (5.2.1)

in which the first term on the right-hand side is related to the effectiveness for transport blocking and the second term deals with the effect of the relative penetration of the structure in vertical direction. This equation is used for the assessment of the impact of a groyne on the wave-induced sediment transport.

The impact on the tide-induced longshore transport is computed from:

$$Q_{t,j} = (1 - E) \left( 1 - \frac{Y_g - Y_{c,j}}{Y_{c,j+1} - Y_{c,j}} \right) Q_{t,j}$$ (5.2.2)

in which the term in between rectangular brackets refers to fraction of the layer in which is the groyne is present..

5.3 Revetments and dikes

5.3.1 Introduction

A revetment or dike is a longshore oriented structure used to affect both the large-scale longshore transport gradient as well as the cross-shore transport gradient.
5.3.2 Structure schematization

A revetment or dike is a non-erodable section in the coastal zone and it is schematised as a box-like horizontal structure with a specific upper level (the top of the structure) and fixed left- and right-hand seaward edges (denoting the extent of the structure).

5.3.3 Effects on hydraulic conditions

A revetment could act as a groyne or dam yielding wave diffraction on the lee side of the structure. Moreover, if the revetment penetrates in the tidal flow zone, contraction effects have to be taken into account also.

These effects are comparable to the effects discussed for the groyne case. These processes will be elaborated in Chapter 7.

5.3.4 Effect on cross-shore transport

Since the box-like structure is non-erodable, no transport across the seaward boundary is allowed. Depending on the level and position of this boundary, the $q_{y,i,j}$ rate for the related layer is set to zero.

5.3.5 Effect on longshore transport

Since the box-like structure is non-erodable, no transport across both the left- and right-hand boundary is allowed. This effect is comparable with the blocking described for groyne-like structures. In this case however the blocking effectiveness is 100% by definition.
6 Refraction, diffraction and contraction

6.1 Introduction

In order to simulate the impact of structures and the behaviour of other special features, three types of physical processes have been elaborated in this chapter. The objective is to define and implement a pragmatic procedure or method to take the related effects into account in the computational model. These processes are:

- Refraction and shoaling of waves from offshore towards the beach line contour;
- Diffraction processes to deal with the redistribution of wave energy next to groynes and revetments;
- Contraction effects to deal with the longshore continuity of the cross-shore integrated tidal flow.

The first two processes relate to the wave conditions, whereas the last process refers to the modification of the tidal flow only.

In all cases considered, the objective is to assess the impact on the sediment transport pattern and consequently to simulate the development of the coastline more adequately.

The three processes, the schematization used and related examples, will be treated in the following three sections.

6.2 Refraction and shoaling

6.2.1 Introduction

Due to the processes of bottom friction, wave refraction and shoaling, the actual wave conditions, in terms of wave height and period as well as the predominant wave direction alter in landward direction. Introducing a feasible description for the most dominant processes in the PONTOS-model yields the opportunity to compute the local wave conditions from the offshore conditions (and vice versa).

It should be noted that in this case only the effects of the wave refraction and shoaling are taken into account. The effect of bottom friction is not incorporated.

6.2.2 Background

Since both the longshore and cross-shore transport are expressed in terms of the offshore wave conditions, it is in fact not necessary to take the refraction and shoaling process into account at all. However, if due to the presence of a structure in the nearshore zone, the local wave field is affected in terms of a modified wave height $H$ or a shift in the wave angle $\theta$ (due to diffraction processes), this basic approach becomes troublesome.
In order to apply the ‘offshore conditions-based transport formulations’ for these more complicated cases also, a direct and unique two-way relation between the (modified) local wave conditions (at depth \(d_1\)) and the accompanying offshore condition (at depth \(d_0\)) is required. Based on such a relation, also the corrected (virtual) offshore conditions can be derived and thus the standard ‘offshore conditions-based transport formulations’ can be applied for (modified) local wave conditions using corrected (virtual) offshore conditions as well. This two-way application of the refraction-shoaling process is discussed in Section 6.3 that deals with the assessment of the effects of diffraction.

The schematization used for the assessment of refraction and shoaling is discussed hereafter.

### 6.2.3 Schematization

Wave refraction and shoaling between the location of the offshore wave climate (at a water depth \(d_0\)) and a more nearshore location (at a water depth \(d_1\)) is computed using the following relationships for wave length and wave celerity.

The local wave length \(L\) is computed from:

\[
L = \frac{g T_p^2}{2\pi} \sqrt{\tanh \left( \frac{4 \pi^2 d}{T_p^2 g} \right)}
\]

and is, for a specific wave period \(T_p\), directly related to the water depth \(d\) [Eckart, 1952]. It should be noted that this formulation for the wave length is an approximation, though far more easy to solve than the more correct expression which reads:

\[
L = \frac{g T_p^2}{2\pi} \tanh \left( \frac{2\pi d}{L} \right)
\]

and has the unknown wave length at both sides of the equal-sign. The approximate expression of (6.2.1) is stated to be correct within 5% [Steetzel et al., 1998].

For given wave length, the wave celerity \(c\) can basically be computed from:

\[
c = \frac{L}{T_p}
\]

or directly from:

\[
c = \frac{g T_p}{2\pi} \sqrt{\tanh \left( \frac{4 \pi^2 d}{T_p^2 g} \right)}
\]

as a function of wave period \(T_p\) and water depth \(d\).

Other related parameters are:
\[ k = \frac{2\pi}{L} \quad (6.2.5) \]

and:

\[ n = \frac{1}{2} \left( 1 + \frac{2 \cdot k \cdot d}{\sinh(2 \cdot k \cdot d)} \right) \quad (6.2.6) \]

These formulations can be used for the assessment of the wave direction and wave height change. It should be noted that the change in the wave period is not taken into account here.

**6.2.4 Wave direction change**

The relation between the wave direction at a nearshore location \( \theta_1 \) (at a water depth \( d_1 \)) and the original direction at the offshore wave climate \( \theta_0 \) (at a water depth \( d_0 \)) is:

\[ \sin \theta_1 = \frac{c_1}{c_0} \sin \theta_0 \quad (6.2.7) \]

or:

\[ \sin \theta_1 = \frac{L_1}{L_0} \sin \theta_0 \quad (6.2.8) \]

in which the wave length is defined according to Equation (6.2.1).

In order to compute the local wave direction \( \theta_1 \) (at a water depth \( d_1 \)) from the offshore direction:

\[ \theta_1 = \arcsin \left( \frac{L_1}{L_0} \sin \theta_0 \right) \quad (6.2.9) \]

whereas for purpose of reciprocal modelling the (virtual) offshore wave direction \( \theta_0 \) (at a water depth \( d_0 \)) can be assessed from the local wave angle \( \theta_1 \) using:

\[ \theta_0 = \arcsin \left( \frac{L_0}{L_1} \sin \theta_1 \right) \quad (6.2.10) \]

**6.2.5 Wave height change**

The relation between the wave height at a nearshore location \( H_1 \) (at a water depth \( d_1 \)) and the original height at the offshore wave climate \( H_0 \) (at a water depth \( d_0 \)) can be assessed from:

\[ H_1 = (K_r \cdot K_s) \cdot H_0 \quad (6.2.11) \]
in which $K_r$ and $K_s$ refer to the refraction and shoaling factor respectively.

