Morphological Modelling using a Modified Multi-layer Approach

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Abstract

*One of the topics of the National Dutch research program COAST*2000 focuses on the long-term (50-100 years) and large-scale (1-100 km) morphological problems of the Dutch coast and the implications for coastal management. Examples of such problems are the effects of climate change and sea-level rise on a partly protected coastline, the long-term effects of on-going sand nourishments, the far-field effects of large-scale land reclamation and of the required sand-mining etc. Within this framework a pilot version of a conceptual model (the so-called PONTOS-model) has been developed, basically capable of simulating the morphological evolution of the Dutch coast at the above-mentioned spatial and temporal scales.*
This present paper focuses on the theoretical background of the model. The results of a preliminary application of the model for the closed coastal section of the Dutch coast between Hoek van Holland and Den Helder are also presented.
The actual PONTOS-model is 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. The main input of the model, to be provided by the user, are the characteristics of the coastal stretch to be studied, including the initial positions of the various layers and offshore hydraulic conditions in terms of wave and tidal climate tables. On the basis of these data the yearly-averaged sediment transport pattern is computed and finally used for the assessment of the coastal evolution.

Introduction

For national decisions regarding coastal management it is important to understand the long-term (50-100 years) effects and large-scale (1-100 km) implications of both natural processes and major coastal engineering projects. Examples of natural processes are the effects of climate change and sea-level rise on the sandy coast partly protected by groins or sea-walls and, in relation to this, the long-term effects of coastline maintenance by on-going sand nourishments. Problems related to major

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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.

One of the topics of the national research program COAST*2000 focuses on understanding these long-term large-scale morphological effects and on developing tools to quantify them. Within this framework, a model is being developed, capable of simulating the morphological evolution of the Dutch coast at the required spatial and temporal scales.

Morphological characteristics of complicated coastal systems can be described using different modelling approaches. 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 predominant 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 computation effort and the numerous iterations and accumulation of rounding-off errors may lead to unrealistic results. PonTos uses a different approach, which is more behaviour-oriented [Steetzel et al., 1998]. 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 smaller 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. Moreover, because of its approach, this model is easier accessible more user-friendly than most process-based models. The results of the pilot version of this model (the so-called PONTOS-model) indicate that it is a promising tool to simulate and quantify the morphological implications of the problems just described.

The multi-layer model

The model is 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, see Figure 1.

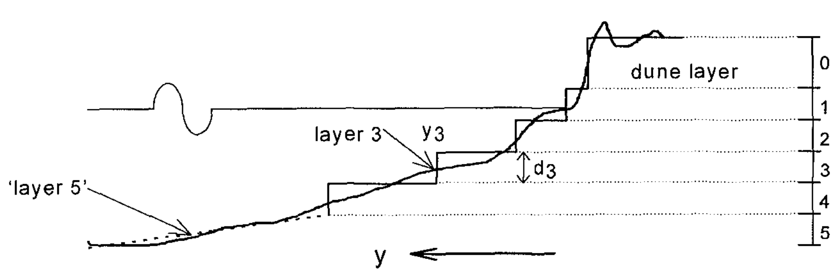

Figure 1: Layer schematization used in the model

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. The present model uses a rectangular grid, with the x-axis in longshore direction, whereas the y-axis in the seaward direction. 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. In the present model, the cross-shore profile is schematised into five horizontal layers and two additional zones. Each individual layer is denoted with an index j, ranging from j = -1 to j = 5, in which layer j = 0 to 4 refer to physical layers. The first physical layer, with index j = 0, refers to the dune layer. Subsequent layers refer to layers positioned further seaward, as shown in Figure 1. The actual position of a layer has to be assessed from the sediment balance of the cross-shore profile. The characteristic layer position y_j for a layer with thickness d_j between lower level Z_{j+1} and upper level Z_j is the average position computed from:

$$y_j = \frac{1}{d_j} \int_{Z_{j+1}}^{Z_j} y(z)\, dz$$

Depending on the actual shape of the local cross-shore profile, the characteristic layer position is located between the position of the depth contours of the boundaries.

