COASTLINE MODELLING FOR NOURISHMENT STRATEGY EVALUATION

B.J.A.Huisman[1,2], Z.B. Wang[1,2], J.G. De Ronde[1], J. Stronkhorst[1] and C.J. Sprengers[1]

Abstract
Coastal zone managers in the Netherlands require new dedicated tools for the assessment of the long-term impacts of coastal maintenance policies. The policies need to be evaluated on the impacts on multiple coastal functions in order to be able to optimize the performance of such strategies. This paper provides the technical backgrounds of such a model. A combined approach with a modified Pelnard-Considere (1956) coastline model and an ASMITA model (Stive & Wang, 2003) was used for this purpose.

1. Introduction

A large part of the Dutch coastal zone consists of sandy beaches and dunes which are maintained with regular nourishments (Van Rijn, 1997). A policy called 'dynamic preservation' was adopted by the Dutch government in 1990, which preserves the coastline at its 1990 position by all means. This policy, however, results in a less dynamic coast, which is unfavorable for some coastal functions like recreation and nature values (Van Koningsveld and Mulder, 2004). Furthermore, the government is eager to find cost-effective nourishment strategies. It has therefore become desirable to come up with coastal maintenance strategies which include other functions than safety more prominently (NWP, 2009). This does, however, require the use of special models, as this is not covered by commonly applied model approaches in detailed process-based models (Lesser et al., 2004). Models for assessing the effectiveness of maintenance policies on the basis of their impacts on coastal indicators (like safety, nature values and recreation) and their costs are therefore needed. This paper describes the technical backgrounds of a new modeling approach for coastal zone management.

2. Model specifications

The new modeling approach has been applied in the Netherlands for the evaluation of coastal maintenance strategies in the framework of the new Delta programme, Building with Nature programme and the Alternative Long Term Nourishment Strategies project. Within these projects the typical requirements and specifications of the so called 'Nourishment impact tool' were set.

Spatially, the model needed to cover the whole Dutch coast and tidal basins of the Waddenzee. It needed to be able to deal with coastal maintenance strategies which differ with respect to their aims (e.g. which coastal sections should be maintained) and the practical realization (e.g. nourishment types, timing and locations). The strategies primarily use nourishments for coastal preservation, and therefore the model should be able to include the alongshore transport of sand at the coastal sections with beaches. Inclusion of multiple nourishments (i.e. nourishment strategy) in the model should be easy for the user. Furthermore, the model will need to be able to place nourishments based on requirements that are specified by the user. Thus, automatically computing required nourishment volumes for the maintenance of a coastline position. The basic effects of coastal structures need to be included, which concerns the (partial) blockage of alongshore sediment transport at harbour moles and the protection against erosion by revetments. Offshore losses need to be accounted for at locations in close proximity of tidal channels. Long-term coastal retreat as a result of sea level rise needs to be accounted for in the model. Furthermore, the

interaction between the coast and the dunes is of relevance for the models predictions for coastal indicators.