The refraction factor $K_r$ is computed the wave angles according to:

$$K_r = \frac{\cos \theta_0}{\cos \theta_1} \quad (6.2.12)$$

whereas the shoaling factor $K_s$ is assessed from:

$$K_s = \sqrt{\frac{n_0 c_0}{n_1 c_1}} \quad (6.2.13)$$

using the relations earlier defined.

In order to assess the (virtual) offshore wave height $H_0$ (at a water depth $d_0$) can be assessed form the (eventually modified) local wave height $H_1$ using:

$$H_0 = \frac{H_1}{K_r K_s} \quad (6.2.14)$$

The latter relation will be used for the assessment of the impact of the structure-induced wave height modification on the local transport capacity.

### 6.2.6 Validation and calibration

A series of computations have been carried out to verify the refraction-shoaling formulae (see [Steetzel et al., 1998]). The main objective of these computations was to check if the approximate expression (6.2.1) for the wave length $L$ has a significant effect on the estimated nearshore wave direction $\theta_1$ and wave height $H_1$. Therefore the results were compared with the results of the computational wave-height decay model ENDEC which takes into account refraction, shoaling and dissipation due to bottom friction (the latter is not included in the schematization discussed above).

The results indicate that the wave lengths computed with the approximate equation are slightly larger than the wave lengths computed with ENDEC. However, the overall similarity is very satisfactory.

Based on these results it is concluded that the computed amount of refraction and shoaling using the approximate equations provides satisfactory results and the formulae can be used for the transformation of wave heights and wave directions form offshore to nearshore and vice versa.

It should be noted that these formulations are only valid for a simple bathymetry with more or less parallel depth contours. Since this constraint is valid for the PONTOS-model also, this provides no problems.
6.3 Diffraction

6.3.1 Introduction

Due to the presence of a structure in the surfzone a distinct shadow zone may occur in case of oblique wave attack. The diffusion of wave energy in the region landward of the seaward extent of this structure will affect the original wave field, due to an increase of the amount of wave energy to the shadow zone and the related reduction of wave energy next to this zone.

Since this process of energy re-distribution has a large impact on the coastal morphology in case of the presence of large structures (like harbour moles) the impact of this process has to be implemented in the PONTOS-model in order to simulate the morphological evolution in such a coastal stretch to a satisfactory extent.

6.3.2 Background

Diffraction plays a role in case of the presence of groynes or revetments penetrating in the surfzone in combination with oblique wave attack. In case of waves approaching at a positive angle (yielding a positive longshore transport rate by definition), the waves just downdrift of the structure will be affected yielding also effects on the transport pattern and ultimately on the evolution of the depth contours.

A typical example of this diffraction process is the development of a sheltering zone next to a groyne, which will cause the shoreline to deviate from the standard coastline evolution. The sheltering will cause the beach sediment to accumulate around the groyne. Immediately after the construction of a groyne, this effect may cause a certain erosion even on the updrift side of the groyne.

The diffraction process plays also an important role in case of offshore longshore orientated dams. The more complicated impact of offshore breakwaters is not elaborated in this phase of the study.

6.3.3 Basic schematization

Due to diffraction wave energy penetrates round the edge of the structure. For schematization purposes, two dominating effects will be considered, namely:
- The modification of the wave direction;
- The modification of the wave height.

The actual formulation for the diffraction coefficient as used in the updated PONTOS-model is based on formulae from Kamphuis [Kamphuis, 1992].

6.3.4 Diffraction formulae

In [Steetzel et al., 1998] a preliminary formulation was proposed for implementation in the pilot version of the PONTOS model. This formula was based on the data of Wiegel [Wiegel, 1962]. The reference rate of the diffraction coefficient on the shadow line (the ratio between
the actual wave height and the original wave height at the diffraction point) was defined as $K_d = 0.55$. Since these data are based on regular monochromatic waves with a single period and a single wave direction, the amount of diffraction is over-estimated.

In the current version of the PONTOS-model a modified function is used which is based on data presented by Kamphuis [Kamphuis, 1992]. These are based on random waves, include the effects of directional spreading and give a better estimate of the wave heights in the shielded zone.

### 6.3.5 Wave direction change

Downdrift of a shadow line, thus for the area where $\theta_o > \theta_i$ the direction is unchanged, whereas for $\theta_o < \theta_i$ the direction modified according to $\theta_o = \theta_i + \theta_d$.

### 6.3.6 Wave height change

For the wave direction in the shadow zone the angle $\theta_o$ is used as the characteristic parameter. It should be noted that the wave period in the diffraction zone remains unchanged in the present model.

### 6.3.7 Procedure

In order to assess the modified characteristic hydraulic conditions landward of the seaward extent of a groyne or revetment (the actual diffraction point), the model goes through the following stepwise procedure:

1. Assessment of the location (co-ordinates) of the diffraction point;
2. Assessment of the (characteristic) water depth $d_1$ at the location of this point (using the continuous version of the layer profile);
3. Assessment of the incoming wave angle $\theta_i$ at this location using the formulations for refraction and shoaling as discussed in Section 6.2. This will result in a local incoming wave height $H_{i_d}$ and wave direction at depth $d_1$ as well as a measure for the ‘diffraction space’ $\Delta \theta_d$;
4. Computation of the shift in the wave angle $\Delta \theta$ as a result of the procedure discussed in Section 6.3.5;
5. Computation of the diffraction coefficient $K_d$ (see Section 7.3.8) yielding the ratio between the diffracted wave height $H_{d}$ and the incoming wave height $H_{i}$ at the diffraction point;

As a result of this procedure, the relevant wave conditions at water depth $d_1$ (the location of the diffraction point) in terms of wave direction $(= \theta_i + \Delta \theta)$ and wave height $(= K_d H_{i})$ are available.

In order to use the ‘offshore conditions-based transport formulations’ the next step is to transform these modified nearshore condition back to offshore yielding a virtual offshore wave condition, which can be directly used in the general applicable formulae for longshore and cross-shore sediment transport as described in Chapters 4 and 5.
It should be noted that in the present version of the PONTOS-model only the impact of the modified wave conditions on the longshore transport is taken into account. The effect of the modified wave conditions on the cross-shore transport is not implemented in the model. As a result the wave height used in the cross-shore transport model is overestimated and the cross-shore transport rates are overestimated as well. If in a later phase of the model development also longshore dams would be implemented in the model (offshore breakwaters) this effect must be taken into account.

