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Development and application of a large-scale morphological model of the Dutch coast

Phase 2: Formulation and application of the PONTOS-model version 1.4

Report
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Alkyon
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H.J. Steetzel and Z.B. Wang

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ABSTRACT:

Large-scale management and maintenance of the Dutch North Sea coast requires insight into the flows of sediment at a national scale with a matching time scale, including the effects of tidal basins. The conceptual model of the Dutch coast proposed by Mulder (2000) divides the Dutch North Sea coast into nine largely independent subsystems, each containing a certain volume of sand. To preserve the long-term resilience of the Dutch coast, the policy decision was made to maintain the total volume of sediment in these subsystems by nourishment. Expected annual nourishment needs per subsystem were estimated. To further substantiate these estimates and the effect of different distributions of the nourishment material in space and time, a long-term morphological model of the Dutch coast is needed.

A combination of the ‘multi-layer’ model PONTOS and the tidal basin model ASMITA is potentially capable of handling the above issues at the proper space- and time-scale. In the present study, version 1.0 of PONTOS is upgraded to version 1.4 (phase 2 of in total 3 model development phases). In addition to various improved process formulations, the effect of outer deltas and related tidal inlet systems is now included through sink-source terms provided by the ASMITA model.

The upgraded model is used to run through four nourishment scenario’s over a 50 year period (2000-2050), combining two nourishment schemes with two rates of sea-level rise (0.20 and 0.65 m/century). The model calibration/verification and application runs indicate that the present simple inlet schematisation is too crude to provide useful results. The more complex inlet schematisation foreseen in phase 3 of the project is expected to produce more useful results.

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Executive’s summary

Large-scale management and maintenance of the Dutch North Sea coast require insight into the flows of sediment at a national scale with a matching time scale, including the effects of tidal basins. Therefore, one of the topics of the Dutch national research program COAST*2005 focuses on the long-term (50-100 years) and large-scale (1-100 km) morphological effects of both natural processes and major coastal engineering projects, and on developing tools to quantify them. Problems of interest are, for example, the effects of climate change and sea-level rise on a partly protected coastline, the far field effects of large-scale land reclamation and related sand mining, and the long-term implications of ongoing nourishment efforts.

To preserve the long-term resilience of the Dutch coast, the policy decision was made to maintain the total volume of sediment in the coastal system by nourishment. A conceptual model of the Dutch coast proposed by Mulder (2000) divides the Dutch North Sea coast into nine largely independent subsystems, each containing a certain volume of sand. Expected annual nourishment needs per subsystem were estimated. To further substantiate these estimates and the effect of different distributions of the nourishment material in space and time, a long-term morphological model of the Dutch coast is needed.

A combination of the ‘multi-layer’ model PONTOS and the tidal basin model ASMITA is potentially capable of handling the above issues at the proper space- and time-scale. In the present study, version 1.0 of PONTOS is upgraded to version 1.4 (phase 2 of in total 3 model development phases). This upgrade involved:

- A re-structuring of the overall structure of the PONTOS model (i.e. the user-interface and the computational model) and an improvement of various process formulations. The major modifications are related to:
  - The use of basic wave climate data (i.e. wave directions referenced to the North) in combination with the definition of a reference coastline.
  - Improved procedures to calibrate the cross-shore behaviour of the coast.
  - The definition and implementation of tidal inlets. In order to make the PONTOS-model concept applicable to the complete Dutch coast, an ‘inlet-extension’ of the PONTOS-concept has been implemented. At present, the effect of ebb-deltas and related tidal inlet systems is included through sink/source terms at the inlet, provided by the ASMITA model. However, the process of definition and testing of a modified schematisation of the tidal inlet is ongoing. It should be noted that this type of extension was originally foreseen in the next phase of the project.

The upgraded model is used to run through four nourishment scenario’s over a 50 year period (2000-2050), combining two nourishment schemes with two rates of sea-level rise (0.20 and 0.65 m/century). The model calibration/verification and application runs indicate that the present simple inlet schematisation is too crude to provide useful results. Nevertheless, preliminary results (with transport at the inlets set to zero), illustrate the potential of the model to evaluate large-scale and long-term effects of various nourishment schemes, including the effect of changing rates of sea-level rise. The more complex inlet schematisation foreseen in phase 3 of the project is expected to produce more realistic results.
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<th>Description</th>
<th>Unit</th>
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<tr>
<td>$A_b$</td>
<td>tidal basin area</td>
<td>$[m^2]$</td>
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<tr>
<td>$A_n$</td>
<td>horizontal area of an arbitrary element</td>
<td>$[m^2]$</td>
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<td>$A_p$</td>
<td>constant in $z = F(y)$ polynoom</td>
<td>[-]</td>
</tr>
<tr>
<td>$A_v$</td>
<td>amplification factor for the tidal current rate</td>
<td>[-]</td>
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<tr>
<td>$B_p$</td>
<td>constant in $y = F(z)$ polynoom</td>
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<tr>
<td>$c$</td>
<td>wave celerity</td>
<td>[m/s]</td>
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<td>$c_e$</td>
<td>overall equilibrium sediment concentration</td>
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<td>$c_i$</td>
<td>sediment concentration in an adjacent element</td>
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<td>$E$</td>
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<tr>
<td>$H_t$</td>
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i  longshore cell number [-]
i_a  characteristic longshore water level gradient [-]
j  cross-shore layer number [-]
k  wave number [m⁻¹]
K_d  diffraction coefficient [-]
K_r  refraction coefficient [-]
K_s  shoaling coefficient [-]
L  wave length [m]
n  wave number [-]
P  tidal prism [m³]
P_h  water level amplification factor [-]
P_H  wave height amplification factor [-]
P_v  tidal flow amplification factor [-]
q  sediment transport rate [m³/m¹/yr]
q_x  longshore sediment transport rate [m³/m¹/yr]
q_x,t  longshore sediment tide-driven transport rate [m³/m¹/yr]
q_x,w  longshore sediment wave-driven transport rate [m³/m¹/yr]
q_y  cross-shore sediment transport rate [m³/m¹/yr]
Q  residual flow rate [m³/s]
Q_x  cross-shore integrated, longshore sediment transport rate [m³/yr]
Q_x,t  cross-shore integrated, tide-driven longshore sediment transport rate [m³/yr]
Q_x,w  cross-shore integrated, wave-driven longshore sediment transport rate [m³/yr]
Q_y  longshore integrated, cross-shore sediment transport rate [m³/yr]
r  distance from diffraction point [m]
s  bedslope [-]
s_e  equilibrium bedslope [-]
S  source or sink [m³/yr]
S_c  cross-shore continuity correction factor [-]
S_d  relative downdrift sheltering extent [-]
S_u  relative updrift sheltering extent [-]
S_a  auto-nourished source or sink [m³/yr]
t  time [yr]
T_p  peak wave period [s]
T_re  long-term residual sediment transport between adjacent elements [m³/s]
v_a  longshore velocity at reference water depth d_c [m/s]
v_j,i  longshore velocity at cell boundary i for layer j [m/s]
V_c  total channel volume in the tidal basin (water volume in channel below MLW) [m³]
V_ce  equilibrium total channel volume in the tidal basin (below MLW) [m³]
V_d  ebb-tidal delta volume relative to a profile of an undisturbed coast [m³]
V_de  equilibrium ebb-tidal delta volume relative to a profile of an undisturbed coast [m³]
V_f  total inter-tidal flat volume in the tidal basin between MLW and MHW [m³]
V_fe  equilibrium total inter-tidal flat volume in the tidal basin between MLW and MHW [m³]
\( V_n \) (dry or wet) volume of an arbitrary element \([\text{m}^3]\)

\( V_{ne} \) (dry or wet) equilibrium volume of an arbitrary element \([\text{m}^3]\)

\( w_s \) vertical exchange rate \([\text{m/s}]\)

\( W_j \) equilibrium distance between layer at level \(Z_j\) \([\text{m}]\)

\( x \) longshore model ordinate \([\text{m}]\)

\( X_i \) right-hand boundary of cell \(i\) \([\text{m}]\)

\( X_p \) horizontal prototype ordinate \([\text{m}]\)

\( y \) cross-shore model ordinate \([\text{m}]\)

\( y_j \) cross-shore position of layer \(j\) \([\text{m}]\)

\( y^a \) shift in layer position due to auto-nourishment \([\text{m}]\)

\( Y_l \) position of landward structure boundary \([\text{m}]\)

\( Y_s \) position of seaward structure boundary \([\text{m}]\)

\( z \) bottom level \([\text{m}]\)

\( Z_j \) upper boundary level of layer \(j\) \([\text{m}]\)

\( Z_p \) vertical prototype ordinate \([\text{m}]\)

\( Z_g \) level of groyne top \([\text{m}]\)

\( \alpha_b \) coefficient in \(F_B\)-function \([-]\)

\( \alpha_s \) coefficient in \(F_S\)-function \([-]\)

\( \beta \) power in cross-shore transport equation \([-]\)

\( \gamma_s \) power for wave steepness in equilibrium beach slope formulation \([-]\)

\( \gamma_D \) power for \(D_s/H_s\)-ratio in equilibrium beach slope formulation \([-]\)

\( \delta_{ni} \) diffusion exchange rate between two adjacent elements \([\text{m}^3/\text{s}]\)

\( \zeta \) mean sea level \([\text{m}]\)

\( \theta \) relative angle of wave attack \(\degree\)

\( \theta_a \) relative direction to shadow line \(\degree\)

\( \theta_c \) coast orientation \(\degree\)

\( \theta_d \) downdrift limit of diffraction zone (diffraction space) \(\degree\)

\( \theta_o \) wave direction at offshore boundary \(\degree\)

\( \theta_u \) updrift limit of diffraction zone \(\degree\)

\( \theta_w \) wave direction \(\degree\)
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.

Modelling approaches

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.

Behaviour-oriented modelling

PonTos and ASMITA use a different modelling approach, which is behaviour-oriented [Steezel et al., 1998; Stive et al., 1998]. In PonTos the physical processes (i.e. cross- and long-shore transport) are parametrized 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, this model is easier accessible and more user-friendly than most process-based models. Calculations with the previous version of this model (PonTos 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 exist 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.

**Present status**

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.

**Improvements**
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 Alkyon Hydraulic Consultancy & Research and WL | Delft Hydraulics mainly by Dr. Ir. H.J. Steetzel (Alkyon) and (Dr.Ir. Z.B. Wang) (WL | Delft Hydraulics).

Ir. M.C. Onderwater (Alkyon), Ir. C. Jacobs (Alkyon) and Mr. P. Santbergen (Alkyon) assisted in further development and improvement of the PC-model, whereas Ir. J. van Overeem (Alkyon) was responsible for the quality control of the Alkyon contribution of this study. Dr. K.M. Wijnberg (WL | Delft Hydraulics) assisted in upgrading the concept of this report to its final version.

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 content of this report can be divided into two parts, namely the theoretical background of the updated PONTOS-model and the application of this model to the Dutch coast.

Model formulations

In the first part of this report, 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.

Model application
In the second part of the report, the application of the model for the Dutch coast is elaborated. Attention has been paid to the general set-up of the application, the calibration and verification of the model as well as the first results of the computations. Since most of the natural coastal systems are influenced by human intervention, both the effects of ‘soft’ and ‘hard’ management strategies are discussed next.

The following items will be discussed:
- The general set-up of the application (Chapter 10);
- The definition of the input (Chapter 11);
- The first results of the model application (Chapter 12).

In Chapter 13 the main conclusions and recommendations with respect to both the model formulation and application are summarized.
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. Is 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:

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

(2.3.3a)
(2.3.3b)

Taking into 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:

\[ y_{c,j}(z = Z_j) = (Y_{j-1} + Y_j)/2 \text{ for } j > 1 \]  
\[ y_{c,j}(z = Z_j) = Y_0 \text{ for } j \leq 1 \]

(2.3.4a)  
(2.3.4b)

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 \( z = Z_j \) and \( y_{c,j+1} \) at \( z = Z_{j+1} \)) according to:

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

(2.3.5)

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 5th layer (or in fact 5th zone) and the 4th layer should be taken into account in the model, whereas no net transport across the seaward boundary of the 5th 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 \( m^{2} / m^{3} / yr \)) 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 \( \Delta V_{i,j} \) is computed from:

\[
\frac{DV_{i,j}}{Dt} = (Q_{x,j,i-1} - Q_{x,j,i}) + (Q_{y,j,i} - Q_{y,j,i+1}) + \frac{DS_{j,i}}{Dt} \tag{2.4.1}
\]

in which \( Q_{x,j,i} \) refers to the longshore transport in layer \( j \) at position \( X_{i} \), \( Q_{y,j,i} \) refers to the cross-shore transport at level \( Z_{i} \) in the interval \( X_{i-1} \ldots X_{i} \) and \( S_{j,i} \) 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, \( \Delta V_{i,j} \) in layer \( j \) and cell with index \( i \) yields a cross-shore shift in the characteristic position of layer \( j \), denoted as \( \Delta y_{i,j} \) according to:
\[ \Delta y_{j,i} = \frac{\Delta \text{Vol}_{jj}}{\Delta X_i \cdot d_{jj}} \]  
(2.4.2)

in which \( d_{ij} \) denotes the thickness of layer \( j \) in the interval \( X_{i-1} \ldots X_i \).