General requirements of the model concerned the need for a fast model, which allows the coastal manager to quickly gain insight into the envisaged impacts of maintenance strategies on coastal functions. Furthermore, automated post-processing of the results on relevant indicators for coastal functions is needed. The model needs to be flexible to include all these features in a simple way. The structure of the model code was setup in a very linear way in order to ease the use of the model (see Figure 1).
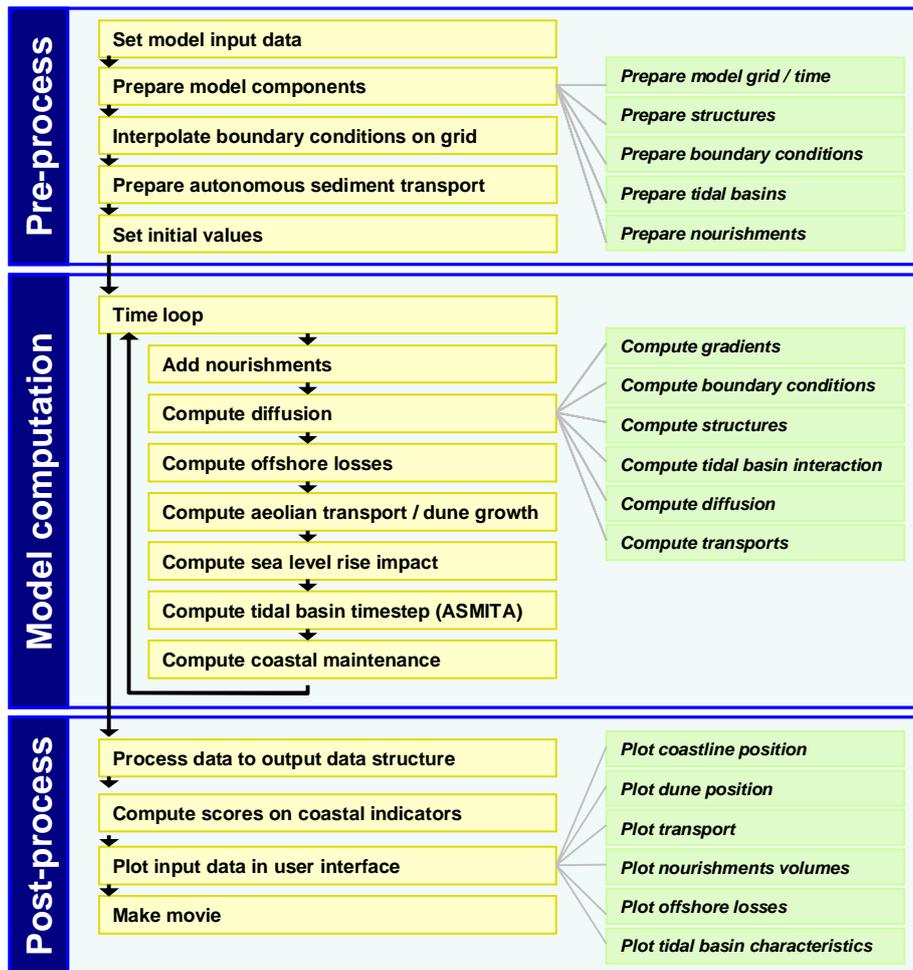

Figure 1. Flow-chart of the structure of the model

3. Model formulations

The large spatial and temporal coverage that is required for coastal maintenance models implies a requirement for the application of an aggregated modeling approach. The equilibrium approaches in behaviour type models are very robust and can very be compared quickly to process based models. A basic coastline model as suggested by Pelnard-Considere (1956) therefore forms the basis of the 'Nourishment impact tool'. This equation is extended with an additional term that includes the autonomous sediment transport ($Q_{LT, autonomous}$) and a term for the extraction or supply of sediment ($q_{sources/sinks}$), which can for example take place through nourishments, aeolian sediment transport and offshore losses.

$$\frac{\partial y}{\partial t} = \frac{\partial}{\partial x}\left(K \frac{\partial y}{\partial x} - \frac{Q_{\text{LT,autonomous}}}{H_{\text{active}}} \right) + \frac{q_{\text{sources/sinks}}}{H_{\text{active}}} \tag{1}$$

With:

x	*Longshore coastline position [m]*
y	*Cross-shore coastline position [m]*
t	*time [yr]*
K	*Diffusion coefficient, determining the spreading of sediment [m²/yr], with $K=D/H_{active}$ (D = Transport coefficient [m³/yr], H_{active} = Active height of the profile [m])*
$Q_{LT,autonomous}$	*Autonomous sediment transport [m³/yr]*
$q_{sources/sinks}$	*Rate of extraction and supply of sediment [m³/m/yr]*

The model disperses nourishments (and other perturbations) in alongshore direction over the coast. The cross-shore perturbation of the nourishment will decrease over time, as the area over which it is dispersed increases. The cross-shore distribution of the sediment within the surfzone is assumed to take place at much smaller time scales than the alongshore transport and is therefore considered to be instantaneously distributed over the active part of the cross-shore beach profile. Coastal structures like revetments and groynes can be included at specific locations along the coast. Furthermore, sediment exchange with the dunes, lower foreshore and tidal basins is included. The semi-empirical model ASMITA (Stive et al., 1998 and Stive and Wang, 2003) is used to compute the time scales of sediment import into the tidal basins. The applied process relations are described in the following paragraphs.