Governing equations

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

$$\frac{\Delta Vol_{j,i}}{\Delta t} = (Q_{x,j,i-1} - Q_{x,j,i}) - (Q_{y,j,i} - Q_{y,j+1,i}) + \frac{\Delta S_{j,i}}{\Delta t}$$

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

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 change in a cell's volume, $\Delta Vol_{j,i}$ in layer j and cell with index i yields a cross-shore shift in the characteristic position of layer j, denoted as $\Delta y_{j,i}$ according to:

$$\Delta y_{j,i} = \frac{\Delta Vol_{j,i}}{d_{j,i}\, \Delta X_i}$$

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

Substitution of this translation yields:

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

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

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

The assessment of the longshore transport for each individual layer and the cross-shore transport rate at each intersection is discussed in the next.

New formulations

Earlier versions of this model [Steetzel, 1995] had the drawback that the interaction between the layers and their response in the longshore direction was determined by a series of pre-defined constants, which had to be determined by the users based on process-based models or on empirical data, see e.g. [Bakker et al., 1988]. This puts 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 on the basis of external conditions such as wave climate, tidal conditions, bathymetry and sediment characteristics. In this way a very user-friendly behaviour-oriented model has been formulated. As such, the multi-layer concept is now more suitable for the evaluation of changes in a coastal system [Steetzel, 1997c, 1998].

Climate schematization

The model uses yearly mean wave climates at the seaward boundary as input. Specifically, wave conditions must be described on the Z_5-depth contour (e.g. at NAP-20m for the Dutch coast). This climate schematization forms the main driving force of the model.

Wave climates

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

- the significant wave height H_s (at the deep water boundary);
- the accompanying peak wave period T_p;
- the angle of wave approach θ_o;
- the storm-related set-up h_s;
- the fraction of occurrence of the combination of previous four parameters.

The wave climate consists of a distinct number of individual conditions for which the total fraction of occurrence equals 1. The longshore variation of the yearly wave climate is taken into account by relating a specific wave climate to a specific longshore position.

Using the yearly-mean wave climates as starting-point, the effect of long-term changes in the governing parameters such as wave heights and wave direction, can be taken into account by a correction of some of the parameters.

Tidal climates

The astronomical conditions are schematised using the mean features of the astronomical climate, viz. the vertical and horizontal tide. A local tidal climate is schematised as a limited number of individual tidal conditions, each having a specific percentage of occurrence. These individual conditions are described by:

- the astronomical water level elevation h_a;
- the accompanying longshore tidal velocity v_a;
- the 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.

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. The distribution of the tidal velocities over the profile is computed with the Chézy-equation.
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 later) to a specific longshore position. 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 corrections of the parameters. E.g. a gradual sea level rise is taken into account by adding the absolute change in the mean water level, denoted as $\Delta h_0(t)$, to the astronomical elevation h_a.

Transport formulations

Processes that have been schematised up to an acceptable level for the present version of the PONTOS-model are:

- the rate and distribution of the wave-induced cross-shore sediment transport;
- the rate and distribution of the wave-induced longshore sediment transport;
- the rate and distribution of the tide-induced longshore sediment transport;
- the effect of groynes on the longshore transport rate,

although some of these formulations will need some further improvement during a later stage of the model development.

The following processes have been conceptually developed and will be implemented in a later stage of the model development:

- refraction and shoaling of waves;
- diffraction around structures;
- flow contraction around structures like cross-shore dams.

In the following the main characteristics of both the cross-shore interaction and the longshore transport assessment is discussed briefly.

Cross-shore transport

The cross-shore interaction between the layers is based on the principle of a wave-based equilibrium profile. Deviations from this equilibrium slope result in a cross-shore exchange of sand between the layers. The rate of adjustment depends, amongst others, on relative water depth and local sediment characteristics. For both the equilibrium slope and the transport rates, formulations have been derived, partly based on empirical formulae and partly based on the results of a series of computations carried out with a process-based model. The process-based computations involved the main processes determining the cross-shore transport i.e. wave asymmetry, gravity and the undertow compensating for the mass-flux above the wave troughs. Relevant input parameters are wave climate and sediment characteristics [Steetzel, 1997a/b].
In the PONTOS-model, the wave-induced cross-shore transport $q_{y,w}$, for a specific hydraulic condition (water level and waves) at a certain depth is computed from:

$$q_{y,w} = q_o \; F_b \left(\frac{s}{s_e} - 1 \right) \left| \frac{s}{s_e} - 1 \right|^{\beta-1}$$