Substitution of this translation yields:

\[ \frac{\Delta y_{j,i}}{\Delta t} = \frac{(Q_{x,j,i-1} - Q_{x,j,i})}{d_{jj} \cdot \Delta X_i} + \frac{(Q_{y,j,i} - Q_{y,j,i+1})}{d_{ji} \cdot \Delta X_i} + \frac{\Delta S_{jj}}{d_{jj} \cdot \Delta X_i \cdot \Delta t} \]  
(2.4.3)

In this equation \( Q_x \) refers to the longshore integrated magnitude, viz. taken into account the width of the cell \( \Delta X_i \). Using \( q_y \) (expressed in \( m^3/m^1/yr \)) instead of \( Q_y \) (expressed in \( m^3/yr \)) yields:

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

The assessment of the longshore transport \( Q_x \) 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 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 $Q_{j,i}(t)$ 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 $q_{0}(x)$. 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 $q_{5}(x)$. 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 $Z_{5}$-level, denoted as $q_{5}(x)$, 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

The present version of the model is able to take tidal inlets and the associated back barrier system into consideration also.

The implementation is largely based on the formulations applied in a preceding version of the layer model. This the so-called MOBIC-model showed promising results with respect to this extension [Steetzel, 1995].

With respect to the boundary, for each individual inlet a pre-described time series is used to define the net sediment transport rate.
2.6 Mathematical 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 COMPAC 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: $Y_s(x)$. 
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 \( Z_5 \)-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 \( H_{o0} \). 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 $H_s$.

**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,

\[ H_s(t) = P_{H}(t) H_s \] (3.2.6)

A gradual (relative) change in wave height is taken into account by multiplying each individual
significant wave height \( H_s \) with a factor, denoted as \( P_{H}(t) \).

A gradual (absolute) change in wave direction is taken into account by adding the absolute
change in the direction, denoted as \( \Delta \theta_s \) to the basic value of \( \theta_s \).

\[ \theta_s(t) = \theta_s + \Delta \theta_s(t) \] (3.2.7)

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 $i_a$ ($= - \frac{dh}{dx}$) is computed from the basic Chézy-equation, according to:

$$ v_a = - C \sqrt{(d_c + h_a)} i_a $$

(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:

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

(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:

$$ v(y) = - C \sqrt{(d(y) + h_a)} i_a $$

for $i_a \geq 0$

(3.3.3a)

and:

$$ v(y) = + C \sqrt{(d(y) + h_a)} |i_a| $$

for $i_a < 0$

(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:

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

(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:

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

(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 \( \Delta h(t) \), to the astronomical elevation \( h_a \), according to:

\[
\text{ht} = h_a + \Delta h(t)
\]  

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

\[
\text{ht} = P_h(t) h_a
\]

Combined with sea level rise this yields:

\[
\text{ht} = P_h(t) h_a + \Delta h(t)
\]
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, $\Delta h_o(t)$, $P_i(t)$ and $P_v(t)$. 
4 Basic transport formulations

4.1 Wave-induced longshore transport

4.1.1 Introduction

The wave-induced longshore transport, denoted as $q_{x,w}$ expressed in m$^3$/m$^1$/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 it 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.

4.1.2 Cross-shore integrated transport rate

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

$$Q_{x,w} = c_{w,0} \left( H_s^2 / D_z \right) \theta_c \theta_w \exp \left( - \left( c_2 \left( \theta_c - \theta_w \right) \right)^2 \right)$$

(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:

$$Q_{x,w} \propto \Delta \theta \exp \left( - \left( c_2 \Delta \theta \right)^2 \right)$$

(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:

$$\Delta \theta_{\text{max}} = \frac{1}{c_2} \left( \sqrt{2} \right)$$

(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 $C_p$ for $45^\circ < |\Delta \theta| < 90^\circ$; according to:
\[ C_\theta = 1 - \left( \frac{\Delta \theta - 45}{45} \right)^2 \] (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:

\[ Q_{cw} = C_\theta \cdot c_{w,0} \left( \frac{H_s^{2.8}}{D_z} \right) \Delta \theta \exp\left\{- (c_2 \Delta \theta)^2 \right\} \] (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 [Steetzel 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 \( Q_{cw,i} \) 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:

\[ Q_{cw,i,j} = F_z \cdot Q_{cw,i} \] (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 $Q_{xw,i}$ taking the related layer orientation as input for $\theta$. 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 PONTOOS-model, the tide-induced longshore transport $q_{x,t}$ for a specific hydraulic condition (water level, wave and tidal current) is computed from:

$$
q_{x,t} = \alpha_{c,0} \left(D_{x}\right)^{2.2} \left(v_w\right)^4 \left[1 + C_w \frac{H_{x}^{1.5}T_{p}}{d v_w^2}\right]
$$

(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 $c_{0,0}$ 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$^1$ in cross-shore direction to a rate per m$^1$ 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:

$$
Q_{x,t,j,i} = B_{j,i} \cdot q_{x,t,j,i}
$$

(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:

$$
B_{j,i} = y_{c,j,i} - y_{c,j,i}
$$

(4.2.3)
The current-related longshore transport rate (expressed in m³/yr per m¹), is defined according to:
\[ q_{c,t} = c_{t,0} \left( D_s \right)^{-2.2} \left( v_a \right)^4 \]  
\[ (4.2.4) \]

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:
\[ q_{c,w} = c_{t,0} \left( D_s \right)^{-2.2} \left( v_a \right)^4 C_w \frac{H_s^{1.5} T_p}{d v_a^2} \]  
\[ (4.2.5) \]
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 \( d/H_s < 3 \).

\[ C_b = \min \left( 1, \frac{d}{3H_s} \right) \]  
\[ (4.2.6) \]
The factor '3' in this equation refers to the lower limit of the wave-impact. The corrected equation for the wave-related contribution equals:
\[ q_{c,w} = c_{t,0} \left( D_s \right)^{-2.2} \left( v_a \right)^4 C_w C_b \frac{H_s^{1.5} T_p}{d v_a^2} \]  
\[ (4.2.7) \]
As a consequence, the final equation applied in the PONTOS-1.0 model reads:
\[ q_a = c_{t,0} \left( D_s \right)^{-2.2} \left( v_a \right)^4 \left[ 1 + C_w C_b \frac{H_s^{1.5} T_p}{d v_a^2} \right] \]  
\[ (4.2.8) \]
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 m¹ 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 $z_{c,i}$-level for the assessment of the characteristic water depth.

4.3 Wave-induced cross-shore transport

4.3.1 Basic formulation

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 is related to the deviation of the local bed slope from the equilibrium slope [Steetzel, 1997a, 1997b].

This equilibrium slope is expressed in terms of the offshore hydraulic conditions and the characteristics of the bed material, whereas the rate of change is 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:

$$q_{yw} = q_o F_b \left( \frac{s}{s_e} - 1 \right) \left( \frac{s}{s_e} - 1 \right)^{-\beta - 1}$$  \hspace{1cm} (4.3.1)

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 reference transport capacity $q_o$ and the slope-related power $\beta$.

The settings used in the present model, that is $q_o = 1250 \text{ m}^3/\text{m}^1/\text{yr}$ and $\beta = 2.0$ are equivalent to the settings in the original model (see [Steetzel et al., 1998]).
It should be noted that the effect of the sediment diameter is not present in the actual formulation, although the bottom material will affect the equilibrium slope and as a consequence the transport rates for different diameters for a given cross-shore profile and hydraulic condition will be different also.

### 4.3.2 Equilibrium profile definition

The incorporation of the equilibrium slope formulation in the model is a good example of a behaviour-oriented element of this 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:

$$s_e(d) = s_o F_s$$  \hspace{1cm} (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 four different zones will be distinguished, namely:
- The duneface having a fixed slope;
- The dry beach with an upward increasing bottom slope;
- The under water profile with downward decreasing bottom slope.

Following Eq. (4.3.1) the beach slope 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, 1999]. A summary of the various approaches for large-scale coastal evolution is provided in [Stive et al., 1999].

### 4.3.3 Beach slope

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

$$s_o = C_s \left( \frac{H_s}{L_o} \right)^{\gamma_s} \left( \frac{D_s}{H_s} \right)^{\gamma_d}$$  \hspace{1cm} (4.3.3)

and depends on the relative wave steepness and the relative sediment diameter.

Based on the work described in [Steetzel et al., 1998], the basic non-dimensional constant $C_s$ equals 0.46, whereas $\gamma_s = -0.25$ (yielding more gentle slopes for steeper waves) and $\gamma_d = 0.265$ (yielding a steeper slope for coarser material).

### 4.3.4 Equilibrium slope distribution

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

$$F_s = \exp \left[ -\alpha_s \left( \frac{d}{H_s} \right) \right]$$  \hspace{1cm} (4.3.4)

in which $\alpha_s$ is a calibration factor with $\alpha_s = 2.0$.

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 (instead 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 slope can be computed from Eq. (4.3.5) using the beach slope from Eq. (4.3.5) and the appropriate distribution function Eq. (4.3.5). 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 duneface, the slope of the duneface is added as an additional parameter.

As a characteristic slope of the duneface, \( s_e = 0.25 \) has been applied, being valid above the transition level of at \( d/H_s < -1 \) (basic model setting).

Above the ‘dune foot level’ at \( d/H_s = -1 \), the equilibrium slope is fixed at a constant level of \( s_e = s_d = 0.25 \).

Shelf slope

Comparable to the incorporation of the slope of the duneface, the slope of the deeper sea floor can be defined also. In the present version of the model a minimum value of \( s_{\text{min}} = 0.001 \) is used as the default setting.

4.3.5 Transport capacity distribution

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].

The \( F_b \)-function describes the relative transport rate as a function of the \( d/H_s \)-ratio according to:

\[ F_b = \exp \left[ -\frac{d}{\alpha_b H_s} \right] \]  (4.3.6)

Based on the results of the UNIBEST-TC-model the \( \alpha_b \) equals 1.5 (see [Steetzel et al., 1998]). It should be noted that this basic expression yields a non-zero transport rate for under water only. Just above the water level the transport capacity is zero by definition.

Transport above waterline

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 duneface transition level of at \( d/H_s = -1 \) (default model setting).

4.3.6 Implementation in the layer model

Above 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.
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:

\[
 s_j = \frac{Y_j - Y_{j-1}}{(d_{j-1} + d_j)/2} \tag{4.3.7}
\]

If for the equilibrium profile this mutual distance is denoted as \( W_j \) the characteristic equilibrium slope \( s_{e,j} \) can be assessed from:

\[
 s_{e,j} = \frac{2 W_j}{(d_{j-1} + d_j)} \tag{4.3.8}
\]

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

\[
 \frac{s_j}{s_{e,j}} = \frac{Y_j - Y_{j-1}}{W_j} \tag{4.3.9}
\]

yielding the actual source term for the assessment of the cross-shore transport rate \( q_{y,j} \).

### 4.3.7 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, due to a yearly net transport, can be taken into account by a pre-defined longshore distribution of the net transport rate, denoted as \( q_b(x) \). According to the coordinate system a positive magnitude implies a seaward loss of sediment.
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 duneface 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:

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

(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:

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

(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:

$$ L = \frac{gT_p^2}{2\pi} \sqrt{\frac{4\pi^2 d}{T_p^2 g}} $$

(6.2.1)

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:

$$ L = \frac{gT_p^2}{2\pi} \tanh \left( \frac{2\pi d}{L} \right) $$

(6.2.2)

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:

$$ c = \frac{L}{T_p} $$

(6.2.3)

or directly from:

$$ c = \frac{gT_p^2}{2\pi} \sqrt{\frac{4\pi^2 d}{T_p^2 g}} $$

(6.2.4)

as a function of wave period $T_p$ and water depth $d$.