Transport coefficients

The diffusion coefficient (K) and autonomous wave-driven alongshore sediment transport were derived from transport computations with the UNIBEST-CL+ model (Van Rijn, 1997) for a large number of profile rays along the Dutch coast. Data from yearly bathymetrical surveys of beach transects (i.e. Jarkus coastline data) and nearshore wave data from a SWAN model were used (Deltares, 2010). The diffusion coefficient was estimated at 2 to 3 million m³/yr with an S-Phi curve for the Holland coast. Equation 1 then gives a linearization of the relation between the coast angle (with respect to the incoming waves) and longshore sediment transport (Figure 2).
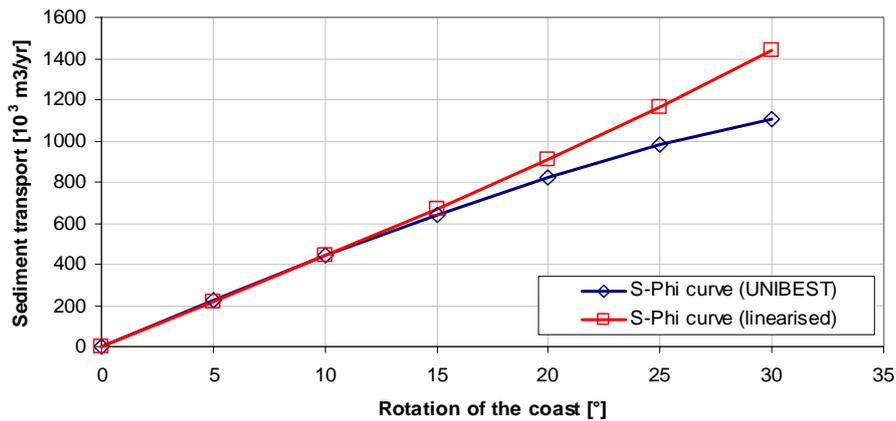

Figure 2. Linearised S-Phi curve for average situation along the Holland coast.

The resulting alongshore sediment transport is shown in equation 2.

$$Q_{LT} = -K \cdot H_{active} \frac{\partial y}{\partial x} + Q_{\text{LT,autonomous}} \tag{2}$$

An example of the applied autonomous sediment transport for different sections of the Dutch coast is presented in Figure 3. Deltares (2012) provides more detailed information on the derivation of autonomous sediment transport rates.
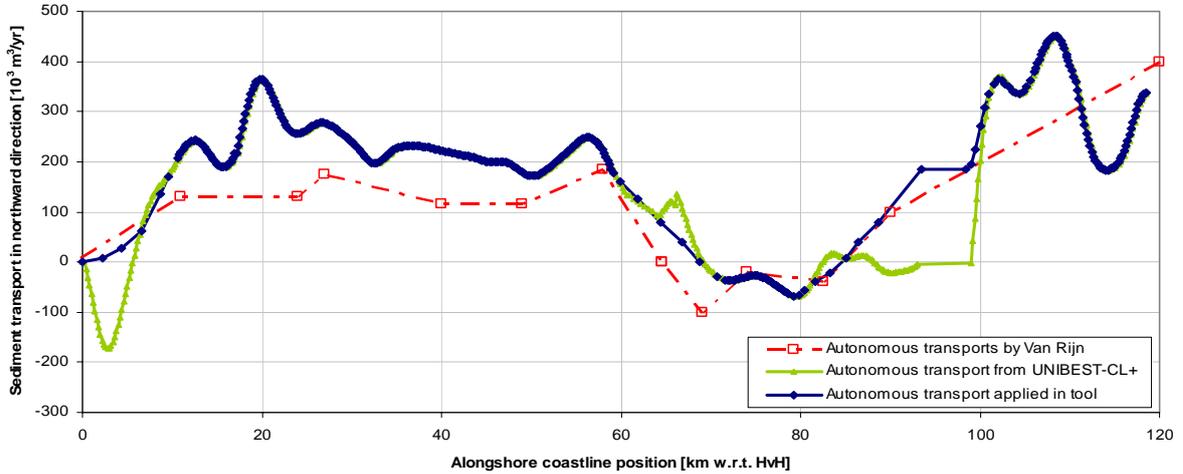