Furthermore it should be noted that the actual longshore variation of the offshore hydraulic conditions is not taken into account correctly. The local offshore conditions are assumed to be characteristic at a more updrift or downdrift diffraction point also. Since this offshore variation is present on a far larger spatial scale, this seems no problem.

6.3.8 Calibration and model coefficients

Based on the schematization of the diffraction process, 4 different coefficients (basic settings of the model) have been defined:

- The degree in which the modification of the wave direction is taken into account.
- The degree in which the wave height modification of the diffraction process is taken into account;
- The basic reference rate of the diffraction coefficient as present at the shadow line, denoted as $K_{d,i}$;
- The reference rate of the updrift angle, denoted as $\theta_u$, up to where diffraction effects are present.

The first two parameters enable the user of the model to turn on/off the related processes. If both parameters are set to zero only the effect of sheltering is taken into account (note: default values equal 1.0).

The latter two parameters refer to the basic shape of the diffraction formulae yielding a gradual stepwise increase of the diffraction factor $K_d(\theta)$ in updrift direction. The stepwise increase is formulated according to:

- For $\Delta \theta < -90^\circ$: $K_d(\theta) = 0.0$;
- For $-90^\circ < \Delta \theta < 0^\circ$ (downdrift of the shadow line) a linear increase from $K_d = 0.0$ at $\Delta \theta = -90^\circ$ to $K_d = K_{d,0}$ at the shadow line;
- For $0^\circ < \Delta \theta < \theta_u$ (updrift of the shadow line) a linear increase from $K_d = K_{d,0}$ at the shadow line to $K_d = 1.0$ at $\Delta \theta = \theta_u$;
- For $\Delta \theta > \theta_u$ : $K_d(\theta) = 1.0$.

‘Diffraction space’-correction

Former described reference distribution for the diffraction coefficient is valid for the situation that the available ‘diffraction space’ $\theta_d$ is more than 90° as present on the updrift side of an offshore breakwater with oblique wave attack. If the available space is less and thus the intermediate angle between the shadow line and the axis of the structure is small, the effects of the diffraction process are more limited.
6.4 Contraction effects

6.4.1 Background

For coasts mainly dominated by horizontal tides the application of different layers to schematise the cross-shore profile leads to an unexpected and incorrect coastal evolution if the continuity of the tide-induced discharge and the disturbance of the overall flow-pattern is not taken into account to some extent.

Due to the presence of ‘some sort of hump’ (either a horizontal sand wave or a structure-induced seaward extension of the beach line) the tide-induced longshore current and thus the tide-induced longshore sediment transport (per m$^1$ in cross-shore direction) will be amplified locally. If this modification is not taken into account and this rate is unaltered, the total tide-induced longshore transport in front of the ‘hump’ is reduced due to the narrowing depth contours and reduced width of the layer-related streamtube. As a consequence the resulting longshore transport gradient will yield accretion at this location whilst erosion is expected.

If the effects of contraction are taken into account, the local tidal velocities would increase, yielding an increased tide-induced longshore transport capacity (per m$^1$ cross-shore) and ultimately an increased total longshore rate and thus the expected erosive behaviour updrift of the centre of the ‘hump’.

A pragmatic approach used in the model to deal with this problem is explained hereafter.

6.4.2 Schematization requirements

For a description of the modified flow pattern in case of large discontinuities penetrating in the ‘tidal river’, two types of corrections should be taken into account:
the overall modification of the flow pattern;
the longshore continuity the overall flow field.

The first item refers to the presence of shadow areas updrift and downdrift of such protruding elements (e.g. large cross-shore dams such as harbours moles).
From a previous study on the rough dimensions of the affected areas, is was found that the distance over which the tidal flow is affected by a structure is related to the distance over which the structure protrudes in the ‘tidal river’ itself (the so-called protrusion distance) [Steetzel et al, 1998]. Furthermore it was found that the affected area downdrift of a structure tends to be slightly larger than the area updrift. If the protrusion distance is denoted as $L_p$, the length of the affected area updrift of the structure was shown approximately $2.0 L_p$, whereas the length of the downdrift area is approximately $2.5 L_p$.
Furthermore is was concluded that the area affected seaward of the structure stretches out over a distance of approximately $L_p$.

Both items will affect the overall flow pattern. In the following the procedure for the implementation of these effects in the layer model will be discussed and the individual steps will be described.
It should be noted that this procedure is restricted to the tidal flow only. How to deal with the continuity of the discharge governed by the wave-induced current may be discussed in a later version of the model.

### 6.4.3 Outline of procedure

Starting point for the assessment of the modified flow pattern are the results of the basic procedure as described in Section 3.3.3. As a result of this, the (uncorrected) tidal flow velocity $v_{j,i}$ in every individual layer $j$ (using the mean water depth as a characteristic value) at every grid cell $i$ along the coast is available.

For the assessment of the modified tidal flow pattern, which takes both the overall flow-pattern as the longshore continuity into account, a stepwise procedure has been devised. The result will be a modified flow pattern denoted as $v^*$ which is related to the original flow field according to:

$$v^*_{j,i} = A_{v,j,i} v_{j,i}$$  \hspace{1cm} (6.4.1)$$

in which the amplification factor is denoted as $A_v$. Initially this amplification factor by definition equals 1.0.

The procedure to assess the required $A_v$-factor is as follows:

1. Assessment of the longshore variation of the cross-shore integrated discharge $D_t(x)$;
2. Assessment of the longshore position of the landward edge of the overall stream tube $Y_s(x)$;
3. Correction of the basic current velocities for the locations where the seaward shift of the landward boundary of the stream tube $Y_s(x)$ yields a position seaward of the original landward boundary of the layer-related stream tube;
4. Computation of the discharge per individual location based on the product of the actual velocity and (possibly corrected) layer-related width;
5. Computation of the longshore variation of the total discharge $D(x)$;
6. Assessment of cross-shore an longshore correction of the amplification factor $A_{v,j,i}$ in order to achieve the boundary condition $D(x) = D_t(x)$;
7. Computation of the final velocity from the product according to Eq. (6.4.1).

In the third step the tidal current in sheltered zones is corrected by setting the amplification factor $A_{v,j,i}$ in these specific cases to zero.

Steps 1, 2 and 3 are discussed in the following section. The tide-driven transport rate is computed from the corrected velocity $v^*$ (yielding a transport rate expressed in $m^3/m^1/yr$), taken the effective width of the layer-related tube $B^*$ into account.

### 6.4.4 Total tide-driven discharge rate

The total, cross-shore integrated tidal discharge rate, denoted as $D_t$ and expressed in $m^3/s$, is initially computed for the (limited number of) locations of the active tidal stations only. For the assessment of this discharge the area landward of the seaward border $Y_s(x)$ (which is defined as input) is taken into account. The actual discharge is computed from:
\[ D_j = \sum_{j=0}^{5} v_{j,i} \cdot B_{j,i} \] (6.4.2)

in which \( v_{j,i} \) refers to the uncorrected velocity for layer \( j \) and position \( i \) and \( B_{j,i} \) to the characteristic width of the layer-related stream tube. In this approach \( j = 5 \) refers to the shelf-layer.