Other related parameters are:

$$ k = \frac{2\pi}{L} $$

(6.2.5)

and:

$$ n = \frac{1}{2} \left( 1 + \frac{2kd}{\sinh(2kd)} \right) $$

(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:

$$ \sin \theta_1 = \frac{c_1}{c_0} \sin \theta_0 $$

(6.2.7)

or:

$$ \sin \theta_1 = \frac{L_1}{L_0} \sin \theta_0 $$

(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:

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

(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:

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

(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:

\[
H_1 = (K_r, K_s) H_0
\]  

(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:

\[
K_r = \sqrt{\frac{\cos \theta_0}{\cos \theta_1}}
\]  

(6.2.12)

whereas the shoaling factor \( K_s \) is assessed from:

\[
K_s = \sqrt{\frac{n_0 c_0}{n_1 c_1}}
\]  

(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 from the (eventually modified) local wave height \( H_1 \) using:

\[
H_0 = \frac{H_1}{K_r, K_s}
\]  

(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,
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 \( \theta_a > \theta_i \) the direction is unchanged, whereas for \( \theta_a < \theta_i \) the direction modified according to \( \theta_n = \theta_i + \Delta \theta_d \).

### 6.3.6 Wave height change

For the wave direction in the shadow zone the angle \( \theta_a \) 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 \( H_{i1} \) 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 $K_{d,s}$;
- 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 $K_d,0$ 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 $90^\circ$ 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 m² 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, it 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 it 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:

$$ v^*_{j,i} = A_{v,j,i} v_{j,i}, $$

(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 $D_i(x)$;
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 \( Y_b(x) \) (which is defined as input) is taken into account. The actual discharge is computed from:

\[
D_t = \sum_{j=0}^{5} v_{j,i} B_{j,i} \tag{6.4.2}
\]

in which \( v_{j,i} \) refers to the uncorrected velocity for layer \( j \) and position \( i \) and \( B_{j,i} \):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 \( B_i \) 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 \( Y_s,i \) 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 $D_{j,i}$, 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 streamtube, 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.
7 Implementation of tidal inlets

7.1 Introduction

In the framework of the present study, the PONToS-model is being modified such that also an interrupted coastline can be used as an application.

In the process of formulation and implementation of required inlet-extension of the PONToS-model, a number of development phases are being distinguished.

In the first step of the development (viz. phase 2), the net transport through the tidal inlet is based on external computations with the AsMiTA-model, whereas the latter conceptual basin model will be incorporated in the overall model in the final phase of the study (viz. phase 3).

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.

7.2 Outer delta modelling

7.2.1 Introduction

In the present phase of the model development, the interaction with the back barrier system is taken into account by applying (a time series of) pre-defined net transport rates. The latter is used as a (cross-shore) boundary condition and derived from separately performed computations with the AsMiTA-model (see Section 7.3 for more details).

7.2.2 Initial approach

The basic initial idea (and initial approach according to the project plan of phase 1) was to use the back barrier-induced boundary condition as a local sink at the seaward tip of the outer delta. However, the results of initial morphological computations showed that the presence of such a very local and continuous sink resulted in rather extreme landward shifts in the location of the relevant layers in this region. As a result the morphological model became instable or required unacceptable small time steps.

From this, it was concluded that this very simple approach was not very successful and that a more sophisticated tidal inlet extension (as already and originally foreseen in phase 3) was required to deal with the impact of the net transport rate in a more smooth way.

7.2.3 Improved schematisation

In order to reach this goal, the schematisation of the outer delta was improved. The first step was the modification of the cross-shore layer definition at the location of the outer delta, such that both the dune layer $Y_0$ and the beach layer $Y_1$ are absent in this region. Next, 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 (see [Steetzel, 1995] for more details).

The idea is that the use of such a mutually coupled set of transport paths will yield a more gentle behaviour of the outer delta region and thus yield a more stable computation.
7.2.4 Present status
In the present version of the model (version 1.4) this mutually coupled set of transport paths in the Y2-layer is not (yet) completely operational.

As a consequence, the net transport rate cannot be taken into account at all in thus program version and the overall evolution of the outer delta and neighbouring coastal sections depends on the basic wave- and tidal transport only.

7.3 Back barrier system

7.3.1 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 (see Figure 7.1):
- 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 \( V_{ne} \) \([\text{m}^3]\) of an arbitrary element \( n \) in a state of morphodynamic equilibrium, has appeared to be highly correlated to the tidal range \( H \) \([\text{m}]\), the tidal prism \( P \) \([\text{m}^3]\) and the basin area \( A_b \) \([\text{m}^2]\):

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

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:

$$\pm \frac{dV}{dt} = \sum_i T_i + A_n \frac{d\zeta}{dt}$$  \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):

$$\pm \frac{dV}{dt} = w_s \cdot A_n \cdot (c_{ne} - c_n) + A_n \frac{d\zeta}{dt}$$  \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:

$$TQ_i + c_i (c_{ne} - c_{ni}) - \delta_i (c_{ni} - c_i)$$  \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.

7.3.2 AsMiTa application for the Wadden

The ASMiTa model is used for the assessment of the net sediment transport through the 5 inlets in the Wadden Sea as shown in Figure 7.2. For each of these inlets an ASMiTa model already exists. These models have been set up by Van Goor (2001) and Kragtwijk (2001) during the preparation of their MSc-thesis. The models for Eijerlandse Gat, Amelander Zeegat and Friesche Zeegat are due to Van Goor (2001) and the models for Marsdiep and Vlie are due to Kragtwijk.

In this study, these existing models are applied to simulate two scenarios of sea level rise rate: 20 cm/century and 65 cm/century. All simulations have been carried out for the period 1970-2050. The existing models were set up in the MATLAB version of ASMiTa. They have been transformed to the FORTRAN version before they are applied.

Each of the considered inlets is schematised into three morphological elements: the intertidal flat, the channel and the ebb tidal delta. The basic geometric data of these morphological elements, i.e. the horizontal area and the initial volume (in 1970), are given in Table 7.1. The tidal ranges in the inlets are also given in this table.

Table 7.1 Basic data ASMiTa Wadden: geometry and tidal range

<table>
<thead>
<tr>
<th>Inlet</th>
<th>Inter-tidal flat</th>
<th>channel</th>
<th>ebb tidal Delta</th>
<th>tidal range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>area (10^6 m^2)</td>
<td>volume (10^6 m^3)</td>
<td>area (10^6 m^2)</td>
<td>volume (10^6 m^3)</td>
</tr>
<tr>
<td>Marsdiep</td>
<td>133</td>
<td>52</td>
<td>522</td>
<td>2160</td>
</tr>
<tr>
<td>Eierlandse Gat</td>
<td>105</td>
<td>106</td>
<td>53</td>
<td>106</td>
</tr>
<tr>
<td>Vlie</td>
<td>328</td>
<td>1230</td>
<td>387</td>
<td>1230</td>
</tr>
<tr>
<td>Amelander Zeegat</td>
<td>178</td>
<td>302</td>
<td>98</td>
<td>302</td>
</tr>
<tr>
<td>Pinkegat</td>
<td>38</td>
<td>19</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Zoutkamerplaag</td>
<td>65</td>
<td>177</td>
<td>40</td>
<td>177</td>
</tr>
</tbody>
</table>

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:

\[ V_{ce} = \alpha_c b^{1.55} \]  

(7.7)

For the ebb tidal delta:
\[ V_{dc} = \alpha_3 P^{1.23} \]  
\[ (7.8) \]

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. The coefficients used in the relations are given in Table 7.2. For the inter-tidal flat the equilibrium volume is given, as it does not change in time during the simulation. The other input parameters in the used models are given in Table 7.3.

Table 7.2 Parameters in the empirical relations for morphological equilibrium

<table>
<thead>
<tr>
<th>Inlet</th>
<th>Inter-tidal flat</th>
<th>Channel, ( \alpha_2 ) ((10^{-6} \text{ m}^{-1.65}))</th>
<th>Delta, ( \alpha_3 ) ((10^{-3} \text{ m}^{-0.69}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marsdiep</td>
<td>50.0</td>
<td>22.0</td>
<td>4.025</td>
</tr>
<tr>
<td>Eierlandse gat</td>
<td>57.83</td>
<td>13.13</td>
<td>8.0</td>
</tr>
<tr>
<td>Vlie</td>
<td>190.0</td>
<td>9.6</td>
<td>2.662</td>
</tr>
<tr>
<td>Amelander Zeegat</td>
<td>131.2</td>
<td>10.24</td>
<td>2.9215</td>
</tr>
<tr>
<td>Pinkegat</td>
<td>30.3</td>
<td>10.14</td>
<td>6.927</td>
</tr>
<tr>
<td>Zoutkamperlaag</td>
<td>70.0</td>
<td>27.266</td>
<td>9.137</td>
</tr>
</tbody>
</table>

Table 7.3 Input parameters ASMITA Wadden

<table>
<thead>
<tr>
<th>Inlet</th>
<th>( C_E ) ((-))</th>
<th>( r ) ((-))</th>
<th>( w_{s-flat} ) ((\text{m/s}))</th>
<th>( w_{s-channel} ) ((\text{m/s}))</th>
<th>( \delta_{cd} ) ((\text{m}^3/\text{s}))</th>
<th>( \delta_{dc} ) ((\text{m}^3/\text{s}))</th>
<th>( \delta_{cf} ) ((\text{m}^3/\text{s}))</th>
<th>( \Delta t ) ((\text{day}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marsdiep</td>
<td>2.00E-04</td>
<td>2</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>1550</td>
<td>2450</td>
<td>980</td>
</tr>
<tr>
<td>Eierlandse gat</td>
<td>2.00E-04</td>
<td>2</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>1500</td>
<td>1500</td>
<td>1000</td>
</tr>
<tr>
<td>Vlie</td>
<td>2.00E-04</td>
<td>2</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>1770</td>
<td>2560</td>
<td>1300</td>
</tr>
<tr>
<td>Amelander Zeegat</td>
<td>2.00E-04</td>
<td>2</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>1500</td>
<td>1500</td>
<td>1000</td>
</tr>
<tr>
<td>Pinkegat</td>
<td>2.00E-04</td>
<td>2</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>1500</td>
<td>1500</td>
<td>1000</td>
</tr>
<tr>
<td>Zoutkamperlaag</td>
<td>2.00E-04</td>
<td>2</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>1060</td>
<td>1290</td>
<td>840</td>
</tr>
</tbody>
</table>

The simulated net sediment transports from the channel element to the delta (negative means import to the basin) are shown in Figure 7.3 through Figure 7.7. In each of these figures the results of the two sea-level rise scenarios are shown.

### 7.3.3 ASMiTA application for the Delta coast

The ASMiTA model has also been used for an estimate of the net sediment transport from/to the Western Scheldt estuary. The most recent model for this area (Western Scheldt plus Eastern Scheldt) was set up by Meangbua (2003).

Due to the complex bathymetry, the schematisation of the area was made in terms of ‘wet volume’ of each element in the schematization: 6 elements for the estuary, 27 elements for the river mouth (outer delta) of the Western Scheldt (Figure 7.8). (NB: ‘Wet volume’ = volume of water between the water level and the bed level). As a consequence, the empirical equilibrium relations described above cannot be used to determine the morphological equilibrium state. Instead equilibrium volumes of each section are determined by calibration. It turned out that the equilibrium volumes for the Western Scheldt were all larger than...
determined in an earlier ASMITA study by Wang (1997), which included only the Western Scheldt. Nevertheless, since the morphological behaviour of the study area could be reproduced well, it was concluded by Meangbua (2003) that results using these equilibrium volumes are qualitatively realistic.

For use in the present study the results of two scenarios in Meangbua (2003) are supplied, viz. the simulations using a rate of sea level rise of 20 cm/century and of 60 cm/century, respectively. Both simulations include the same dredging scenario for the estuary, which is presented in Table 7.4. (Note: since the results of the present ASMITA-model for the Western Scheldt are qualitative in nature, the difference between a 60 and 65 cm/century sea level rise scenario (the latter being used in the Wadden inlet cases) was neglected in the current application).

Table 7.4: Dredging-dumping scenario ASMITA Western Scheldt

<table>
<thead>
<tr>
<th>Net annual dredging-dumping volume (million m$^3$/year) Western Scheldt estuary</th>
</tr>
</thead>
<tbody>
<tr>
<td>section 1</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>-3.5</td>
</tr>
</tbody>
</table>

(negative value = dredging)

Input parameters in the model are (Meangbua, 2003):

Table 7.5: Input parameters ASMITA Western Scheldt

<table>
<thead>
<tr>
<th>Inlet</th>
<th>$C_E$ (-)</th>
<th>$r$ (-)</th>
<th>$w_s$ (m/s)</th>
<th>$\delta_{6.7}$ (m$^3$/s)</th>
<th>$\delta_{6.8}$ (m$^3$/s)</th>
<th>$\delta_{6.9}$ (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Scheldt</td>
<td>1.00E-05</td>
<td>2</td>
<td>0.01</td>
<td>20550</td>
<td>1597</td>
<td>213333</td>
</tr>
</tbody>
</table>

The simulated net transport from the estuary to the river mouth area for the two scenarios is shown in Figure 7.9. Both cases show an export of sediment from the estuary to the river mouth, with a decrease in magnitude over time. The finding of sediment export from the estuary is in agreement with observations (Jeuken et al., 2003). Meangbua (2003) explains the decrease over time by the dredging activity in the eastern part of the estuary, which demands sediment from the western part of the estuary, which then decreases its export of sediment to the river mouth area.