in which the s denotes the actual local bed slope and s_e refers to the local equilibrium slope and β equals 2.0. Due to the terms on the right-hand side, a relatively too steep slope, viz. $s > s_e$, yield offshore directed, viz. positive transport.
The F_b-function describes the relative transport rate as a function of the d / H_s-ratio according to:

$$F_b = \exp\left[\frac{-d}{\alpha \; H_s} \right]$$

in which α equals 1.5. The coefficient q_o was used for calibration.
In the following the equation for the term s / s_e will be derived.
In the model, the equilibrium slope s_e is expressed in terms of the offshore hydraulic conditions and the characteristics of the bed material.
For a concave cross-shore profile as a starting point, this function is schematised as:

$$s_e(d) = s_o \; F_s$$

in which s_o refers to the bottom slope at the water level and $F_s(d)$ describes the vertical variation assessed from:

$$F_s(d) = \left(1 + d / \alpha_s H_s \right)^{-\gamma}$$

The slope in the model at layer boundary Z_j denoted as s_j is assessed using the mutual distances between the two layers, according to:

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

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

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

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

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

yielding the source term for the assessment of the cross-shore transport rate $q_{y,j}$ as discussed before.

Longshore transport

Formulations for both the wave-induced and the tide-induced longshore transport are implemented in the model. These formulations are also based on series of computations carried out with a process-based model. Relevant input parameters are wave climate, horizontal and vertical tide and sediment characteristics.

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 an longshore current in the breaker zone mainly. The wave-induced transport rate mainly depends on the incoming wave energy and the direction of wave propagation relative to the coastline. For the assessment of the wave direction the offshore direction is used in the present set-up of the model. An approach to account for the effects of wave refraction will be taken into account in the next version of the model.

The total, viz. cross-shore integrated wave-induced longshore transport $Q_{x,w}$ for a specific wave condition and grid cell, is computed from:

$$Q_{x,w,j,i} = F_z\, c_{w,0} \left(H_s^{2.8} / D_{50}\right)(\phi_c - \phi_w)\exp\left(-c_2(\phi_c - \phi_w)^2\right)$$

in which ϕ_c denotes the orientation of a specific layer, ϕ_w the direction of the incoming waves and c_2 a constant. The coefficient $c_{w,0}$ is used for calibration.

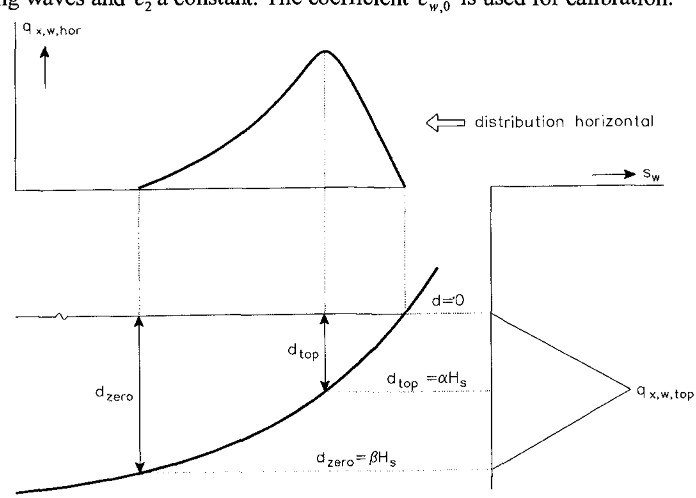

Figure 2: Shematization of wave-induced longshore transport

The above equation accounts for the total wave-induced long-shore sediment transport, which then has to be distributed over the different layers. In the present version of the model, this is schematised as a triangle, as illustrated in Figure 2. The fraction of the total transport present in a specific layer is defined by the factor F_z, with $0 \leq F_z \leq 1$. This factor is derived from the triangle schematization, depending on the level of the upper and lower boundary of the layer relative to the water level.

The distribution of this transport over the various layers is schematised as a triangle in the present version of the model, as illustrated in Figure 2 .
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.