The characteristic width of an individual layer \( B_j \) is computed from the mutual distance between the positions of the \( Z_{j+1} \) and \( Z_j \)-contour. The related cross-shore positions are assessed from the schematic cross-shore profile definition.

The actual longshore variation of this discharge rate is assessed using a standard linear interpolation between the \( D_t \)-values at individual stations, yielding the longshore variation of the total tide-driven discharge rate \( D_t(x) \) as a result.

Any longshore gradient in this discharge rate will yield an additional exchange of water through the seaward border \( Y_b(x) \) by definition.

### 6.4.5 Landward edge of overall stream tube

The assessment of the landward edge of the overall stream tube, denoted as \( Y_s(x) \) is computed from the characteristic dimensions of the shadow areas. In order to compute the position of the \( Y_s \)-boundary, three subsequent steps are taken into account, namely:

1. Assessment of the position of the waterline at every grid cell in longshore direction from the position of the intersection between the local schematic cross-shore profile and the local water level;
2. The possible seaward correction of this initial \( Y_s \)-boundary due to the effect of downstream sheltering by checking if the individual shift between \( Y_s,j \) and the downdrift \( Y_s \)-position obeys the maximum rate of change in this position;
3. The corresponding check for the effect of the updrift sheltering.

This procedure yields a modified flow pattern \( v^* \) as a result.

### 6.4.6 Assessment of the continuity correction

In order to obey the longshore continuity of the discharge \( D_t(x) \), the discharge rates per individual layer, denoted as \( D_{j,t} \) are modified by applying a non-standard value of the amplification factor \( A_{v,j,i} \).

In the present version of the model the magnitude of this correction factor is defined as a uniform function, yielding a cross-shore uniform correction. As a result of this approach the correction rate is sensitive to the exact location of the seaward border.

Since the impact will be dominant in the landward part of the streamtub, a far better method would be to apply a cross-shore distribution for the correction factor which takes the expected non-uniformity to a greater amount into account.

### 6.4.7 Calibration coefficients

In former described procedure a number of coefficients are involved, related to three groups, namely:
General process factor $C_t$

A general parameter denoted as $C_t$ in order to defined the relative amount in which all the former described effects are taken into account, ranging from $C_t = 0$ for no correction to $C_t = 1$ for full correction. This parameter can be used to investigate the effect of the procedure. The default value is $C_t = 1$.

Flow pattern modification

Two calibration parameters are used to simulate the extent of downdrift and updrift shadow zones; these are defined as $S_d = 2.5$ for downdrift sheltering and $S_u = 2.0$ for updrift sheltering [Steetzel et al., 1998]. These parameters are of interest for the assessment of the landward edge of the overall stream tube (step 2) in former described procedure).

In case the two sheltering coefficients are defined as $S_d = 0.0$ (downdrift sheltering) and $S_u = 0.0$ (updrift sheltering) the procedure takes into account only the effect of the continuity correction. The additional pragmatic incorporation of the overall modification of the flow pattern will improve the results obtained with the model.

Continuity correction $C_c$

A parameter denoted as $C_c$ is used to define the relative amount in which the correction for discrepancies in the total discharge are taken into account ranging from $C_c = 0$ for no correction to $C_c = 1$ for full correction. The default value is $C_c = 1$.

A second calibration factor $S_c$ is used for the cross-shore distribution of the continuity correction, where $S_c = 1.0$ refers to the basic triangle-like modification (with the largest modifications next to the shoreline) and $S_c = 0.0$ yields a cross-shore uniform modification. This parameter is related to step 6) in former described procedure.
Implementation of tidal inlets

7.1 Introduction

In the framework of the present study, the PONTOS-model has been modified such that also an interrupted coastline can be used. In the process of formulation and implementation of required inlet-extension of the PONTOS-model, a number of development phases have been distinguished.

In the first step of the development, the net transport through the tidal inlet has been based on external computations with the ASMiTA-model, whereas a conceptual basin model has been incorporated in the overall model in the final phase of the study.

In the following, more details are presented on both the PONTOS-part (the outer delta) and the ASMiTA-part (the back barrier system) of the model.

The next items will be discussed in more detail:

- The conceptual model for the outer delta;
- The interaction with the back-barrier system;
- The evolution of the back barrier system;
- The actual implementation of a tidal inlet system in the computational model.

7.2 Outer delta forcing

7.2.1 Basic transport pattern

The (equilibrium) shape of the outer delta can be seen as the ultimate result of the underlying transport pattern in the outer delta region.

To be more specific, the seaward-directed net transport in the ebb-channel acts as a source in the coastline model. As a result the most seaward position of the outer delta contour is located at the location of the ebb-channel.

On the other hand, the two (virtual) flood channels on the updrift and downdrift side of the outer delta act as a sink. In a very basic approach, the flood channel transport rate is half of the ebb-channel transport rate.

In practical applications, the mutual distribution of the ebb channel transport over the two flood channels is based on the transport capacity along the outer delta fringes. The latter depends on the actual orientation of the individual contours (see Section 7.2.3 for more details).

Figure 7.1 provides this basic outline of the transport pattern which acts as the starting point for the “outer delta model” which has been implemented in the computational model. The schematized transport pattern, provided in Figure 7.2, shows the seaward directed transport in the ebb channel and the two compensating flood channel transports.
7.2.2 Modification of the coastline model

In the basis set-up of the PONTOS-model, five different layers are present. At the location of a tidal inlet, both the dune layer (layer 0) and the beach layer (layer 1) are absent. As a consequence, this holds also for the related longshore transports (in both layer 0 and 1) and cross-shore transport (at the dune boundary as well as at the interface between the dune and beach layer as well as the beach and surfzone layer).

As a result only three layers are active, namely the surfzone layer (layer 2) and the upper and lower shoreface (layer 3 and 4 respectively).

This modified cross-shore profile is shown in Figure 7.3.

The net transport pattern related to the (virtual) ebb- and flood-channels is implemented in the surfzone layer (in between the NAP-7m and NAP-2m level). The virtual flood-channel transport is implemented as a longshore transport in the updrift and downdrift edge of the inlet. The ebb-channel related transport is schematized as cross-shore transport at the virtual ebb-channel location.

7.2.3 The equilibrium situation

In the equilibrium situation an outer delta looks more or less like a triangle. In order to maintain this shape a distinct stable transport pattern needs to be present. In such an equilibrium situation, the seaward-directed transport at the tip of the outer delta is compensated by updrift en downdrift transports along the outer contour of the delta (see also Figure 7.2). The magnitude of these (wave-induced) compensating transports is directly related to the angle of the outer delta contour as well as to the existing wave climate.