For a larger rate of sea level rise, the decrease in export rate occurs at a faster rate. This may be explained by the increased sediment demand in the eastern part of the estuary, because for a faster rate of sea level rise the elements deviate more from their equilibrium volumes, hence are more strongly stimulated to develop towards their equilibrium state.

7.3.4 On the reliability of AsMiTA results

The studies by Kragtwijk (2001), Van Goor (2001) and Meangbua (2003), which provided the ASMITA models for the above transport calculations, also included considerations regarding the sensitivity of the ASMITA model to the setting of various calibration parameters. Although they focussed on different aspects of model sensitivity (error analysis of the calibration process itself, sensitivity analysis on the critical rate of sea level rise for drowning of the tidal basin, and sensitivity analysis on wet volume estimates, respectively), a general picture seems to emerge.

It appears that the ASMITA model is rather sensitive to the setting of $\delta$, the horizontal diffusion exchange rate, followed by the setting of $C_E$, the overall equilibrium concentration. $\delta$
is a measure for the system's capacity to distribute sediment internally, while \( c_E \) reflects the availability of sediment to the inlet system. As such they influence the time-scale of the response of the system: an increase (decrease) in \( \delta \) or \( c_E \) causes a decrease (increase) in the morphological time-scale and thus the rate at which the system responds to a forcing.

Further, the specification of the morphological element boundaries is a source of error in the calibration process, especially concerning the outer delta. Volumes of the delta are calculated relative to a reference coastal profile (which would be present in absence of the inlet). The definition of this reference coast is subject to user interpretation. Measurement errors and interpolation errors in the data are considered of little importance in the calibration process (Kragtwijk, 2001).

According to Van Goor (2001), ASMITA is capable of modelling the long-term morphological response of a tidal inlet to a rising sea level in terms of order of magnitude. More data of tidal inlet systems over longer periods of times are needed, preferably from disturbed systems (by nature or by man), to improve the estimates of the morphological time-scales, and thus \( \delta \) and \( c_E \). The data can also be used to increase the reliability of the empirical equilibrium relations and thus the reliability of the predictions.
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.

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 $\text{Vol}_n$.

The equation used to compute the displacement of a specific layer according to:
\[
\frac{\Delta y_{j,i}}{\Delta t} = \frac{(Q_{x,j,i+1} - Q_{x,j,i})}{d_{j,i} \Delta X_j} + \frac{(q_{y,j,i} - q_{y,j,i+1})}{d_{y,i} \Delta X_j} + \frac{\Delta S_{j,i}}{d_{y,i} \Delta X_j, \Delta t}
\]  

(8.2.1)

is given in Section 2.4.

The source term in the right-hand term \(\Delta S_{j,i}/\Delta t\) 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:

\[
\Delta S_{j,i}^a = \Delta y_{j,i}^a d_{j,i} \Delta X_{j,i}
\]  

(8.3.1)

in which \(\Delta y_{j,i}^a\) 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

The present formulations applied in the present version of the model are described in the previous chapters.
In the following a brief summary is provided of the model improvements and modifications that have been implemented since version 1.0 of the model, viz. during phase 2 of 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 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.
A brief summary of the most relevant improvements of the model:

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. The testing and improvement of this module is ongoing.

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 mode 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. The testing and improvement of this calibration tool is ongoing.

With respect to the model output, both the number and extent of output blocks has been increased significantly yielding more insight in especially the integrated, time- and place-averaged, result 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 definition and implementation of tidal inlets;
- The procedures to calibrate the cross-shore behaviour of the coast.

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.

The process of definition and testing of a modified schematisation of the tidal inlet is ongoing. It should be noted that this type of extension was originally foreseen in the next phase of the project.

By adding a robust climate-averaged correction for the cross-shore transport rate, the overall calibration of the cross-shore coastal behaviour will become significantly easier and more straightforward. The required formulations have been tested. However, the most recent modifications of these routines have not yet been used for the present application.
10 Model application for the Dutch coast

10.1 Introduction

The in the preceding chapters described model is applied for the Dutch coast. Some general aspects of this application are discussed hereafter. A more detailed description of the applied input is provided in the following chapter.

10.2 General set-up

For the definition of the model, the Dutch coast is schematised along a so-called reference line. This reference line more or less follows the curved coastline of Belgium and The Netherlands.

The definition of the reference line has been adjusted compared to the original reference line [Steetzel et al., 1999]. These adjustments are:

- An additional curved section at the south side of the model in order to take into account the overall shape of the Belgium coastline;
- An additional curved section at the northeast side of the model in order to take into account the eastern Dutch Wadden Islands.

In the PONTos-model the reference line is schematised as a straight line. All data (layer positions and environmental conditions) are defined with reference to this straight line. Figure 10.1 shows the general set-up of the reference line. A detail of the Dutch coast is shown in Figure 10.2.

10.3 Hydraulic conditions

For the hydraulic conditions time-averaged climates have been used.

The wave conditions have been determined using measured time series at a number of wave stations along the Dutch coast. In order to provide enough information for the southern part of the model, an additional wave climate station at the WestHinderBank (WHB) has been used.

In order to apply the basic wave direction formulation (using the direction the waves come from), a special procedure has been developed to translate the offshore wave conditions to an arbitrary position along the reference line.

For the definition of the mean tidal climate, use has been made of a computation with the so-called KUSTSTROOK-model.
10.4 Coastal management

10.4.1 Nourishments (model input)
In order to take into account the effects of coastal management, the possibilities to define and apply pre-defined nourishment schemes have been extended. Basically, two types of pre-defined nourishment schemes can be used, namely:

− A scheme simulating the performed nourishments (until present);
− An anticipated nourishment scheme simulating future efforts.

For the latter anticipated schemes two scenarios have been defined.

As mentioned before, in order to test the concept of ‘system nourishments’, a special auto cell-nourishment option has been defined.

10.4.2 Coastal State Indicators (model output)
Using the output of the model, the evolution of specific layer positions or volumes in specific sections can be assessed.

For the assessment of the location of the so-called BCL, the position of the upper layer (representing the Y1- and Y2-layer; from NAP-7m till NAP+3 m) can be used as a first estimate.

In order to take into account the local vertical boundaries (which vary along the coast) more accurately and (possibly) also the level of the mean sea level, some additional processing of the basic layer information may be required.

The model can directly be used to assess the evolution of the volume in a specific coastal section. A distinction may be made between the volumes in the lower zone (the Y3- and Y4-layer; representing the area between the NAP-20m and the NAP-7m depth contour) and the upper zone (the area between the NAP-7m depth contour and the local dune top). The results can be presented in terms of absolute changes (in Mm³) or time-averaged rates (in Mm³/yr).

It should be noted the location of the so-called “afslaglijn”, cannot be computed using the PONTOS-model, since yearly-averaged climates are applied by definition. The computation of the position of “afslaglijnen” requires more extreme surge conditions and a more detailed computational model (DUROSTA/DUINTOETS). However, the location of the dune foot (represented by the location of the Y0-layer) is available.

10.5 Calibration and verification
The period 1970 – 2000 has been used for calibration and verification purposes. Basically, the first half (1970 – 1985) is used for calibration; the second half (1985 – 2000) is used for verification.

In the calibration phase (1970 –1985) the conclusions on the performance of the model will primarily be based on the comparison between the computed movement of the various layers and the observed displacement of these layers.

If the model is able to produce a reasonable resemblance, the applied calibrations factors for both the longshore- and cross-shore processes will be used for both the verification and prediction phase.
For the verification phase (1985 – 2000) two different tests will be performed, namely a model run in which the performed nourishment schemes are applied in the model (as input) and the resulting layer positions (2000) are compared with the observed positions.

In a second run, the model will be used to assess the required nourishment efforts if the initial coastline is defined as critical. In this case the conclusions on the model’s performance will be based on the comparison of the estimated nourishment rates (output) with the executed schemes.

10.6 Predictions

The predictions are performed for the period 2000 – 2050.

For the mean sea level two specific scenarios have been used, namely:

1. A low scenario using 0.20 m/century;
2. A high scenario using 0.65 m/century.

For the anticipated nourishment schemes (period 2000 – 2050), two different management scenarios are defined, namely:

[B] A nourishment scheme based on the mean efforts in the period 2001 - 2003 with a total invariable rate of 13.0 Mm$^3$/yr.

The latter two management schemes ([A] and [B]) are combined with the two sea level rise schemes ([1] and [2]), yielding four combinations ([1A], [1B], [2A] and [2B]) as shown in the following table.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Management [A]</th>
<th>Management [B]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea level rise [1]</td>
<td>[1A]</td>
<td>[1B]</td>
</tr>
<tr>
<td>Sea level rise [2]</td>
<td>[2A]</td>
<td>[2B]</td>
</tr>
</tbody>
</table>

More details on these scenarios are provided in the following chapter.

With respect to the results of the various computations, special attention will be given to the evolution of BCL-like layers as well as the volume in specific sections.

In order to gain insight in the effect of the various scenarios, also the relative impacts will be assessed.
11 Model input

11.1 Introduction

In the following the input of the model for the Dutch coast application is described. Referring to the modified model set-up, nine different groups of input parameters are being distinguished. These groups are given in the following table.

<table>
<thead>
<tr>
<th>Group no.</th>
<th>Parameter group</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Geometry</td>
<td>Levels, positions</td>
</tr>
<tr>
<td>2</td>
<td>Bed material</td>
<td>Sediment size</td>
</tr>
<tr>
<td>3</td>
<td>Structures</td>
<td>Dikes, dams</td>
</tr>
<tr>
<td>4</td>
<td>Tidal inlets</td>
<td>Inlet characteristics</td>
</tr>
<tr>
<td>5</td>
<td>Conditions</td>
<td>Waves, tides, changes</td>
</tr>
<tr>
<td>6</td>
<td>Boundaries</td>
<td>Longshore, cross-shore, inlets</td>
</tr>
<tr>
<td>7</td>
<td>Management</td>
<td>Nourishments</td>
</tr>
<tr>
<td>8</td>
<td>Run specifications</td>
<td>Time stepping, output</td>
</tr>
<tr>
<td>9</td>
<td>Calibration factors</td>
<td>Longshore, cross-shore</td>
</tr>
</tbody>
</table>

In the following sections the group specific input is described. In some cases, a more detailed elaboration is provided separately in an appendix.

11.2 Geometry

11.2.1 Reference line

The reference line, which describes the overall contour of the (Dutch) North Sea coast, consist out of five subsequent sections namely a circle segment, a straight line and next three other circle segments. Some basic characteristics of the reference line are summarized in the following table (see also Figure 10.1 and 10.2).

<table>
<thead>
<tr>
<th>Section</th>
<th>$X_1$ [km]</th>
<th>$X_2$ [km]</th>
<th>$R$ [km]</th>
<th>Shape</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-50.00</td>
<td>28.284</td>
<td>250</td>
<td>Circle</td>
<td>South of updrift boundary</td>
</tr>
<tr>
<td>2</td>
<td>28.284</td>
<td>93.431</td>
<td>-</td>
<td>Straight line</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>93.431</td>
<td>211.241</td>
<td>150</td>
<td>Circle</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>211.241</td>
<td>296.919</td>
<td>150</td>
<td>Circle</td>
<td>East of downdrift boundary</td>
</tr>
<tr>
<td>5</td>
<td>296.919</td>
<td>400.000</td>
<td>150</td>
<td>Circle</td>
<td></td>
</tr>
</tbody>
</table>

Along this reference line, the coastline angle gradually changes. This coastline angle is used to transfer the (interpolated) offshore wave directions (given relative to the North) towards the morphological wave direction (relative to the local coastline and with a positive angle yielding positive transport).

11.2.2 Layer levels

The upper level of the dune layer (the $Z_0$-level) depends on the location along the coast. The actual dune level used in the computations is based on the Jarkus-dataset.

For the other layer levels the default values have been used.
### 11.2.3 Layer positions

The actual position of an individual layer is assessed from either the JARKUS-data set or the bottom topography applied in the so-called KUSTSTROOK-model. For each individual profile the results are transferred to the reference grid.