The tide-induced transport, denoted as $q_{x,t}$, is determined by the tidal currents, and is furthermore affected by the water depth, the sediment characteristics, and the presence of waves (stirring up the sediment).
In the PONTOS-model, the tide-induced longshore transport $q_{x,t}$ for a specific hydraulic condition (water level, wave and tidal current) is computed from:

$$q_{x,t,j,i} = c_{t,0} \left(D_{50}\right)^{-2.2} \left(v_a\right)^4 \left[1 + 2\frac{H_s^{\,1.5} T_p}{d\, v_a^{\,2}}\right] \left(\frac{\Delta y}{\Delta z}\right)$$

in which the term in between squared brackets accounts for the effect of additional stirring due to the presence of waves and the coefficient $c_{t,0}$ is used for calibration..
The $\Delta y / \Delta z$-term on the right-hand side is needed to transform the transport rate per m^1 in cross-shore direction to a rate per m^1 in vertical direction needed for the layer-concept. To assess the transport in a specific layer, the computed rate has to be multiplied by the height of the layer (to be derived from the width in cross-shore dircction).

A simple formulation for wave diffraction has been defined to account for the modified wave field around structures. In a later stage it is envisaged to also defined and include the effect of flow contraction around structures [Steetzel and de Vroeg, 1997].

Conceptual validation

The present model has been conceptually validated for a large number of theoretic cases, specifically to check the mathematical implementation of the developed formulations. In addition, the following cases have been studied in more detail:

- the evolution of a cross-shore profile for individual waves and wave climates;
- the impact of changing tidal conditions (sea-level rise);
- the behaviour of a closed coastal section for perpendicular, oblique and spatially varying wave conditions;
- the effect of a single groyne;
- the effect of nourishments.

In Figure 3 as an illustration, the cross-shore evolution is given for an initially steep cross-shore profile using one single wave condition as a forcing agent.

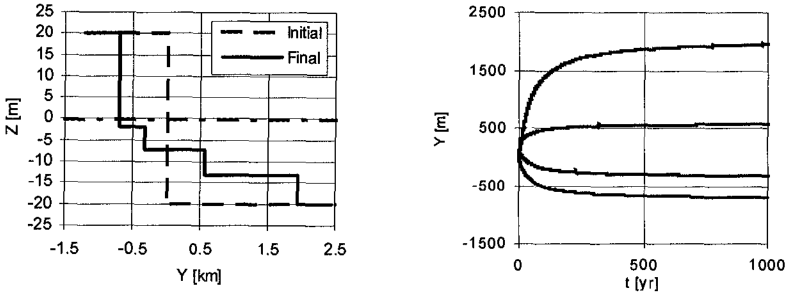

Figure 3: Cross-shore profile development

As can be seen from the right-hand panel, the final equilibrium profile is reached asymptotically in time. In addition to this relatively simple example the effects of wave climates, additional tidal climates, large-scale nourishments and sand mining, climate change and sea level rise have been studied in more detail.

Application of the pilot-version

The PONTOS-model is designed in such a way that it is generally applicable. A specific application has been carried out for a part of the Dutch coast. This application focuses on the uninterrupted coast, excluding therefore the delta coast in the south and the tidal inlets in the north of the Dutch coast. The goal of this application was to show the ability of the model to simulate the large-scale transport patterns along the Holland coast, taking into account the non-uniform wave and tidal climate [Steetzel et al., 1998].

Set-up

For the study of the Dutch coast using a multi-layer model, the overall contour of the whole Dutch coastline was schematised using a series of straight and curved lines.
The position and orientation of the coastline contours have been transferred to this new co-ordinate system, using this reference line and resulting in a stretched coastline. For the present application, the central Dutch coast (i.e. the Holland coast) was modelled in more detail, with the southern boundary at X_m = 98 km and the northern boundary at X_m = 208 km, resulting in a stretch of 110 km.
The layer positions were derived on the basis of the JARKUS data-set (dataset with results of yearly nearshore surveys with fixed rays). For this first model set-up the layer positions were determined for a number of specific JARKUS profiles (year 1990) in order to implement the main bathymetrical features of the Dutch coast in the model (See Figure 4).