Figure 3. Example of the applied autonomous sediment transport along the Holland coast.

Boundary conditions
The formulation by Pelnard-Considere (1956) is evaluated in the model in a discretised way by means of an explicit scheme. This scheme is kept within a stable region by limiting the step size in the model through the following formulation:

$$dt \le \frac{dx^2}{2 \cdot K} \tag{3}$$

With:
dx   Minimum spatial step [m]
dt   Maximum stable time step [yr]

A couple of options can be used to set the sediment transport and coastline position at the model boundaries. These boundaries can either be closed to sediment transport, fixed to a certain coastline position or kept at the same coastline angle in time. Equations 4 to 6 show the boundary conditions for the left boundary. The right boundary has similar equations.

$$\text{Closed :} \qquad \frac{dy_{bound}}{dx_{bound}} = 0 \tag{4}$$

$$\text{Fixed :} \qquad \frac{dy_{bound}}{dx_{bound}} = \frac{dy_{i=1}}{dx_{i=1}} \tag{5}$$

$$\text{Angle constant :} \qquad \frac{dy_{bound}}{dx_{bound}} = 2 \cdot \frac{dy_{i=1,t=0}}{dx_{i=1,t=0}} - \frac{dy_{i=2,t=0}}{dx_{i=2,t=0}} \tag{6}$$

With:
i   Alongshore index of grid cells

Structures

Schematised harbour moles and revetments can be applied in the 'Nourishment impact tool'. Harbour moles (partially) block the local sediment transport. Full blockage by a structure is implemented in the model by setting a zero coastline gradient between the grid cell on the left and right side of the structure. A sediment bypass at the structures can be enforced by setting a coastline gradient over the structure instead of a zero gradient. Revetments are included in the model by specifying the longshore coordinates and a value for a 'threshold cross-shore position'. The cross-shore coastline position can not exceed the 'threshold cross-shore position' in landward direction. This is achieved by a reduction of the sediment transport gradients at the revetment when the cross-shore coastline position gets close to the specified 'threshold cross-shore position'. The actual availability of sediment determines the maximum outgoing transport (i.e. gradient in coastline orientation) in a grid cell. The model can deal with positive and negative gradients in the transport, as well as with transport divergence.

Nourishments

The coastal maintenance strategy can be included in the model through specification of a time-series of nourishments (i.e. properties like location, width and volume). Nourishments are added as a coastline change to the model. The cross-shore profile change due to the nourishment depends on the applied volume of the individual nourishment, the alongshore length of the nourishment and the specified active height of the profile. The effect of multiple nourishments is superimposed on each other.

Dune growth / erosion and beach width development

The transport of sediment from the swash zone to the beach and from the beach to the dunes is a very complex process that depends on numerous physical parameters. Arens (1994) describes various physical parameters that may impact aeolian transport. Additionally, De Vries et al. (2012) showed that supply limitations and bed armouring may have a large influence on aeolian transport rates. A verified model which includes all these physical parameters is not yet available. Therefore a simplified relation is adopted which includes the beach width, which is a parameter that implicitly includes some physically relevant parameters (like fetch length). The beach width (B) is used to compute the average dune growth rate (volume per year per meter length of the beach), which is the difference between the aeolian transport towards the dunes and erosion processes. It is assumed that the dune growth is in equilibrium at a critical beach width (B_{thr}). The formulation also contains a maximum growth rate (C_{max}) for infinitely wide beaches and a relaxation factor (B_{half}) which will determine the relation between the dune growth and beach width. Erosion of the coast is included by assuming that a minimum coastline width (B_{thr}) should be present. If the beach width is smaller than the minimum beach width (B_{thr}), a volume of sediment is transported instantaneously from the dunes to the beach (setting the beach width at the minimum coastline width). Equations 7 and 8 show the relations that are used for situations with dune growth and dune erosion. The estimated transport rate from the beach to the dunes is then used to adjust the coastline and dune face position.