In this equilibrium situation, the equilibrium magnitude of the relative shift in the angle depends on the wave-induced transport capacity. The latter is related to the steepness of the so-called “S-phi-curve” which relates the wave-induced transport capacity to the relative angle of wave attack.

For a given rate of the ebb-channel transport and an intense wave climate, only a moderate shift in the angle is needed to drive the required compensating transports along the outer delta edges. As a result the equilibrium shape of the outer delta is relatively flat. On the other hand, for a less intense wave climate, the required shift in the angle will be more extreme and thus the triangular shape of the outer delta will be more pronounced.

In the present version of the PONTOS-model, the equilibrium transport rate in the ebb channel is assessed from the shape-parameters.
Two parameters are defined, namely the relative protrusion of the outer delta \( \lambda \) and the relative offset \( \phi \). The definition of these parameters is shown in Figure 7.4a.

For a specific (pre-defined) equilibrium shape of the outer delta, the magnitude of the two compensating transports along the seaward edge of the outer delta can now be assessed from the wave climate-based “S-phi-curve”. This procedure is illustrated in Figure 7.4b. Next, the forcing ebb channel transport can be computed as well as the flood channel transports.

Latter flood channel transports are directly based on these two compensating transports.
So, starting from a predefined equilibrium shape, the underlying shape-forcing transport pattern is assessed by the numerical model.

### 7.2.4 Additional improvements

It should be noted that in the PONTOS-model, the actual delta volume is computed from the positions of the various layers in the tidal inlet region taking only the excess position (relative to the layer positions at the updrift and downdrift edges).

Specific attention has also been paid to the effect of a net longshore current pattern. Due to the distinct change in the layer positions (especially for layer 2), the schematized flow pattern as well as the tide-induced transport pattern will show discontinuities at the outer delta edges by definition. The schematisation for especially the discharge-related correction has been improved such that these irregularities are suppressed to a large extent.

### 7.2.5 Example of tidal delta evolution

An example of the development of a tidal delta is provided in Figure 7.5. Starting with an initial situation with no specific outer delta, the computational model is used to develop a stable equilibrium shape.

In this case, the evolution is computed for a specific rate of the relative protrusion of the outer delta. The actual time scale is related to the applied wave climate.

As can be observed, the final shape has indeed the anticipated triangular shape.

More details with respect to the evolution are presented in Figure 7.6. The upper panel shows the development of the layer positions at the outer delta centre. The time scale for the lower layers is relatively long. The evolution of the outer delta excess volume, denoted as $V_d$, is shown in the middle panel. The lower panel provides both the outer delta excess volume as the volume in the delta area. The latter is relatively smaller due to the erosion of the coastline.

Figure 7.7 shows, comparable to Figure 7.5, the evolution of a non-symmetric outer delta. In this case the centre of the outer delta is located on the left side of the tidal inlet, whereas the positive offset results in a seaward shift of the downdrift (right) coastline in the (near-) equilibrium case (shown in the lower panel).

### 7.3 Coupling with the back-barrier system

In the previous elaboration, an equilibrium transport pattern has been used. In case of a net sediment exchange in the tidal inlet, the transport in the virtual ebb-channel is modified. The net exchange (a negative rate in case of a sediment importing tidal basin) is superimposed on the equilibrium ebb-channel transport. In case of an exporting basin, the magnitude of the virtual flood channels transports is increased.

As a result the coastal stretch, including the outer delta, erodes and the outer delta itself moves in landward position. The outer delta region erodes, while the excess volume of the outer delta, $V_d$, remains constant.
Apparently, a net import towards a tidal basin (e.g. due to sea level rise) results in an overall erosion of the coastal stretch. The outer delta is hardly affected and acts as an intermediate reservoir only.

An example of the evolution of an eroding tidal inlet system is shown in Figure 7.8 and 7.9. Starting point for this computation is the computed equilibrium from Figure 7.5. As can be observed in Figure 7.9, the outer delta area erodes whereas the outer delta excess volume remains more or less stable.

### 7.4 Modelling the back barrier system

#### 7.4.1 Concept of the AsMiTA-model

The AsMiTA (Aggregated Scale Morphological Interaction between a Tidal basin and the Adjacent coast) model, has recently been introduced by Stive et al (1998, see also Van Goor et al, 2002 and Kragtwijk et al, 2003).

The basic idea of the approach is that a tidal inlet can be schematised into a number of morphological elements. For each element a volume can be defined acting as integral state variable. The level of schematisation is similar to that of the ebb-tidal delta by Dean and Walton (1975). A tidal inlet is thus schematised into:

- the ebb-tidal delta (state variable = integral excess sediment volume relative to an undisturbed coastal bed profile, \( V_d \));
- the inter-tidal flat area in the tidal basin (state variable = integral sediment volume between MLW and MHW, \( V_f \));
- the total channel volume in the tidal basin (state variable = integral water volume below MLW, \( V_c \)).

Following this schematisation the adjacent coastal stretches are considered as an external boundary - "the outside world" - which can exchange sediment with the considered inlet system.

The important hypothesis used in the model concept is that a morphological equilibrium can be defined for each element depending on the hydrodynamic conditions (e.g. tidal prism, tidal range) and morphometric conditions (e.g. basin area). Theoretical arguments for the existence of such equilibrium were given by Dronkers (1998), but is also supported by various field investigations, which have resulted in empirical relations between state variables and parameters of the governing hydrodynamic and morphometric conditions (cf. Eysink 1990). In general, the (dry or wet) volume \( V_{ne} \) \([m^3]\) of an arbitrary element \(n\) in a state of morphodynamic equilibrium, has appeared to be highly correlated to the tidal range \(H\) \([m]\), the tidal prism \(P\) \([m^3]\) and the basin area \(A_b\) \([m^2]\):

\[
V_{ne} = V_{ne}(P, H, A_b)
\]

(7.1)

According to this hypothesis no morphological change takes place when all elements in the system are in equilibrium. When one or more elements are out of equilibrium morphological changes will take place tending to restore the system to (a possibly new) equilibrium.
Obviously, sediment transport must accompany morphological changes. It is assumed that suspended load is representative for the transport mode. The sediment transport formulation is basically the same as for any other suspended sediment transport model. However, unlike process-based models describing flow and sediment transport within tidal cycles residual sediment transport \( T \) is directly modelled here. This means that the long-term (time scale much larger than tidal period) mass-balance is considered for every morphological element:

\[
\pm \frac{dV_n}{dt} = \sum T_{ni} + A_n \frac{d\zeta}{dt} \tag{7.2}
\]