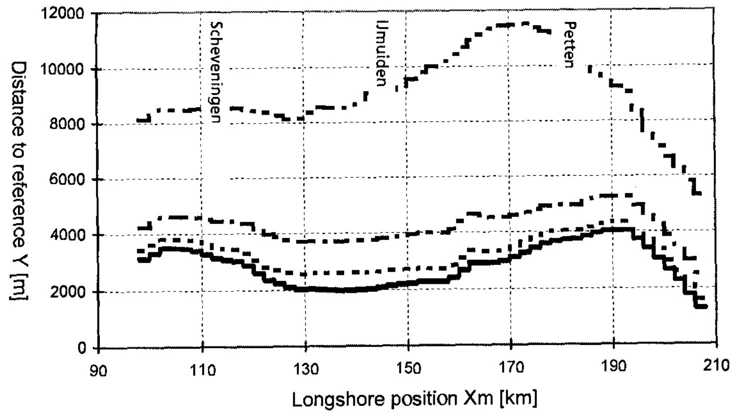

Figure 4: Overview of layer positions for the Holland coast.

The long-term wave data from the stations Light Vessel Goeree, Noordwijk and Eierland were used to schematise the along-coast varying wave climate.
The tidal climate along the coast was characterised by a "morphological tide". This is a tide which is considered to be representative for the neap-spring tidal cycle. In order to account for the non-linear relationship between the sediment transport and the flow velocities the tidal range of the morphological tide is somewhat larger than the mean tidal range. For this first application of the PONTOS-model for the Dutch coast, the basic computations were carried out with one representative tide for the entire central coast, as derived on a depth of NAP-8m near Noordwijk.

Calibration and verification

The simplified representation of the coastal structures does not allow for a detailed verification of the sediment balance and coastline development in the region next to these structures. For this reason both long groynes and harbour breakwaters have not yet been included in the verification of the model for the Dutch coast.

Verification and calibration of the model has been carried out in 4 steps:
- step 1 : Verification of the wave-induced longshore transports
- step 2 : Verification of the tide-induced longshore transports
- step 3 : Verification of the cross-shore transports
- step 4 : Verification of the sediment balance

Results

The basic runs for the longshore transports show promising results. Without any fine-tuning or calibration, the results show a fair similarity with the more detailed computations based on computations with a process-based model as presented by van Rijn (1995, 1997), see Figure 5. The transports in the upper part of the profile are

based on the wave-induced transports only. If the tide is included in the upper part of the profile, the net northward transports are somewhat larger.
If the effect of wave refraction between the seaward boundary and the breaker zone is included in the model, the resulting transports can be expected to change somewhat.

In the regions with the relatively gentle profile in the central section of the model area, the computed cross-shore transports are rather high. This can be expected on the basis of the cross-shore concept which is based on an equilibrium slope. The relatively small variations in the wave-climate along the coast do not justify the relatively large variations in the profile slope. It is expected that some calibration of the equilibrium

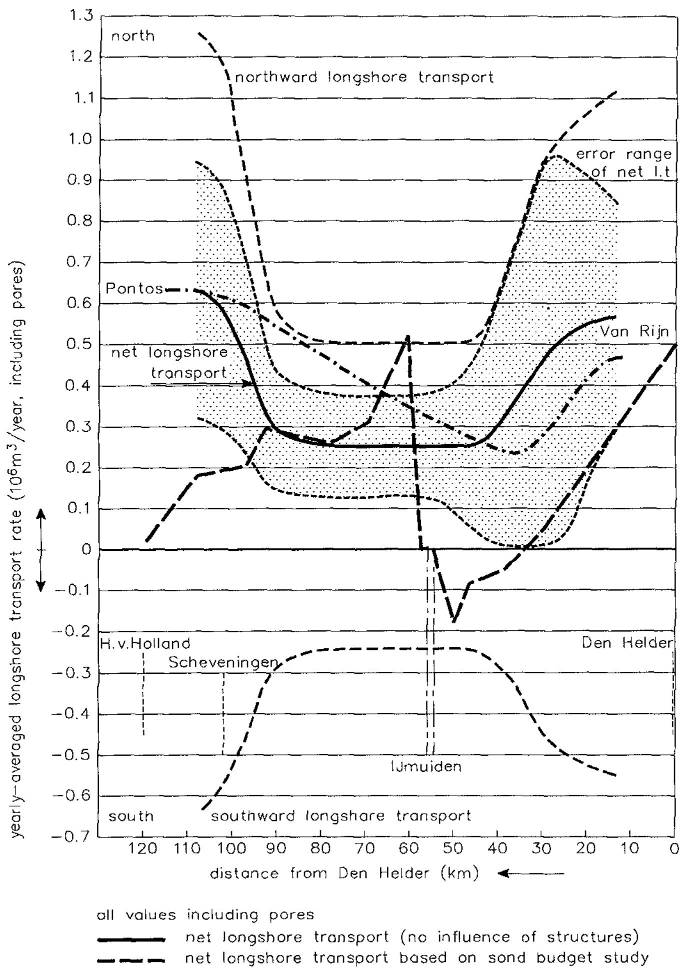

Figure 5: Comparison of computed wave-induced longshore transport [Van Rijn, 1995,1997].

slopes in some regions along the coast will be necessary for a fine-tuning of the model. Variations of the sediment size should be taken into account in a detailed verification.