The following layers have been considered.

<table>
<thead>
<tr>
<th>Level</th>
<th>$Z$ [m]</th>
<th>Description</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_0$</td>
<td>&gt;NAP + 3 m</td>
<td>Depends on X-ordinate along coast</td>
<td></td>
</tr>
<tr>
<td>$Z_1$</td>
<td>NAP + 3 m</td>
<td>Transition beach/dune</td>
<td></td>
</tr>
<tr>
<td>$Z_2$</td>
<td>NAP – 2 m</td>
<td>Transition surfzone layer /beach</td>
<td></td>
</tr>
<tr>
<td>$Z_3$</td>
<td>NAP – 7 m</td>
<td>Transition middle shoreface / surfzone</td>
<td></td>
</tr>
<tr>
<td>$Z_4$</td>
<td>NAP – 13 m</td>
<td>Transition lower / middle shoreface</td>
<td></td>
</tr>
<tr>
<td>$Z_5$</td>
<td>NAP – 20 m</td>
<td>Lower shoreface level</td>
<td></td>
</tr>
</tbody>
</table>

More details on the procedures applied to define these data are provided in Appendix A.

### 11.2.4 Outer boundary

For the first applications, the location of the seaward boundary is located at a fixed position, namely 20,000 m seaward from the reference line.

### 11.3 Material

#### 11.3.1 Longshore distribution
For the western part a constant sediment size has been applied whereas a gradual decrease of the diameter has been applied for the northerly Wadden Coast.

More details on the background of these values are provided in Appendix B.

#### 11.3.2 Cross-shore distribution
No specific cross-shore distribution of the sediment size is taken into account. The DSZ-value equals 1.0 for all levels.

### 11.4 Structures

#### 11.4.1 Revetments and dikes
The location of revetments and dikes is based on the extensive overview provided in the ‘Afslagkaart’-study [Alkyon, 2002].

More details on the various (longshore oriented) structures are provided in Appendix C.

#### 11.4.2 Dams and groynes
Along the Dutch coast a limited number of large dams is present.
The mayor structures are summarized in the following tabel.

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>$X_s$ [km]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoek van Holland</td>
<td>Northerly dam</td>
<td>97.900</td>
<td></td>
</tr>
<tr>
<td>Scheveningen</td>
<td>South dam</td>
<td>115.200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Northerly dam</td>
<td>115.500</td>
<td></td>
</tr>
<tr>
<td>IJmuiden</td>
<td>South dam</td>
<td>161.300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Northerly dam</td>
<td>162.200</td>
<td></td>
</tr>
<tr>
<td>Texel</td>
<td></td>
<td>245.100</td>
<td>Build in 1995</td>
</tr>
</tbody>
</table>

In addition to these large structures, a large number of smaller groynes are present. More details on the various (cross-shore oriented) structures are provided in Appendix C also.

### 11.5 Tidal inlets
Along the northerly Wadden coast, five mayor tidal inlet systems are present. In addition two more easterly inlets are defined (in between the Schiermonnikoog and Borkum) as well as the Western Scheldt estuary.

As a consequence, in the Dutch coast model the following eight inlets are defined.

<table>
<thead>
<tr>
<th>No.</th>
<th>$X_l$ [km]</th>
<th>$X_r$ [km]</th>
<th>Location</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.0</td>
<td>30.0</td>
<td>Western Scheldt</td>
<td>Next phase</td>
</tr>
<tr>
<td>2</td>
<td>209.0</td>
<td>227.0</td>
<td>Marsdiep</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>243.0</td>
<td>253.0</td>
<td>Eijerlandse Gat</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>263.0</td>
<td>278.0</td>
<td>Vliestroom</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>295.0</td>
<td>310.0</td>
<td>Borndiep</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>326.0</td>
<td>343.0</td>
<td>Friesche Zeegat (double system)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>350.0</td>
<td>360.0</td>
<td>Eems (1)</td>
<td>Next phase</td>
</tr>
<tr>
<td>8</td>
<td>364.0</td>
<td>380.0</td>
<td>Eems (2)</td>
<td>Next phase</td>
</tr>
</tbody>
</table>

The characteristics of the back barrier system and the net transport through the tidal inlet are defined separately.

Using this schematisation the total coastline of 377 km consists of 111 km tidal inlets / outer deltas (30 %) and 266 km of dunes (70 %).

### 11.6 Hydraulic conditions

#### 11.6.1 Wave climate stations
Time averaged wave information is defined using five wave climate stations. The position and description of these stations is provided in the following table.

<table>
<thead>
<tr>
<th>No.</th>
<th>$X_l$ [km]</th>
<th>Station identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-10.0</td>
<td>WHB</td>
</tr>
<tr>
<td>2</td>
<td>55.0</td>
<td>EUR</td>
</tr>
<tr>
<td>3</td>
<td>155.0</td>
<td>YM6</td>
</tr>
<tr>
<td>4</td>
<td>240.0</td>
<td>ELD</td>
</tr>
<tr>
<td>5</td>
<td>340.0</td>
<td>SON</td>
</tr>
</tbody>
</table>
It should be noted that the nearshore information from ‘Meetpost Noordwijk’ (MPN) is not taken into account.

11.6.2 Individual wave climates
In each of the stations, a wave climate table is assessed from the available time series. In total 9 different wave directions with 10 wave height classes each have been defined as well as one residual class (with non-relevant wave conditions). As a consequence the average wave climate is defined using 91 (\(= 9 \times 10 +1\)) conditions, each with a specific frequency of occurrence.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Magnitudes</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave directions</td>
<td>0, 30, 60, 90, 210, 240, 270, 300, 330</td>
<td>9</td>
</tr>
<tr>
<td>Wave heights</td>
<td>0.50, 1.00, 1.50, 2.00, 2.50, 3.00, 3.75, 4.75, 5.75, 6.75</td>
<td>10</td>
</tr>
<tr>
<td>Wave period</td>
<td>Related to wave direction/height</td>
<td>90</td>
</tr>
</tbody>
</table>

More details on the assessment of the characteristics per wave climate station are provided in Appendix D.

11.6.3 Tidal climate stations
Comparable to the wave climate stations a limited number of points has been used. The required time series are obtained from a computation with the so-called KUSTSTROOK-model. In total, 9 different tidal wave climate stations have been defined.

<table>
<thead>
<tr>
<th>No.</th>
<th>Output</th>
<th>(X_i , [\text{km}])</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>#03</td>
<td>-19.0</td>
<td>Near WHB (southerly boundary)</td>
</tr>
<tr>
<td>2</td>
<td>#06</td>
<td>30.2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>#07</td>
<td>61.0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>#11</td>
<td>120.3</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>#16</td>
<td>183.4</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>#23</td>
<td>236.6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>#29</td>
<td>279.7</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>#40</td>
<td>338.3</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>#45</td>
<td>373.3</td>
<td>Near Borkum (easterly boundary)</td>
</tr>
</tbody>
</table>

The output number refers to the output number of the original model run (see Appendix E).

11.6.4 Individual tidal climates
In each of the stations, a tidal climate table is assessed from the computed time series. In total 12 different tidal conditions have been defined, each with a different water level, longshore velocity and percentage of occurrence.

More details on the assessment of the characteristics per tidal climate station are provided in Appendix E.

As a consequence the average hydraulic climate along the coast is defined as a longshore varying climate using 1,092 (\(= 91 \times 12\)) individual combinations of wave and tidal conditions.

11.6.5 Sea level rise
For the mean sea level two specific time series have been used, namely:

1. A low scenario using 0.20 m/century;
2. A high scenario using 0.65 m/century.
As a consequence the next input for the CSL-array is used.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>0.00</td>
<td>0.00</td>
<td>Present situation</td>
</tr>
<tr>
<td>2050</td>
<td>0.10</td>
<td>0.325</td>
<td>Depending on sea level rise rate</td>
</tr>
</tbody>
</table>

It should be noted that in the initial runs for the period 1970 - 2000 no change in the mean sea level has been applied.

These scenarios will also be applied for the computation of the net transport rate through individual inlets. For each inlet, time series for both sea level rise scenario [1] and [2] will be present.

**11.6.6 Wave height change**
The default setting with no relative wave height change has been used. A CWH-value of 1.0 has been used for the complete period.

**11.6.7 Wave direction change**
The default setting with no absolute wave direction change has been used. A CWD-value of 0.0 has been used for the complete period.

**11.6.8 Tidal range change**
The default setting with no relative tidal range change has been used. A CTR-value of 1.0 has been used for the complete period.

**11.6.9 Tidal velocity change**
The default setting with no relative tidal velocity change has been used. A CTV-value of 1.0 has been used for the complete period.

**11.7 Boundary conditions**

**11.7.1 Left-hand updrift boundary**
For the left-hand, southerly boundary of the model (located at \( X = 5.000 \) km at the easterly dam of Zeebrugge harbour), a free open boundary has been used for the initial runs.

**11.7.2 Right-hand downdrift boundary**
For the right-hand, easterly boundary of the model (located at \( X = 382.000 \) km near Borkum), a free open boundary has been used for the initial runs.

**11.7.3 Dune boundary**
In order to take into account the net sediment transport across the first dune row, a net boundary transport at the landward boundary has been applied. Comparable to the original application for the Wadden Coast [Steetzel, 1995], a constant rate of \( q_0 = -2 \) m\(^3\)/m\(^1\)/yr (sediment loss in landward direction) has been used. This value is assumed to be independent of both time (years 1970 – 2050) and location along the coast (\( X = 5 – 382 \) km) [Steetzel, 1995]. For the complete stretch of 266 km (= (382 – 5) – 111) consisting of dunes, this transport contribution yields a net sediment loss of 0.532 Mm\(^3\)/yr.
11.7.4 Seaward boundary
In order to take into account the net sediment transport across the lower shoreface boundary, a net boundary transport at the seaward boundary has been applied. Comparable to the original application for the Wadden Coast [Steetzel, 1995], a constant rate of $q_b = -5 \text{ m}^3/\text{m}^2/\text{yr}$ (sediment gain in landward direction) has been used. This value is assumed to be independent of both time (years 1970 – 2050) and location along the coast ($X = 5 – 382 \text{ km}$) [Steetzel, 1995]. For the complete stretch of 377 km ($= 382 – 5$) this transport contribution yields a net sediment gain of $1.885 \text{ Mm}^3/\text{yr}$.

11.7.5 Tidal inlet boundaries
For each of the tidal inlets the net sediment transport across the landward model boundary is computed using the AsMiTa-model. In the present phase of the study, these computations have been performed for inlet no. 2 (Marsdiep) until inlet no. 6 (Friesche Zeegat).

The results for sea level scenario [1] (0.20 m/century), are summarized in the following table (expressed in Mm$^3$/yr).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>-0.939</td>
<td>-0.392</td>
<td>-0.987</td>
<td>-0.384</td>
<td>-2.415</td>
<td>-5.118</td>
</tr>
<tr>
<td>1980</td>
<td>-0.767</td>
<td>-0.334</td>
<td>-1.051</td>
<td>-0.419</td>
<td>-0.939</td>
<td>-3.509</td>
</tr>
<tr>
<td>1990</td>
<td>-0.723</td>
<td>-0.321</td>
<td>-1.076</td>
<td>-0.437</td>
<td>-0.559</td>
<td>-3.116</td>
</tr>
<tr>
<td>2000</td>
<td>-0.702</td>
<td>-0.316</td>
<td>-1.089</td>
<td>-0.450</td>
<td>-0.403</td>
<td>-2.960</td>
</tr>
<tr>
<td>2010</td>
<td>-0.691</td>
<td>-0.313</td>
<td>-1.100</td>
<td>-0.462</td>
<td>-0.331</td>
<td>-2.897</td>
</tr>
<tr>
<td>2020</td>
<td>-0.688</td>
<td>-0.312</td>
<td>-1.110</td>
<td>-0.472</td>
<td>-0.299</td>
<td>-2.880</td>
</tr>
<tr>
<td>2030</td>
<td>-0.689</td>
<td>-0.312</td>
<td>-1.120</td>
<td>-0.481</td>
<td>-0.286</td>
<td>-2.888</td>
</tr>
<tr>
<td>2040</td>
<td>-0.695</td>
<td>-0.312</td>
<td>-1.132</td>
<td>-0.489</td>
<td>-0.283</td>
<td>-2.910</td>
</tr>
<tr>
<td>2050</td>
<td>-0.703</td>
<td>-0.312</td>
<td>-1.144</td>
<td>-0.496</td>
<td>-0.284</td>
<td>-2.939</td>
</tr>
</tbody>
</table>

The total rate of sediment loss is about $3 \text{ Mm}^3/\text{yr}$.