The left-hand side of this equation represents the erosion rate within the element. Its sign is positive for a wet volume and negative for a dry volume. The right-hand side represents the sum of the transports leaving the element via all connections to other elements including the outside world. The erosion rate is assumed to be proportional to the difference between the local equilibrium concentration and the actual concentration like the depth-averaged model for suspended sediment transport of Galappatti and Vreugdenhil (1985):

\[
\pm \frac{dV_n}{dt} = w_s \cdot A_n \cdot (c_{ne} - c_n) + A_n \frac{d\zeta}{dt} \tag{7.3}
\]

Herein \( w_s \) [m/s] is the vertical exchange rate, \( A_n \) [m\(^2\)] is the horizontal area of the element, and \( \zeta \) is the mean sea level. Erosion occurs when the actual sediment concentration \( c_n \) is smaller than the equilibrium concentration \( c_{ne} \), sedimentation occurs when the actual sediment concentration is larger than the equilibrium concentration. Also like any suspended sediment transport model the (long-term residual) sediment transport between two elements is assumed to be of the advective-diffusive type:

\[
T_{ni} = Q_n (c_n + c_i) + \delta_n (c_n - c_i) \tag{7.4}
\]

Herein \( Q \) [m\(^3\)/s] is the residual flow rate, \( \delta \) [m\(^3\)/s] the diffusion exchange rate between the two elements and \( c_i \) the sediment concentration in the adjacent element.

Substitution of (7.3) and (7.4) into (7.2) yields an equation for the sediment concentration for each element. In this way a system of coupled equations for the sediment concentrations in all elements is established. It can readily be solved if the local equilibrium concentration is known. Equilibrium sediment concentration according to most sediment transport theories can be considered as proportional to a certain power of the flow velocity. In an aggregated scale model as considered here, flow velocity is not an available hydrodynamic parameter. However, the ratio between the equilibrium volume and the actual volume of e.g. the channel can be considered as the ratio between the flow velocity and that under equilibrium condition. Therefore the following formulation is used:

\[
c_{ne} = c_E \cdot \left( \frac{V_{ne}}{V_n} \right)^r \tag{7.5}
\]

The magnitude of power \( r \) is larger than one, commonly taken as 2 in compliance with a third power for the sediment transport as a non-linear function of the mean flow velocity. Its
sign depends on the definition of the element volume, \( V_n \), positive for wet volume and negative for dry volume.

The parameter \( c_E \) has the dimension of sediment concentration. When the whole system is in equilibrium the sediment concentration in all elements will be the same and equal to \( c_E \). Therefore it is called the overall sediment concentration. It is usually prescribed at the outside world as boundary condition if the outside world can be considered as in equilibrium, which physically means that there is no limitation for supply or accommodation of sediment adjacent to the system under consideration. In the cases that we describe this is proven to be valid. However, in case the adjacent coast is protected, constrained by headlands, or in general insufficiently dynamic this assumption may not hold. In this case the adjacent coast needs to be introduced as an intrinsic morphological element to the system.

For all the considered inlets the empirical relations used for the morphological equilibrium are as follows.

For the inter-tidal flat:

\[
V_{fe} = \alpha_f A_f H
\]  
(7.6)

For the channel:

\[
V_{ce} = \alpha_c P^{1.55}
\]  
(7.7)

For the ebb tidal delta:

\[
V_{de} = \alpha_d P^{1.23}
\]  
(7.8)

In these equations \( A_b \) is the area of the basin, i.e. the sum of the area of the flat and that of the channel. \( H \) is the tidal range and \( P \) is the tidal prism:

\[
P = A_b H - V_f
\]  
(7.9)

where \( V_f \) is the volume of the inter-tidal flat.

### 7.4.2 Impact of coastal evolution

The evolution of the coastal region is assessed using the multi-layer model. As a result, the cross-shore position of the coastline in the outer delta region may change. In case of an eroding coast, the volume of the outer delta will increase by definition. In the online-mode, this correction of the delta base position can be taken into account in the AsMita-computations which are carried out to compute the net exchange in the tidal inlet.
7.5 Implementation of a the tidal inlet system in the model

7.5.1 Introduction

For the definition of tidal inlets (parameter group #4 in the PONTOS-model; see Annex A of part II of this report), four different types of parameters are being distinguished, namely:

1. The tidal inlet characteristics;
2. The related tidal basin characteristics;
3. The related tidal inlet coefficients (related to the PONTOS-model);
4. The related tidal basin coefficients (related to the ASMiTA-model).

In total 15 different inlet systems can be defined in the PONTOS-model.

7.5.2 Tidal inlet characteristics

The tidal inlet characteristics per individual inlet system refer to PonTos-model-related items (in the coastline model) such as:

- The position of the left-hand (updrift) boundary $X_{left}$;
- The location of the (virtual) ebb-channel or the most seaward location of the outer delta $X_{centre}$ (delta tip);
- The position of the right-hand (downdrift) boundary $X_{right}$.

These parameters define the overall geometry of the outer delta. The width of the outer delta is computed from the distance between the left- and right-hand boundaries.

7.5.3 Basin characteristics

With respect to the basin characteristics per individual inlet system, the (initial) dimensions of the basin area are defined:

- The area of the flats $A_f$ (in Mm$^2$);
- The area of the channels $A_c$ (in Mm$^2$);
- The area of the outer delta $A_d$ (in Mm$^2$);
- The (local) tidal range $H$ (in m);
- The volume of the flats $V_f$ (in Mm$^3$);
- The volume of the channels $V_c$ (in Mm$^3$);
- The volume of the outer delta $V_d$ (in Mm$^3$).

The tidal prism is computed from the flat and channel area’s and the tidal range, is used to define the equilibrium volume of the outer delta $V_{d,eq}$.

7.5.4 Tidal inlet coefficients

The next parameter group is referred to as the tidal inlet coefficients. These coefficients, which are directly related to the PONTOS-model, are used to relate the equilibrium shape of the outer delta to the “shape-forcing transport pattern” in the outer delta region.
In the initial set-up of the model (version 1.6), the magnitude of the transport in the ebb-channel was used as a tidal inlet coefficient.

In the present version of the model (version 1.8) this transport rate is related to the equilibrium shape of the outer delta and the available wave-induced sediment transport capacity.

Within the parameter group two shape-related parameters are defined, namely:

- The relative protrusion of the outer delta $\lambda_r$;
- The relative offset of the outer delta $\phi_r$.

For a more extensive elaboration of the principle of this “outer delta forcing” reference is made to Section 4.2.

### 7.5.5 Basin coefficients

The last parameter group is referred to as the basin coefficients. These coefficients are similar to the coefficients used in the original (offline) AsMiTa-model. The following coefficients are present per individual inlet system:

- The $\alpha$-coefficients for the flats, the channels and the outer delta: $\alpha_f$, $\alpha_c$ and $\alpha_d$;
- The $C_E$-parameter;
- The $r$-parameter;
- The fall velocities for the flats, the channels and the outer delta: $w_f$, $w_c$ and $w_d$;
- The $\delta$-coefficients for the flats-channel-interaction and channel-delta-interaction: $\delta_{fc}$ and $\delta_{cd}$.