$$\text{Dune growth:} \quad \text{if } B_{thr} < B: \quad q_{beach \to dune} = \max\left(C_{max} \cdot \left(1 - e^{-(B-B_{thr})/B_{half}} \right), 0 \right) \quad (7)$$

$$\text{Dune erosion:} \quad \text{if } B_{thr} \geq B: \quad q_{beach \to dune} = \frac{B_{thr} - B}{1 + \dfrac{H_{active}}{H_{active,dunes}}} \cdot \frac{H_{active}}{dt} \quad (8)$$

With:

$q_{beach \to dune}$ *Rate of dune volume change [$m^3/m/yr$]*

B	Beach width [m]
B_{thr}	Threshold beach width at which dune growth starts [m]
B_{half}	Relaxation time, defining the dune growth between zero and maximum transport [m]
C_{max}	Coefficient with maximum rate of dune volume change [m³/m/yr]
$H_{active,dune}$	Active height of the dune [m]

De Vries et al. (2010) recently investigated the historical changes in the beach width and the dune growth along the Holland coast. The dune growth trends varied from (roughly) 5-35 m³/m/year. The mean measured beach width along the Holland coast was 82 m, with more than 85% of all profiles within a 20 m range relative to this mean beach width. The current model therefore uses an average beach (B_{thr}) of 80 meter. The maximum aeolian transport rate is set at 80 m³/m/yr and the relaxation distance (B_{half}) at 150 meter. This results in dune growth rates of 0 to 40 m3/m/yr for the existing beaches along the Dutch coast.

Sea level rise
The effects of sea level rise are included in the model by means of the Bruun rule. This means that a landward shift of the coastline (eq. 9) is applied. This landward shift depends on the rate of sea level rise and the average slope of the cross-shore profile for which redistribution is expected in the considered time frame.

$$\frac{dy_{slr}}{dt} = -\frac{SLR}{\theta} \tag{9}$$

With:

y_{slr}	Position of the coastline [m]
SLR	Sea level rise [m/yr]
Θ	Average slope of the beach (1:slope) [-]
t	Time [yr]

Typical values that are used are a foreshore slope of 1:100 to 1:1000. A slope of 1:600 is used as a reference value for the foreshore, as it is expected that a considerable part of the profile may be influenced by profile reshaping due to sea level rise within a period of 90 years.

Offshore losses
Offshore losses are relatively small for most sections of the Dutch coast except for specific locations with narrow beaches and nearby tidal channels. The offshore losses at these specific locations should therefore be accounted for. For this purpose, the losses are assumed to be directly related to the seaward extension distance of the coastline and by a constant offshore loss factor for coastal sections with nearby tidal channels (equation 10 and 11).

$$if \ y_c > 0 \quad : q_{loss} = C_1 \exp\left(-C_2 \cdot (y_{offset} / y_c - 1)\right) + q_{loss,0} \tag{10}$$

$$if \ y_c \leq 0 \quad : q_{loss} = q_{loss,0} \tag{11}$$

With:

q_{loss}	Rate of offshore losses in time [m3/m/yr]
$q_{loss,0}$	Initial rate of offshore losses in time [m3/m/yr]
C_1	Coefficient with rate of offshore loss depending on coastline position [m3/m/m/yr]
C_2	Coefficient describing the non-linear increase of offshore losses [-]
y_c	Cross-shore coastline position [m]
y_{offset}	Width of the coastal profile [m] (e.g. distance between tidal channel and shoreline)

Default values used for this formulation are a C_1 of 400 m^3/m/yr and a C_2 of 1. An initial rate of offshore losses ($q_{loss,0}$) was estimated at the Oostgat (10 m^3/m/yr) and at the 'Onrust' (5 m^3/m/yr) on the basis of observed coastline retreat in the 'Dutch coastal trend charts' (RWS, 2009).