The results for sea level scenario [2] (0.65 m/century), are summarized in the following table.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>-0.939</td>
<td>-0.392</td>
<td>-0.987</td>
<td>-0.384</td>
<td>-2.415</td>
<td>-5.118</td>
</tr>
<tr>
<td>1980</td>
<td>-0.767</td>
<td>-0.334</td>
<td>-1.051</td>
<td>-0.419</td>
<td>-0.939</td>
<td>-3.509</td>
</tr>
<tr>
<td>1990</td>
<td>-0.723</td>
<td>-0.321</td>
<td>-1.076</td>
<td>-0.437</td>
<td>-0.559</td>
<td>-3.116</td>
</tr>
<tr>
<td>2000</td>
<td>-0.700</td>
<td>-0.322</td>
<td>-1.072</td>
<td>-0.438</td>
<td>-0.393</td>
<td>-2.925</td>
</tr>
<tr>
<td>2010</td>
<td>-0.758</td>
<td>-0.466</td>
<td>-1.061</td>
<td>-0.460</td>
<td>-0.439</td>
<td>-3.185</td>
</tr>
<tr>
<td>2020</td>
<td>-0.856</td>
<td>-0.603</td>
<td>-1.169</td>
<td>-0.565</td>
<td>-0.531</td>
<td>-3.724</td>
</tr>
<tr>
<td>2030</td>
<td>-0.955</td>
<td>-0.703</td>
<td>-1.308</td>
<td>-0.677</td>
<td>-0.610</td>
<td>-4.253</td>
</tr>
<tr>
<td>2040</td>
<td>-1.049</td>
<td>-0.777</td>
<td>-1.449</td>
<td>-0.782</td>
<td>-0.674</td>
<td>-4.732</td>
</tr>
<tr>
<td>2050</td>
<td>-1.139</td>
<td>-0.833</td>
<td>-1.584</td>
<td>-0.875</td>
<td>-0.729</td>
<td>-5.160</td>
</tr>
</tbody>
</table>

The total rate of sediment loss increases from $3 \text{ Mm}^3/\text{yr}$ to $5 \text{ Mm}^3/\text{yr}$ in 2050. More details are provided in Appendix F. The data with respect to net sediment transport at the Western Scheldt Estuary (inlet no. 1) are presented in Section 7.3.
11.8 Management

11.8.1 Pre-defined performed schemes
Until now (2000), a large number of nourishments have been performed. For each individual nourishment, the location along the coast, the cross-shore position (level interval), the nourishment period as well as the nourished volume have been determined. In the first runs, a total number of 145 individual nourishments have been taken into account. The total nourishment volume amounts to 89.3 Mm$^3$, representing an average nourishment effort of approximately 3 Mm$^3$/yr (in the period 1970 – 2000).

More details on the performed nourishment schemes are provided in Appendix G.

11.8.2 Pre-defined anticipated schemes
For the anticipated nourishment schemes (period 2000 – 2050), two different scenarios are defined, namely:

[A] A nourishment scheme based on the predictions of [Mulder, 2000] with a total constant rate of 11.9 Mm$^3$/yr;

[B] A nourishment scheme based on the mean efforts in the period 2001 - 2003 with a total constant rate of 13.0 Mm$^3$/yr.

These two management schemes ([A] and [B]) are combined with the two sea level rise schemes ([1] and [2]), yielding four combinations ([1A], [1B], [2A] and [2B]).

Apart from the different rate, the location of the nourishments is also different. In the following table the pre-defined distribution of the nourishments over the various coastal cells is presented.

<table>
<thead>
<tr>
<th>Section</th>
<th>Name</th>
<th>Vn [A]</th>
<th>Vn [B]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (1)</td>
<td>Delta</td>
<td>2.9</td>
<td>1.7</td>
</tr>
<tr>
<td>4 (2)</td>
<td>Hoek van Holland - IJmuiden</td>
<td>0.7</td>
<td>3.3</td>
</tr>
<tr>
<td>6 (3)</td>
<td>IJmuiden – Petten</td>
<td>0.4</td>
<td>2.5</td>
</tr>
<tr>
<td>7 (4)</td>
<td>Marsdiep</td>
<td>3.0</td>
<td>4.5</td>
</tr>
<tr>
<td>8 (5)</td>
<td>Eijerlandse Gat</td>
<td>1.1</td>
<td>0.0</td>
</tr>
<tr>
<td>9 (6)</td>
<td>Vliestroom</td>
<td>1.8</td>
<td>0.5</td>
</tr>
<tr>
<td>10 (7)</td>
<td>Amelander Zeegat</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>11 (8)</td>
<td>Friesche Zeegat</td>
<td>1.4</td>
<td>0.0</td>
</tr>
<tr>
<td>12 (9)</td>
<td>Eems</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>(1) – (9)</td>
<td>Total</td>
<td>11.7</td>
<td>13.0</td>
</tr>
</tbody>
</table>

The left column refers to the coastal section, whereas the number between brackets refers to the original numbering by Mulder.

In vertical / cross-shore direction it is assumed that 30% of the nourishment volume is positioned on the beach (in the Y$_1$- layer between NAP-2 m and NAP+3 m) and 70% in the interval between NAP-8 m and NAP-5 m.

As a consequence 2/3 of this 70% (46.7% of the total) is placed in the Y$_2$- layer between NAP-7 m and NAP-2 m and 1/3 (23.3% of the total) is placed in the Y$_3$- layer between NAP-13 m and NAP-7 m.
The detailed longshore distribution per individual coastal section is based on the present distribution of the nourishment efforts. More details are provided in Appendix H.

11.8.3 Auto layer-nourishments

In the first runs no auto layer nourishments have been applied. The application of a critical $Y_1$-position for specific stretches according to the location of the basal coastline (the so-called BCL-position) is however foreseen in the next phase of the application.

11.8.4 Auto cell-nourishments

In the first runs the (only recently implemented) auto cell nourishments have not yet been applied. For future applications, this option will be used to evaluate the system nourishment strategy [Mulder, 2000].

11.9 Additional run information

11.9.1 Computational grid

The following table provides the detail of the computational grid used for the initial runs.

<table>
<thead>
<tr>
<th>X [km]</th>
<th>dX [m]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.000</td>
<td>1000</td>
<td>Easterly harbour dam Zeebrugge</td>
</tr>
<tr>
<td>96.000</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>103.000</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>156.000</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>168.000</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>347.000</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>350.000</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>382.000</td>
<td></td>
<td>Centre of Borkum-island</td>
</tr>
</tbody>
</table>

The basic grid size equals 1 km. Near the dams at Hoek van Holland and IJMuiden a grid size of 500 m has been applied.

Using this schematization in total 389 grid cells are present on a 377 km long stretch.

11.9.2 Time range

The applied time range is summarized in the following table.

<table>
<thead>
<tr>
<th>Year</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>Start</td>
</tr>
<tr>
<td>1985</td>
<td>Calibration/verification transition</td>
</tr>
<tr>
<td>1990</td>
<td>Intermediate point related to management change</td>
</tr>
<tr>
<td>2000</td>
<td>Start prediction period</td>
</tr>
<tr>
<td>2010</td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td></td>
</tr>
<tr>
<td>2050</td>
<td>Final</td>
</tr>
</tbody>
</table>

The total computational time period amounts to 80 years.

The first period (1970 – 2000) will be used for calibration and verification purposes. The model predictions will be performed for the second period (2000 – 2050).
11.9.3 Time-stepping constraints
The basic time-stepping constraints are summarized in the following table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dt_min</td>
<td>0.001 year</td>
</tr>
<tr>
<td>Dt_max</td>
<td>1.0 year</td>
</tr>
<tr>
<td>DY/dt_max</td>
<td>10 m</td>
</tr>
</tbody>
</table>

The actual time step is to a large extent related to the mobility of the individual layers and thus to the last parameter.

11.9.4 Balance sections
According to [Mulder, 2000] nine different coastal sections have been defined. In addition two small sections for the ‘Euromaas-geul’ and the ‘IJ-geul’ are present. Since the updrift boundary is located at ‘Zeebrugge’, another updrift section is defined. A summary of the 12 computational sections is provided in the following table.

<table>
<thead>
<tr>
<th>No. [-]</th>
<th>X_l [km]</th>
<th>X_r [km]</th>
<th>D_X [km]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.0</td>
<td>11.0</td>
<td>6.0</td>
<td>Additional section</td>
</tr>
<tr>
<td>2</td>
<td>11.0</td>
<td>96.0</td>
<td>85.0</td>
<td>1 – Delta coast</td>
</tr>
<tr>
<td>3</td>
<td>96.0</td>
<td>98.0</td>
<td>2.0</td>
<td>&lt;&lt; Euromaas geul</td>
</tr>
<tr>
<td>4</td>
<td>98.0</td>
<td>161.0</td>
<td>63.0</td>
<td>2 – Hoek van Holland - IJmuiden</td>
</tr>
<tr>
<td>5</td>
<td>161.0</td>
<td>162.5</td>
<td>1.5</td>
<td>&lt;&lt; IJgeul</td>
</tr>
<tr>
<td>6</td>
<td>162.5</td>
<td>210.0</td>
<td>47.5</td>
<td>3 – IJmuiden – Petten</td>
</tr>
<tr>
<td>7</td>
<td>210.0</td>
<td>230.0</td>
<td>20.0</td>
<td>4 – Marsdiep</td>
</tr>
<tr>
<td>8</td>
<td>230.0</td>
<td>255.0</td>
<td>25.0</td>
<td>5 – Eijerlandse Gat</td>
</tr>
<tr>
<td>9</td>
<td>255.0</td>
<td>285.0</td>
<td>30.0</td>
<td>6 – Vliestroom</td>
</tr>
<tr>
<td>10</td>
<td>285.0</td>
<td>318.0</td>
<td>33.0</td>
<td>7 – Amelander Zeegat</td>
</tr>
<tr>
<td>11</td>
<td>318.0</td>
<td>347.0</td>
<td>29.0</td>
<td>8 – Friesche Zeegat</td>
</tr>
<tr>
<td>12</td>
<td>347.0</td>
<td>382.0</td>
<td>35.0</td>
<td>9 – Eems (next phase)</td>
</tr>
<tr>
<td>1 - 12</td>
<td>5.0</td>
<td>382.0</td>
<td>377.0</td>
<td>Total coastal stretch</td>
</tr>
</tbody>
</table>

The outer boundaries of the first and last coastal section correspond with the first and last point of the computational grid.

11.9.5 Profile locations
No specific profile locations have been used.

11.9.6 Depth contours
No specific depth contours have been used.

11.10 Calibration factors

11.10.1 Wave-induced longshore transport
Initially, no corrections for the wave-induced longshore sediment transport have been applied. The default CWX-value of 1.0 has been used for the complete stretch.

11.10.2 Wave direction corrections
Initially, no corrections for the wave direction have been applied.
The default CWD-value of 0.0 has been used for the complete stretch.

11.10.3 Tide-induced longshore transport
Initially, no corrections for the tide-induced longshore sediment transport have been applied. The default CTX-value of 1.0 has been used for the complete stretch.

11.10.4 Wave-induced cross-shore transport
Initially, no corrections for the wave-induced cross-shore sediment transport have been applied. The default CCX-value of 1.0 has been used for the complete stretch.

11.10.5 Cross-shore profile steepness
No corrections for the cross-shore steepness have been applied. The default CSX-value of 1.0 has been used for the complete stretch. For the cross-shore equilibrium profile calibration, the more robust layer width calibration facto has been used.

11.10.6 Cross-shore profile shape
No corrections for the profile shape calibration have been applied. The default CPX-value of 1.0 has been used for the complete stretch. Comparable to the CSX, the more robust layer width calibration facto has been used For the cross-shore equilibrium profile calibration.

11.10.7 Cross-shore layer width
The CWXj-value refers to the new cross-shore process calibration. For the various runs a first estimate for this cross-shore correction has been defined. Since the definition of the calibration factor is ongoing, the final setting has not yet been determined.
12 Preliminary model results

12.1 Introduction

In the following some of the initial results of the model are presented. It should be noted that these results are preliminary, since the process of calibration and verification of the model application as well as the mathematical implementation of tidal deltas has not yet reached a sufficient and acceptable level.

Moreover, the complexity of both the model itself and the application ask for a stepwise modification of the input. The initial runs have for example been performed using a straight coast. Very recently the number of structures has been increased. For the initial layer position in the final runs described hereafter, the same 2000-situation has been used for all cases.