If the model is used in the offline mode, the $\alpha_{fr}$-parameter is used to compute the equilibrium volume of the outer delta as a function of the tidal prism $P$.

### 7.5.6 Calibration parameters

For each individual tidal inlet, three calibration parameters have been defined.

The first parameter is a multiplier for the ebb-channel transport rate (default: 1.0).

The second parameter acts as a multiplier for the computed or pre-defined net transport in the tidal inlet (default: 1.0).

The last parameter defines to what extent the coastal evolution of the outer delta is taken into account in the AsMiTa-computations which are used to compute the net transport in the tidal inlet.

### 7.5.7 Online versus offline mode

The application of the individual parameters depends of the way the net transport through an individual tidal inlet is assessed.

Two methods are available, namely:

- Using the *offline mode* by applying pre-described time-series for this net transport;
- Using the *online mode* by using an AsMiTa-routine to assess the net transport as a function of a series of parameters and momentary conditions.
It should be noted that if a pre-described time-series for the net transport is available, the model is used in the offline mode by definition.

In the online mode, the various coefficients are used in the ASMiTA-routine to calculate both the evolution of the basin characteristics (e.g. the flat volume and the tidal prism) and the net transport through the inlet.

In order to use pre-described net transport rates use can be made of a pre-described boundary condition (parameter group #6.5 in the PONTOS-model). Using this option the time evolution of the net transport through an individual inlet can be defined. This time series can be based on the result of an ASMiTA-computation taking into account the impact of sea level rise.

In that case, the computational model will be used in the so-called offline mode. As a consequence, the basin characteristics (parameter group #4.2) will not vary in time and the initial basin settings remain valid during the whole simulation period.

If the boundary condition for a specific inlet is absent, the model will be run in the online mode and the basin characteristics will be treated as initial settings only. The momentary net transport rate through the inlet will be assessed using an ASMiTA-routine.
8 Coastal management

8.1 Introduction

In addition to the so-called ‘hard measures’ such as the application of revetments or groynes, ‘soft measures’, e.g. nourishments can be used in order to maintain the coastline at least at a pre-described acceptable position (the so-called BCL-approach).

To achieve this goal, within the framework of the PONTOS-model two different approaches have been formulated, namely to possibility to use a series of pre-defined nourishments (to take into account already executed nourishments) or to use a specific well-defined management strategy (to take future nourishments into account).

Pre-defined nourishments

Pre-defined nourishments, or in general terms sources and sinks, can be used to add, withdraw or even displace quantities of sediment in coastal zone.

In the latter case a related source and sink of equal quantity has to be defined.

Preservation nourishments (layer positions and cells volumes)

In order to maintain the actual coastline (for example the basal coastline; BCL) at a required minimum position, nourishments can be carried out depending on the computed future behaviour of the coast.

In order to assess these future nourishment requirements, the PONTOS-model has been equipped with so-called ‘auto-nourishment’ options. Using this option the model will, depending on the computed evolution of individual layers, instantaneously nourish a specific computational cell in the related layer until a non-critical pre-defined position is achieved.

An initial version of such a layer-nourishment tool has been used for the assessment of future nourishment requirements for the Dutch Wadden Coast in the period 1990 to 2040 for different scenarios of sea level rise and sediment import to the back barrier system [Steetzel, 1995].

In the framework of the present study, a so-called auto-cell nourishment routine has been defined. Using this option, comparable to these layer nourishments, future nourishments can be assessed using a restricted rate of change of the total volume in coastal cells [Mulder, 2000].

More details on the applied formulations are presented in the following.
8.2 Pre-defined nourishment schemes

Pre-defined nourishments, or in general terms sources and sinks, can be used to add, withdraw or displace large quantities of sand in coastal zone.

An individual nourishment (source or sink) is identified using its location in both longshore direction by a $X_l$ and $X_r$-position of the left- and right-hand nourishment boundary, the $Z_l$ and $Z_r$-boundary of the depth zone, the period in which the nourishment is carried out, viz. $T_{\text{start}}$ and $T_{\text{end}}$ and of course the total volume involved $Vol_l$.

The equation used to compute the displacement of a specific layer according to:

$$\frac{\Delta y_{j,j}}{\Delta t} = \frac{(Q_{x,j,j-1} - Q_{x,j,j})}{d_{j,j} \Delta X_j} + \frac{(q_{y,j,j} - q_{y,j+1,j})}{d_{j,j} \Delta X_j} + \frac{\Delta S_{j,j}}{d_{j,j} \Delta X_j \Delta t}$$

(8.2.1)

is given in Section 2.4.

The source term in the right-hand term $\Delta S_{j,j} / \Delta t$ can be assessed from the relative positions of the nourishment (in which superscript $p$ refers to the pre-defined contribution to this term).

It should be noted that in the present version of the model, the outer boundaries of the nourishment location do not have to coincide with either the longshore grid definition or the cross-shore layer definition.

8.3 Auto layer nourishments

In order to maintain the coastline at a minimum position, nourishments can be carried out using a criterion that uses critical positions of individual layers. Depending on the evolution of the coastal layers in time, the model will auto-nourish a layer until a non-critical position is achieved.

In the case that an initially computed position of a layer is situated landward of its critical position, the additional source needed to correct this is computed from:

$$\Delta S_{j,j}^a = \Delta y^a d_{j,j} \Delta X_{j,j}$$

(8.3.1)

in which $\Delta y^a$ denotes the required seaward shift and the superscript $a$ refers to the adjusted state.

Both the longshore distribution as the time evolution of the required layer nourishments rates will be the result of the computation.

8.4 Auto cell nourishments

In order to maintain the total volume in a specific cell (or series of cells) at a minimum (initial) amount, cell nourishments can be carried out using a criterion that uses critical volume changes in such a cell. Depending on the evolution of coastal layers in time, the
model will auto-nourish a cell (or series of cells) until a non-critical volume change is achieved.

In the definition of these balance areas, a distinction has been made between the so-called ‘check area’ (defined in longshore direction by a $X_l$- and $X_r$-position of the left- and right-hand boundary and the $Z_l$- and $Z_u$-boundary of the depth zone) and the so-called ‘dump area’ (also defined by $X_l$- and $X_r$-positions and $Z_l$- and $Z_u$-boundaries).

In case of an overall loss of sediment in the ‘check area’ the deficit is nourished in the ‘dump area’.

Comparable to the layer nourishment case, both the longshore distribution as the time evolution of the required cell nourishments rates will be the result of the computation.
9 Summary of model improvements

9.1 Introduction

In the following a brief summary is provided of the model improvements and modifications that have been implemented in this project.

9.2 General improvements

In very general terms, the overall structure of the PONTOS-model has been re-structured. This holds both for the user-interface (the VISUAL BASIC-environment) as well as the computational model (the FORTRAN-environment).