The response of the model is as can be expected on the basis of the modelled processes. Considerable improvement is possible if the effect of structures is modelled in more detail. The results presented in Figure 6 give the impression that in that case fine-tuning of the model is very well possible.

Conclusions regarding the application

The first application of the pilot-version of the PONTOS-model for the central Dutch coast yields promising results. On the basis of simple schematization procedures for the wave- and tidal climate the direction and magnitude of the net yearly transports show a fair agreement with the results of the more in-depth study of van Rijn (1995, 1997).
For this first application of the model, attention has been focused mainly on the sediment transports. Detailed calibration of the model on the basis of the sediment balance was not yet possible, since some important effects were not yet included in the model. These are:
- the effect of wave diffraction around large structures;
- the effect of flow contraction around large structures;
- the effect of wave refraction;
- the interaction between tide- and wave-induced currents in the surf zone.

The above processes do partly affect the magnitude of the sediment transports and they all affect the sediment balances on a scale of kilometres to tens of kilometres. Implementation of the above mentioned effects is therefore necessary in order to be able to fine-tune the model on the basis of the detailed balances.

General conclusions

From the trial applications performed with the pilot-version of the model it was concluded that:
- the rather simple and straight-forward formulations of both the wave-induced as tide-driven longshore transport proved to be able to 'simulate' to a large extent the results of more complicated models;
- the way the cross-shore transport is taken into account in the model and specifically the explicit formulation of an equilibrium profile proved to have an advantage compared to standard approaches (especially for applications in which the interaction between cross-shore and longshore transport is complicated);
- the method of representing spatial and temporal climates seems to be an effective way to characterise the main driving forces of the model;
- the first application of the model for the Dutch coast yielded promising results;

on the basis of a simple schematization procedure for the wave- and tidal climate, both the direction and magnitude of net yearly transports showed a fair agreement with the results of a more in-depth study [Van Rijn, 1995];
- the behaviour-oriented multi-layer model provides a conceptual tool which seems to be able to 'model' to a large extent the evolution of a coastal system.

With respect to the conceptual approach it was concluded that:
- since both the longshore and the cross-shore transport processes are linked to the offshore hydraulic conditions, the effect of changing conditions (e.g. sea level rise) will be taken directly into account in the model and no other assumptions (e.g. Bruun-rule) have to be made;
- the use of more layers (compared to a single line-model) has the advantage that processes such as the bypass of sediment around the seaward tip of a groyne can be taken into account in a more correct way. However, the impact of structures for a case with more layers becomes far more complicated; in order to model this correctly, additional processes have to be accounted for);
- in a simple way both the effects of 'soft' and 'hard' management strategies can be taken into account, is an important advantage of the model as most of the natural coastal systems are influenced by human intervention; This makes it a useful tool for coastal management decisions;
- the auto-nourishment option (used to maintain at least a specific minimum shore line position by computational nourishments) proved to be a valuable tool to estimate the relative effect of structures and other human interference on the nourishment needs.

Future work

In order to update the present pilot-version of the PONTOS-model to a version that can be applied for practical cases, the following extensions are foreseen:
- to improve the input and assessment of the hydraulic conditions, the link between cross-shore profiles and layer schematization as well as the model output;
- to incorporate the processes which have been conceptually developed until now in an update of the mathematical model, yielding a version capable of simulating coastal evolution at a higher level of reliability;
- to improve the formulations for the interaction between tide- and wave-induced currents in the surf zone;
- to extend the model in seaward direction by adding one layer as a characterisation of the behaviour of the shelf, this in order to incorporate the effect of withdrawal of large quantities of sediment for land reclamation purposes;
- to perform a more integrated validation of the model concept.

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