Interaction with tidal basins
The semi-empirical ASMITA model (Stive et al., 1998 and Stive and Wang, 2003) is used to compute the time scales of the impacts of coastal maintenance strategies on the development of the tidal basins. A total of six tidal basins is schematized into the model (Marsdiep, Eijerlandse Gat, Vlie, Amelandse zeegat, Pinkegat and Zoutkamperlaag). The empirical data for the models of the tidal basins of the Waddenzee were obtained from Kragtwijk (2001), who calibrated the applied ASMITA models for the tidal basins in the Waddenzee.

The interaction with tidal basins consists of wave-driven sediment transport from the coast to the basin at the boundary (Q_{LT}) and sediment bypass from the ebb-delta to the coast (Q_{bypass}). Figure 4 shows an overview of the interaction between the coastline models and ASMITA.
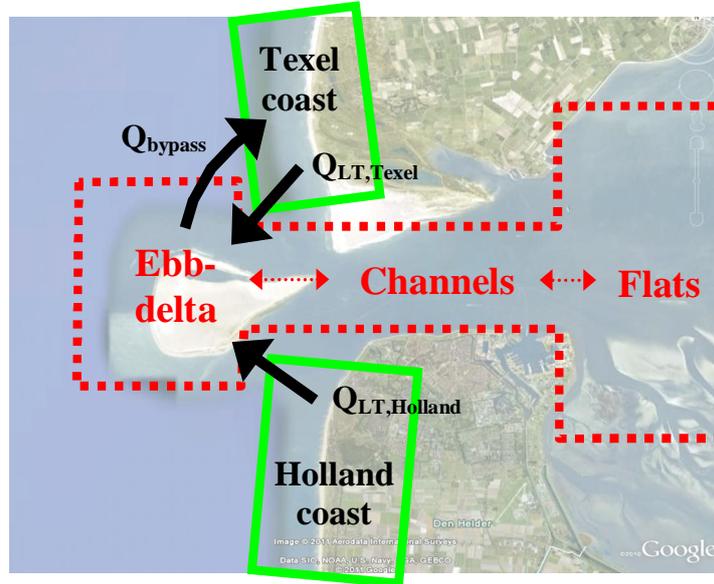

Figure 4. Interaction between tidal basin and adjacent coastline

The exchanged sediment is accounted for through a correction on the volume of the ebb-tidal delta ($dV_{ebb-delta}$) at every timestep of the coastline simulation (see eq. 12). This correction is, however, corrected for the autonomous influx of sediment (Q_{REF}) from the coast to the basin, as the calibrated ASMITA models for the Waddenzee basins do already include an exchange of sediment with the outside world (on the basis of a reference sediment concentration).

$$dV_{\text{ebb-delta}}(t) = (Q_{\text{LT}} - Q_{\text{bypass}} - Q_{\text{REF}}) \cdot dt \qquad (12)$$

With:

$dV_{ebb-delta}(t)$	*Correction of the ebb-delta volume in the ASMITA model at time step t on the basis of the difference between the actual and reference longshore transport and sediment bypass [m3]*
Q_{LT}	*Supply of sediment from adjacent coastal sections by longshore drift [m3/yr]*
Q_{bypass}	*Long-term averaged bypass of sediment from the ebb-delta to the adjacent coastal section(s) [m3/yr]*
Q_{REF}	*Reference sediment exchange from the coast to the basin [m3/yr] (uses initial rate)*

The sediment flux from the coast to the basin (i.e. Q_{LT}) is determined directly from the computed longshore sediment transport at the boundary of the coastline model (see equation 6). The applied boundary condition of the coastline model fixes the coastline position next to the basin, resulting in a sediment transport that is related to the coastline angle of the adjacent coast. The sediment flux from the basin to the adjacent coast (i.e. Q_{bypass}) is considered a constant as the total volume of the ebb-delta is not expected to change significantly. The applied values are shown in Table 1.