The general set-up of the input-file has also been re-defined yielding a number of specific input groups (see Chapter 11). While saving the input file, additional information is added to the input file. As an example wave characteristics are added to the table with individual wave conditions per wave climate table.

In order to be able to deal with the entire Dutch North Sea Coast, the size of the various arrays has been increased to 500 points.

9.3 Specific improvements

In addition to the aforementioned general improvements of the model, some more specific problems were tackled.

With respect to the hydraulic climate schematisation the formulations have been modified such that basic wave climate data (w.r.t. the North) can be used directly.

In order to do this, the additional definition of a so-called reference line was required. The various routines that are used to translate the information from two wave climate stations to a reference location in between these stations had to be improved and modified also.

In order to use various wave climate stations in combination with a curved reference line, the definition of a specific window was required to select the relevant wave directions from an individual wave climate table.

Much effort has also been paid to the interaction of an eroding coast with structures. The original formulation used in version 1.0 of the PONTOS-model, showed that the interaction with especially revetment-like structures was not correct.

With respect to the schematised processes, the various refraction modules have been revised and made more robust. As a result the final governing longshore wave climate (being the result of a series of translation and interpolation routines) shows only gradual changes.
The routines that deal with the contraction of the longshore tidal flow have been tested more thoroughly and modified such that the longshore distribution of the net cross-shore integrated discharge is correctly related to the locations of the tidal climate stations.

With respect to tidal inlet, the schematisation of the outer delta was modified such that both the dune layer $Y_0$ and the beach layer $Y_1$ are absent in this region. A number of transport paths were defined in the outer delta representing the basic transport patterns in this area, namely the transport through the ebb- and flood channels.

Much attention has also been paid to the implementation of management scenarios. In addition to the pre-defined nourishments, two auto-nourishments modes have been implemented. The model has also been equipped with additional output, yielding insight in the pre-defined, the layer-nourished and the cell nourished volumes, both with respect to the longshore distribution as the time evolution of the nourishment rates.

Special attention has been paid to the calibration of the cross-shore behaviour of a coastal stretch. An additional climate-averaged correction has been defined and implemented in the model.

With respect to the model output, both the number and extent of output blocks have been increased significantly yielding more insight in especially the integrated, time- and space-averaged, results of the model. Special attention has been given to the results for pre-defined coastal sections.

### 9.4 Improved approaches and concepts

In summary, the mayor modifications of the model with respect to the concept of the model are related to:

- The use of basic wave climate date in combination with the definition of a reference line;
- The procedures to calibrate the cross-shore behaviour of the coast;
- The definition and implementation of tidal inlets.

The first item has been tackled and the related computational routines have been tested extensively and are operational in the present version of the model.

By adding a robust climate-averaged correction for the cross-shore transport rate, the overall calibration of the cross-shore coastal behaviour has become significantly easier and more straightforward. A more detailed description of the cross-shore transport model as well as the calibration procedure is presented in Chapter 3.

The modified schematisation of tidal inlets is elaborated in Chapter 7 in more detail.
References


Hanson, H.H. and M. Larson, 1999: Extension of ‘GENESIS’ into the cross-shore dimension-from 1-line to n-line, Proceedings COPEDEC 99, Cape Town, South Africa.


Model concept and layer approach
Schematisation of the cross-shore profile
Basic set-up of the model

LARGE-SCALE MODEL OF THE DUTCH COAST

file: A1000F6_2_r0.xls; October 2004
Basic schematisation of the cross-shore transport model PONTOS-2.0
Transport rate as a function of the relative beach slope
Using default beta-value

Fig. 4.1

Relative transport rate $q/(q_0 F_b)$ [-]

Relative slope $(s/s_e)$ [-]

too flat

too steep
Definition of the equilibrium beach slope

Example of some individual results
Definition of the vertical equilibrium slope distribution
Example for $s_o = 0.05$ (slope 1 : 20)
Basic and modified formulation with boundary formulations
Definition of the vertical transport capacity distribution
On linear and logarithmic scales

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LARGE-SCALE MODEL OF THE DUTCH COAST
Z3334/A1000 WL / Alkyon  Fig. 4.4
Cross-shore profile evolution

Example of the development of an equilibrium profile for a combined wave and tidal climate

LARGE-SCALE MODEL OF THE DUTCH COAST Z3334/A1000 | WL / Alkyon | Fig. 4.5
Cross-shore profile evolution

Example of the development of layer positions, cross-shore transport rates and mutual layer distances

LARGE-SCALE MODEL OF THE DUTCH COAST

PONTOS-2.0

WL / Alkyon

Fig. 4.6
Cross-shore profile evolution

Example of the development of layer positions, cross-shore transport rates and mutual layer distances
Equilibrium slope distribution and related cross-shore equilibrium profile

LARGE-SCALE MODEL OF THE DUTCH COAST Z3334/A1000 WL / Alkyon

Fig. 4.8
Implementation of tidal inlets
Transport patterns in the outer delta
Definition of the "shape-forcing transport pattern"
Implementation of tidal inlets
Schematized transport pattern in outer delta
using pre-defined transport in flood and ebb channels

LARGE-SCALE MODEL OF THE DUTCH COAST
Z3334/A1000 WL / Alkyon Fig. 7.2
Implementation of tidal inlets
Modified model schemation at a tidal inlet
Schematisation of the cross-shore profile

PONTOS-2.0
WL / Alkyon
Fig. 7.3
a) Geometric schematization of outer delta shape

b) Assessment of "shape-forcing" transport in ebb channel
Implementation of tidal inlets
Example of evolution of a stable tidal delta system
Initial, intermediate and equilibrium situation

LARGE-SCALE MODEL OF THE DUTCH COAST

PONTOS-2.0
Run_3_v

Fig. 7.5
Implementation of tidal inlets
Example of evolution of a stable tidal delta system
Evolution of layer positions, outer delta volume and other volumes

LARGE-SCALE MODEL OF THE DUTCH COAST Z3334/A1000 WL / Alkyon Fig. 7.6
Implementation of tidal inlets
Example of evolution of a stable oblique tidal delta system
Initial, intermediate and equilibrium situation

LARGE-SCALE MODEL OF THE DUTCH COAST
Z3334/A1000

PONTOS-2.0
Lambda_r = 0.05; phi_r = 0.05

Run_4_v

Fig. 7.7
Implementation of tidal inlets
Example of evolution of an eroding tidal delta system
Initial, intermediate and final situation

LARGE-SCALE MODEL OF THE DUTCH COAST
Z3334/A1000

WL / Alkyon
Run_3_v

Fig. 7.8
Implementation of tidal inlets
Example of evolution of an eroding tidal delta system
Evolution of layer positions, outer delta volume and other volumes

LARGE-SCALE MODEL OF THE DUTCH COAST  Z3334/A1000 WL / Alkyon Fig. 7.9