The basic idea is that the performance of the model can be related to the degree of detail and complexity of the model. In this way problems can be dealt with effectively.

As a result, the present results are not to be considered as final. The results will be improved in the next phase of the project.

Figure 12.1 shows an overview of the North Sea coast along the reference line as well as the location of the various coastal cells as discussed in the preceding chapter.

12.2 Calibration and verification

Some of the initial results of the calibration and verification computations are presented in Figure 12.2 to 12.5.

In the present phase of the study, model-runs have been performed for the entire calibration/verification period: from 1970 – 2000.

The initial layer positions applied for CASE_CV are presented in Figure 12.2. The lower panel shows both the initial 1970- and computed 2000-position of the layers.

Figure 12.3 shows the development of the performed nourishment rates. The upper panel shows the longshore distribution of the time-averaged nourishment efforts in the period 1970 – 2000. The lower panel shows the time-evolution of the nourishment effort. It should be noted that the applied input refers to the period 1970 – 1999 only. The more recent nourishments will be taken in the account in the next phase of the study.

A more detailed comparison of the layer position is given in the upper plot of Figure 12.4. The thick lines refer to the computed positions. As can be observed the resemblance for the Holland coast is not very good yet. The model yields a seaward movement of the Y3-layer. Application of the improved procedure for the cross-shore transport calibration is expected to yield better results.

The lower panel of this figure shows the longshore sediment transport along the Dutch coast. The overall pattern, a north-easterly increasing rate, seems in accordance with the results of
other studies. The change in the direction of the wave-drive transport in the east is due to an incorrect definition of the reference line orientation in this region and will be corrected in the next study phase.

Figure 12.5 shows the results of a time-averaged (period 1970 – 2000) behaviour of the dune layer, the upper layers (beach and surf zone), the lower layers (middle and lower shoreface) as well as the overall total behaviour.

The upper panel shows the section-averaged rate. Although the overall trend (for all layers) is only minor, the landward displacement of the dune and upper layer is not correct. Given the applied nourishment schemes, the location of these layers should be more or less stable.

The average trend for the upper layer (beach and surfzone layer) is given in more detail in the lower panel. In addition to the section-averaged rate, the detailed results per individual grid cell are presented also.

As mentioned, the process of testing and improvement of calibration procedures is ongoing.

### 12.3 Predictions

The model has been applied for four different cases as presented in the following table.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Management [A]</th>
<th>Management [B]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea level rise [1]</td>
<td>CASE_1A</td>
<td>CASE_1B</td>
</tr>
<tr>
<td>Sea level rise [2]</td>
<td>CASE_2A</td>
<td>CASE_2B</td>
</tr>
</tbody>
</table>

Figure 12.6 presents a summary of the applied nourishment schemes. The upper and lower panel show the longshore distribution of the time-averaged nourishment rates for the A- and B-scenario respectively.

The results of these computations are summarized in Figures 12.7 –12.10 respectively. The upper panel of each figure shows the initial 2000-position as well as the computed 2050-position of the various layers. Comparable to Figure 12.5, the average trend for the upper layer (beach and surfzone layer) is given in more detail in the lower panel. In addition to the section-averaged rate, the detailed results per individual grid cell are presented also.

Mutual comparison between the various runs shows that the differences are related to the combination of sea level rise rate and nourishment scheme.

Examples of such relative impacts are shown in Figure 12.11. The upper panel shows the impact of increased sea level rise (scenario 2A instead of scenario 1A), where the lower panel shows the effect of a different management scenario (scenario 1B instead of scenario 1A).

In both plots, the relative behaviour of the upper layer (comparable to the BCL-layer) is shown. Increased sea level rise yields an additional seaward displacement of this layer (due to the so-called Bruun-rule). The use of the B-scenario has positive effects for the Holland coast (see also Figure 12.6).
Similar results are provided in Figure 12.12. However, the behaviour of the dune layer is used as a reference. As to be expected, increased sea level rise yields an accompanying retreat of the dune layer. These results indicate that the definition of the layer boundaries has a great impact on the results. Consequently, attention has to be paid to the translation of model results to the so-called BCL-layer.

Finally, Figure 12.13 shows an integrated result of the model in terms of time-averaged changes in coastal cells for scenario 1A. The upper panel shows the time-averaged changes (period 2000 – 2050) in both the lower and upper layer, expressed in Mm³/yr. As can be observed, the cross-shore processes for especially the Holland coast are not yet correct. The panel below shows the cross-shore integrated result per coastal cell, whereas the lower panel shows the overall, longshore integrated result. It should be noted that these results do not include the exchange with the tidal basins. Comparable figures can for the other scenarios are provided in Figure 12.14 to 12.16. The relative effects of sea level rise and management scenarios are shown in Figure 12.17 to 12.18.
13 Conclusions and recommendations

13.1 Conclusions

13.1.1 Model concept
In this phase of the project the model has been improved on various points. The first results of the model show promising results, however some problems (or better challenges) have to be dealt with.
This holds especially for the neat incorporation of the way the tidal inlet is implemented in the model.
Also the calibration of the cross-shore processes needs additional attention. The formulation and application of a climate-averaged correction factor seems to be an effective method and will be applied in the next study phase.

13.1.2 Model application
The application of the model showed that it is very difficult to define a simple and robust application for a difficult case. For a neat simulation of the tidal delta system, the ‘tidal inlet model’ should be complex enough. Intermediate solutions give rise to all kind of other problems for the Dutch coast application.
After implementation of the improved tidal-inlet extension, the effect of the back barrier system can be taken into account also.

In the process of using more detailed and complex input to run the model, the desired level (with more detailed layer contours, tidal inlets and the most relevant structures) is almost obtained.

13.2 Activities in the next project phase

13.2.1 Model concept
With respect to the model concept the two main items are the implementation of an improved tidal inlet extension and the applications of a climate-based cross-shore transport calibration.

The overall recommendations with respect to the model improvement are in accordance with the original plans.

In addition it is recommended to define specific output for the assessment of a characteristic position of the BCL-related layer.

13.2.2 Model application
After finalising the inlet extension and the cross-shore transport calibration procedures, the model must be tested using the complete input.

The next step will be to calibrate the model for the period 1970 – 1985 and subsequently define the calibration factors that will be used for verification and prediction purposes.

As elaborated in more detail in Section 10.5, the next step will be to verify the models behaviour and to run the model for different scenarios for the 2000-2050 period.
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.


Kamphuis, J.W., 1992: Computation of coastal morphology, Short course ICCE, Venice, Italy.


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

LARGE-SCALE MODEL OF THE DUTCH COAST

PONTOS-1.4

WL / Alkyon
Fig. 2.1
Macro-scale elements of a tidal basin
Overview tidal inlets Western Wadden Sea
Sediment transport at the inlet
From the basin to the ebb-tidal delta

Marsdiep (inlet 2)

![Graph showing sediment transport over time with SLR scenarios.
SLR = 0.65 m/century, SLR = 0.20 m/century]

-1.2
-1
-0.8
-0.6
-0.4
-0.2
0

sediment transport (Mm³/yr)
time (year)
Sediment transport at the inlet
From the basin to the ebb-tidal delta

Eijerlandse Gat (inlet 3)

SLR = 0.65 m/century
SLR = 0.20 m/century

Sediment transport (Mm$^3$/yr)

Time (year)
Sediment transport at the inlet
From the basin to the ebb-tidal delta

Vlie (inlet 4)

<table>
<thead>
<tr>
<th>Time (year)</th>
<th>Sediment transport (Mm$^3$/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>-1.8</td>
</tr>
<tr>
<td>1975</td>
<td>-1.6</td>
</tr>
<tr>
<td>1985</td>
<td>-1.4</td>
</tr>
<tr>
<td>1995</td>
<td>-1.2</td>
</tr>
<tr>
<td>2005</td>
<td>-1</td>
</tr>
<tr>
<td>2015</td>
<td>-0.8</td>
</tr>
<tr>
<td>2025</td>
<td>-0.6</td>
</tr>
<tr>
<td>2035</td>
<td>-0.4</td>
</tr>
<tr>
<td>2045</td>
<td>-0.2</td>
</tr>
<tr>
<td>2055</td>
<td>0</td>
</tr>
</tbody>
</table>

SLR = 0.65 m/century
SLR = 0.20 m/century

Fig. 7.5

LARGE-SCALE MODEL OF THE DUTCH COAST Z3334/A1000 WL / Alkyon Fig. 7.5
Borndiep / Amelander Zeegat (inlet 5)

Sediment transport at the inlet
From the basin to the ebb-tidal delta

Fig. 7.6

LARGE-SCALE MODEL OF THE DUTCH COAST
Z3334/A1000

ASMITA
5 - Borndiep

SLR = 0.65 m/century
SLR = 0.20 m/century
Sediment transport at the inlet
From the basin to the ebb-tidal delta

**Friesche Zeegat (inlet 6)**

![Graph showing sediment transport over time with two lines representing different sea-level rise (SLR) scenarios: SLR = 0.65 m/century (pink) and SLR = 0.20 m/century (blue). Time ranges from 1965 to 2055, with sediment transport values ranging from -3 to 0.]
Schematization of Western and Eastern Scheldt inlet

[Meangbu, 2003]
SC1 = 0.2 m/century, SC2 = 0.6 m/century, (SC3 = 1.0 m/century)
'west' refers to section 6 of the estuary (see fig. 7.8)

[source: Meangbua (2003)]
Overview of the North Sea Coast
Position of the applied reference line

LARGE-SCALE MODEL OF THE DUTCH COAST

Fig. 10.1
Detail of the Dutch North Sea Coast
Position of the applied reference line

LARGE-SCALE MODEL OF THE DUTCH COAST
Z3334/A1000
PONTOS-1.4
WL / Alkyon
Fig. 10.2
Location of large-scale coastal cells

Overview of North Sea coast along the reference line

Position along reference line [m]

Texel
Vlieland
Terschelling
Ameland
Schiermonnikoog
Borkum (D)
Zeebrugge
Walcheren
Voornse Putten
Goeree-Overflakkee
Schouwen-Duiveland
Hoek van Holland
IJmuiden
Den Helder
Vieland
Terschelling
Ameland
Rotterdamerplaat
Rottumeroog
Lauwersmeer
Waddenzee
IJsselmeer

Fig. 12.1

LARGE-SCALE MODEL OF THE DUTCH COAST

Z3334/A1000
WL / Alkyon
PONTOS-1.4
file: A1000F1r1.xls; november 2003
Initial 1970-position and computed 2000-position
Initial layer positions with respect to reference line
Preliminary result calibration/verification run

Case_CV
1970-2000

Note: Exchange with tidal basins not included
Comparison between initial and final layer positions

Longshore distribution of initial longshore transport rate

Preliminary result calibration/verification run 1970-2000

Note: Exchange with tidal basins not included
Detailed and section-averaged behaviour of upper layer

Time- and section-averaged behaviour of dune, upper and lower layer

Preliminary result calibration/verification run 1970-2000

Case C_V

Note: Exchange with tidal basins not included
Summary of applied nourishment schemes 2000-2050 for both the A- and B-scenario

Longshore distribution of time-averaged nourishment rates

**Fig. 12.6**

**A-scenario**

- Position along reference line [m]
- dv_pn/yr [m³/m²/yr]
- dv_pn/yr [m³/m²/yr] (sections)
- dv_pn/yr [m³/m²/yr] (gridcells)

**B-scenario**

- Position along reference line [m]
- dv_pn/yr [m³/m²/yr]
- dv_pn/yr [m³/m²/yr] (sections)
- dv_pn/yr [m³/m²/yr] (gridcells)
Preliminary result scenario 1A (0.20 m/century; 11.7 Mm³/yr) 2000-2050

Comparing initial and final layer positions

Detailed and section-averaged behavior of upper layer

Note: Exchange with tidal basins not included
Detailed and section-averaged behavior of upper layer
Comparison between initial and final layer positions
Preliminary result scenario 1B (0.20 m/century; 13.0 Mm³/yr) 2000-2050

Note: Exchange with tidal basins not included
Detailed and section-averaged behaviour of upper layer

Comparison between initial and final layer positions

Preliminary result scenario 2A (0.65 m/century; 11.7 Mm³/yr) 2000-2050

Note: Exchange with tidal basins not included
Detailed and section-averaged behaviour of upper layer
Comparison between initial and final layer positions
Preliminary result scenario 2B (0.65 m/century; 13.0 Mm³/yr) 2000-2050

Note: Exchange with tidal basins not included
Effect management scenario; Case 1B minus Case 1A
Effect sea level rise scenario; Case 2A minus Case 1A
Preliminary result for (fixed) upper layer behaviour (NAP-7m - NAP+3m) 2000-2050
Effect different nourishment scenario