Table 1. Reference bypass volumes of considered tidal basins.

Basin name	Q_{bypass} [m³/yr]
Marsdiep	3.00E+05
Eierlandsegat	3.00E+05
Vlie	2.00E+05
AmelanderZeegat	2.00E+05
Pinkegat	5.00E+04
Zoutkamerplaag	5.00E+04

4. Model verification

The 'Nourishment impact tool' was applied for various verification cases. For example, the effects of different boundary conditions and structures were evaluated. One of these tests investigated the model diffusivity by means of a comparison of the computed coastline changes with the 'Nourishment impact tool' and the UNIBEST-CL+ coastline model. For this purpose, the diffusion of an initially disturbed coastline was modelled. Figure 5 shows the development of the coastline in time for both models. The computed impact with the 'Nourishment impact tool' is plotted with continuous lines and the UNIBEST-CL+ reference results are plotted as dashed lines. The model results showed good agreement of the diffusive processes in both models for a situation with three nourishments of 4 million m³.
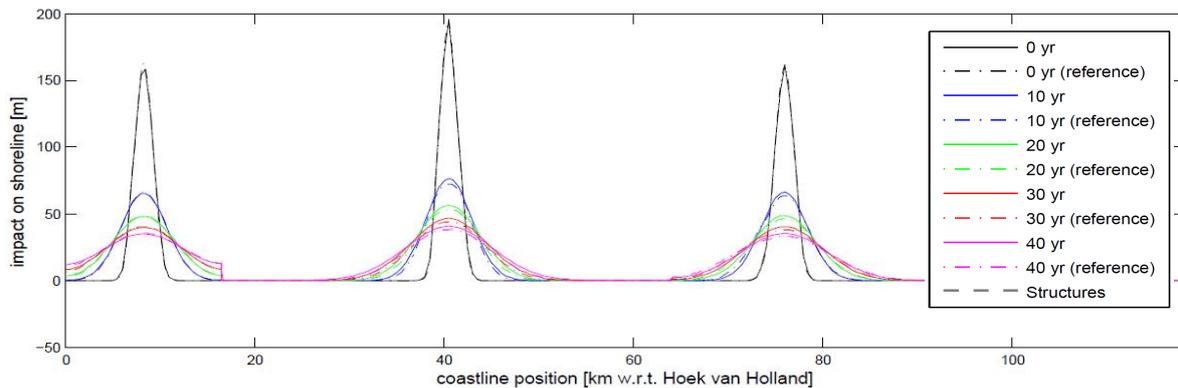

Figure 5. Coastline development and sediment transport in time for 3 initial nourishments of 4 million m³ each with the 'Nourishment impact tool' and the UNIBEST-CL+ as a reference model.

5. Model application

The 'Nourishment impact tool' was applied for the evaluation of various nourishment strategies at the Dutch coast. Typical output of the model consisted of the alongshore position of the coastline and dune foot position. Figure 6 shows an example of the estimated results of the continuation of the current maintenance policy for the period between the year 2010 and 2100.
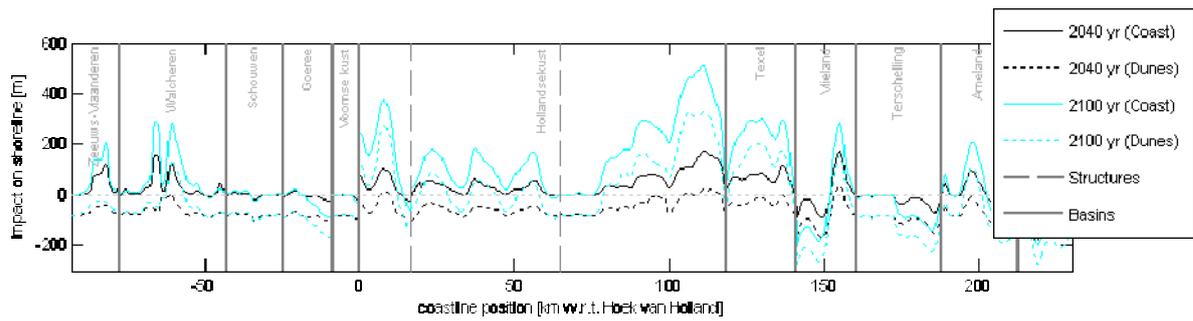
Figure 6. Example of the impact of a nourishment strategy that continues the current nourishment strategy

The impact of coastal nourishment strategies on a number of coastal indicators (i.e. dyke ring safety, safety of structures, drinking water, recreation, costs and sand mining) is then evaluated quickly by means of a post-processing spreadsheet. For this purpose, the physical parameters like the average coastline position, dune foot position and beach width at relevant locations along the coast were translated to impacts on coastal functions. Figure 7 gives an example overview of the impact of four maintenance strategies on three coastal functions. This method proved to be a very efficient way of evaluating the effects of coastal maintenance strategies.
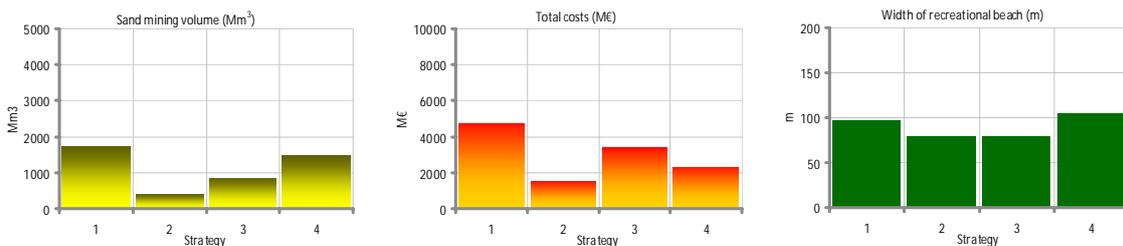

Figure 7. Example of the impact of the evaluation of the nourishment strategies on three coastal indicators

6. Conclusions and Discussion

This paper describes the setup of a new type of integrated model that can be used to quickly assess the impacts of coastal maintenance strategies (i.e. combinations of nourishments) for the whole Dutch coastline. It is concluded that:

- A behaviour oriented modelling approach is very suitable for long-term coastal impact studies. A combined approach with a modified Pelnard-Considere (1956) coastline model and an ASMITA model (Stive & Wang, 2003) was very useful in this study.
- Impacts of cross-shore processes, like sediment exchange with the dunes through aeolian transport and offshore losses, can be included in coastline models by means of simple process formulations.
- The assessment of the impacts of coastal maintenance strategies can be simplified considerably by means of automated post-processing routines which translate physical properties of the coast (like coastline position) to impacts on indicators of relevant coastal functions.

The main discussion with respect to the setup of these behaviour oriented modeling approaches relates to the knowledge basis that is available for the process relations. It is considered relevant to investigate the following items to gain more understanding of relevant coastal processes:

– Knowledge on the contribution of processes on aeolian transport at beaches is needed. This concerns aspects like wind conditions, aeolian pick-up and deposition, supply limitations (De Vries, 2012) as well as the influence of shells and moisture content.

– Means to assess offshore losses at beaches. More physical understanding should be obtained on the small net transports at the interface of the upper and lower shoreface and the influence of coastal nourishments on these transports. Furthermore, better understanding should be obtained on the influence of nearby tidal channels on the offshore transport.

– Very little is known on the interaction between tidal basins and the adjacent coastline sections. What complicates matters is that the modeling approaches for both areas do not fit in very well with each other. It is considered relevant to study the paths of the sediment that is transported from the coast to the tidal basin and their relative contribution to the delta, channels and flats.

– The link between indicators of coastal functions and the physical properties of the coast should be investigated in more detail.

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