Effect increased sea level rise

Effect different nourishment scenario

Note: Exchange with tidal basins not included
Effect increased sea level rise

Effect different nourishment scenario

Note: Exchange with tidal basins not included
### TIME-AVERAGED BEHAVIOUR OF COASTAL CELLS

#### PONTOS-1.4

**ACCRETION RATE EXPRESSED IN Mm³/yr**

| Layer                  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 0.11 | 0.09 | 0.01 | 1.97 | 0.09 | 6.07 | 0.20 | 5.86 | 0.67 | 2.18 | 1.34 | 0.85 | 0.83 | -0.78 | 0.42 |
|------------------------|----|----|----|----|----|----|----|----|----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| All layers             |    |    |    |    |    |    |    |    |    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Upper layer & dunes    |    |    |    |    |    |    |    |    |    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Lower layer            |    |    |    |    |    |    |    |    |    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| All layers             |    |    |    |    |    |    |    |    |    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |

**Note**: Exchange with tidal basins not included

---

**FILE**: A1000F1r1.xls; November 2003

**CASE**: 1A

**SCENARIO**: 2000-2050

**FIG**: 12-13

**PONTOS-1.4**

**CASE**: 1A

**WL / ALKYON**

**Z334/A1000**

---

**Note**: Exchange with tidal basins not included
### Preliminary Integrated Balance Results for Scenario 1B

**Fig. 12.14**

Accretion rate expressed in Mm³/yr

Time-averaged behaviour of coastal cells

<table>
<thead>
<tr>
<th>Layer</th>
<th>Case 1B 2000-2050</th>
<th>Case 1B 2000-2050</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All layers</td>
<td>12.52</td>
<td></td>
</tr>
<tr>
<td>Lower layer &amp; dunes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper layer &amp; dunes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Exchange with tidal basins not included.
### Preliminary integrated balance results for scenario 2A

**Time-averaged behaviour of coastal cells**

**Accretion rate expressed in Mm$^3$/yr**

<table>
<thead>
<tr>
<th>Layer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>0.10</td>
<td>1.08</td>
<td>-0.08</td>
<td>-5.57</td>
<td>-0.09</td>
<td>-4.41</td>
<td>1.12</td>
<td>-1.08</td>
<td>0.62</td>
<td>-0.28</td>
<td>0.09</td>
<td>0.42</td>
</tr>
<tr>
<td>Upper</td>
<td>0.01</td>
<td>1.99</td>
<td>0.09</td>
<td>6.08</td>
<td>0.20</td>
<td>5.86</td>
<td>0.68</td>
<td>2.18</td>
<td>1.34</td>
<td>0.85</td>
<td>0.83</td>
<td>-0.77</td>
</tr>
</tbody>
</table>

#### Note:
- Lower layer
- Upper layer & dunes
- All layers

<table>
<thead>
<tr>
<th>Layer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>0.11</td>
<td>3.06</td>
<td>0.01</td>
<td>0.51</td>
<td>0.10</td>
<td>1.45</td>
<td>1.80</td>
<td>1.10</td>
<td>1.96</td>
<td>0.57</td>
<td>0.91</td>
<td>-0.35</td>
</tr>
</tbody>
</table>

#### All layers

<table>
<thead>
<tr>
<th>Layer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.23</td>
<td>11.23</td>
<td>11.23</td>
<td>11.23</td>
<td>11.23</td>
<td>11.23</td>
<td>11.23</td>
<td>11.23</td>
<td>11.23</td>
<td>11.23</td>
<td>11.23</td>
<td>11.23</td>
<td>11.23</td>
</tr>
</tbody>
</table>

**Accretion rate expressed in Mm$^3$/yr**

**Time-averaged behaviour of coastal cells**

**Preliminary integrated balance results for scenario 2A**

**LARGE-SCALE MODEL OF THE DUTCH COAST**

**Note:** Exchange with tidal basins not included
## Preliminary integrated balance results for scenario 2B

- **Time-averaged behaviour of coastal cells**
- **PONTOS-1.4**

### Note: Exchange with tidal basins not included

**LARGE-SCALE MODEL OF THE DUTCH COAST**

<table>
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<th>Case 2B</th>
<th>2000-2050</th>
<th>PONTOS:1.4</th>
<th>WL / Alkyon</th>
<th>File A1000F1r1.xls; November 2003</th>
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### Table for all layers

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- **lower layer**

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- **upper layer & dunes**

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### Table for all layers

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### Note: Exchange with tidal basins not included
LARGE-SCALE MODEL OF THE DUTCH COAST

Relative accretion rate expressed in Mm3/yr

Effect sea level rise scenario: Case 2A minus Case 1A

Preliminary relative integrated balance results

Upper layer & Dunes

Lower layer

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

Note: Exchange with tidal basins not included

File: A1000F1r1.xls; November 2003

2000-2050

Fig. 12.17
### Preliminary relative integrated balance results

Effect management scenario: Case 1B minus Case 1A  
Relative accretion rate expressed in Mm³/yr  

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<td>0.76</td>
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1.30 all layers

### Note
Exchange with tidal basins not included
Appendix A
Definition of individual layer positions
Based on JARKUS data set

Dune height (w.r.t. NAP) along the reference line

Definition of layer positions

LARGE-SCALE MODEL OF THE DUTCH COAST Z3334/A1000

PONTOS-1.4 WL / Alkyon Fig. A.1
Definition of layer positions

Layer position for layer Y0

Based on JARKUS data set and KustStrook-model
Definition of layer positions

Layer position for layer Y1

Based on JARKUS data set and KustStrook-model

LARGE-SCALE MODEL OF THE DUTCH COAST Z3334/A1000 WL / Alkyon Fig. A.3
Definition of layer positions
Layer position for layer Y2
Based on JARKUS data set and KustStrook-model

LARGE-SCALE MODEL OF THE DUTCH COAST Z3334/A1000 WL / Alkyon Fig. A.4
Definition of layer positions

Layer position for layer Y3

Based on JARKUS data set and KustStrook-model

LARGE-SCALE MODEL OF THE DUTCH COAST

Z3334/A1000

PONTOS-1.4

WL / Alkyon

Fig. A.5
Definition of layer positions

Layer position for layer Y4

Based on JARKUS data set and KustStrook-model

LARGE-SCALE MODEL OF THE DUTCH COAST
Appendix B
Definition of sediment characteristics
Grain size distribution along the Dutch coast

Information obtained from different sources

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Appendix C
Definition of dikes and dams
Location of structures along the Durth coast
Revetments, dikes, dams and groynes
With reference to Paris co-ordinate system
Location of structures along the Durth coast
Revetments, dikes, dams and groynes
With reference to PonTos co-ordinate system

LARGE-SCALE MODEL OF THE DUTCH COAST

PONTOS-1.4

Fig. C.2
Appendix D
Definition of average wave conditions
Definition of average wave conditions
Yearly average wave climate for Westhinder

LARGE-SCALE MODEL OF THE DUTCH COAST
Z3334/A1000

PONTOS-1.4
WHB

WL / Alkyon
Fig. D.1
Definition of average wave conditions
Yearly average wave climate for Europlatform

LARGE-SCALE MODEL OF THE DUTCH COAST Z3334/A1000 WL / Alkyon Fig. D.2
Definition of average wave conditions
Yearly average wave climate for Meetpost Noordwijk

LARGE-SCALE MODEL OF THE DUTCH COAST
Z3334/A1000 WL / Alkyon Fig. D.3
Definition of average wave conditions
Yearly average wave climate for IJmuiden

LARGE-SCALE MODEL OF THE DUTCH COAST
Z3334/A1000

PONTOS-1.4
IJM6

Fig. D.4
Definition of average wave conditions
Yearly average wave climate for Eijerlandse Gat
Definition of average wave conditions
Yearly average wave climate for Schiermonnikoog

LARGE-SCALE MODEL OF THE DUTCH COAST
Z3334/A1000 WL / Alkyon Fig. D.6
Appendix E
Definition of average tidal conditions
Definition of average tidal conditions

Output locations of the KustStrook model
Definition of average tidal conditions
Summary of computed tidal conditions at location 3

LARGE-SCALE MODEL OF THE DUTCH COAST

Figure E.2

- Residual flow velocity: 0.00 m/s
- Maximum flood velocity (NAP-10 m): 0.59 m/s
- Maximum water level: 2.16 m+NAP
- Minimum ebb velocity (NAP-10 m): -0.42 m/s
- Minimum water level: -1.95 m+NAP
- Average water level: 0.04 m+NAP
- Depth: 10.00 m-NAP
Definition of average tidal conditions
Summary of computed tidal conditions at location 6

Residual flow velocity: 0.00 m/s
Maximum flood velocity (NAP-10 m): 0.50 m/s
Maximum water level: 1.80 m-NAP
Minimum ebb velocity (NAP-10 m): -0.40 m/s
Minimum water level: -1.48 m-NAP
Average water level: 0.04 m-NAP
Depth: 8.92 m-NAP
Definition of average tidal conditions
Summary of computed tidal conditions at location 7

LARGE-SCALE MODEL OF THE DUTCH COAST Z3334/A1000 WL / Alkyon Fig. E.4
Definition of average tidal conditions
Summary of computed tidal conditions at location 11

Residual flow velocity: 0.03 m/s
Maximum flood velocity (NAP-10 m): 0.59 m/s
Maximum water level: 1.16 m+NAP
Minimum ebb velocity (NAP-10 m): -0.41 m/s
Minimum water level: -0.67 m+NAP
Average water level: 0.07 m+NAP
Depth: 8.48 m-NAP
Definition of average tidal conditions
Summary of computed tidal conditions at location 16

LARGE-SCALE MODEL OF THE DUTCH COAST

Residual flow velocity: 0.01 m/s
Maximum flood velocity (NAP-10 m): 0.60 m/s
Maximum water level: 0.76 m+NAP
Minimum ebb velocity (NAP-10 m): -0.46 m/s
Minimum water level: -0.60 m+NAP
Average water level: 0.03 m+NAP
Depth: 7.73 m-NAP
Definition of average tidal conditions
Summary of computed tidal conditions at location 23

Residual flow velocity: 0.01 m/s
Maximum flood velocity (NAP-10 m): 0.61 m/s
Maximum water level: 0.72 m NAP
Minimum ebb velocity (NAP-10 m): -0.47 m/s
Minimum water level: -0.74 m NAP
Average water level: 0.05 m NAP
Depth: 7.32 m NAP
Definition of average tidal conditions
Summary of computed tidal conditions at location 29
Definition of average tidal conditions
Summary of computed tidal conditions at location 40

Residual flow velocity: 0.03 m/s
Maximum flood velocity (NAP-10 m): 0.36 m/s
Maximum water level: 0.92 m+NAP
Minimum ebb velocity (NAP-10 m): -0.26 m/s
Minimum water level: -1.07 m+NAP
Average water level: 0.03 m+NAP
Depth: 9.02 m-NAP

LARGE-SCALE MODEL OF THE DUTCH COAST Z3334/A1000 WL / Alkyon Fig. E.9
Definition of average tidal conditions
Summary of computed tidal conditions at location 45

Residual flow velocity: 0.10 m/s
Maximum flood velocity (NAP-10 m): 0.46 m/s
Maximum water level: 0.93 m-NAP
Minimum ebb velocity (NAP-10 m): -0.23 m/s
Minimum water level: -1.10 m-NAP
Average water level: 0.00 m-NAP
Depth: 8.08 m-NAP
Appendix F
Definition of net transport for each inlet
Time evolution of import through tidal inlets

Results for inlet no. 2, 3, 4, 5 and 6

for sea level scenarios [1] and [2]

LARGE-SCALE MODEL OF THE DUTCH COAST
Appendix G

Definition of performed nourishment schemes
Summary of nourishment schemes
Performed nourishments between 1965 and 1998
Nourishment volumes

Nourishment size [Mm³]
### Summary of nourishment schemes

- **Performed nourishments between 1965 and 1998**
- **Nourishment rate evolution**

#### Fig. G.2

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**Chart Details**
- **X-axis**: Nourishment period [yr]
- **Y-axis**: Nourishment rate
- **Legend**: Different symbols represent different nourishment schemes.
- **Data Source**: A1000A1r1.xls; November 2003

**References**
- **Z3334/A1000**
- **WL / Alkyon**
- **File**: A1000A1r1.xls; November 2003
Appendix H
Definition of anticipated nourishment schemes
Summary of nourishment schemes

Anticipated nourishment efforts

LARGE-SCALE MODEL OF THE DUTCH COAST

PONTOS-1.4

Z3334/A1000

WL / Alkyon

Fig. H.1