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IMPACT OF BEACH STATES ON ALONGSHORE TRANSPORT

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Abstract

Impact of spatial variability in the nearshore bathymetry on net sediment transport rates has been investigated for a selection of observed beach states at the Dutch coast. The beach states comprise a longshore bar trough and two transverse bar rip situations, which were present at the large scale Sand Motor nourishment at the Holland coast. These observed bathymetric features were then applied multiple times next to each other along a longer stretch of coast to obtain a repeating pattern of the considered beach state. The wave transformation towards the shore, alongshore wave-driven and water-level setup driven currents and sediment transport were computed with the Delft3D model, which has been applied successfully for many other studies at the Sand Motor. It was found that net sediment transport is considerably influenced for the most pronounced transverse bar rip configuration, which was most prominent for conditions with small wave angles (i.e. less than 10° from shore-normal). Furthermore, a decrease in transport rates is found for conditions from larger angles of wave incidence (i.e. 30 to 45° from shore-normal). Impacts of the bathymetries of longshore bar trough and the less pronounced transverse bar rip system on net sediment transport rates were much smaller. The actual cause for the enhancement (or decrease) of the net transport for the transverse bar rip configuration is expected to be related to 1) the oblique orientation of the rip-channel for the considered configuration as well as to 2) a more diffusive pattern of the wave breaking as a result of the refraction on the spatially variable bathymetry.

Key words: hydrodynamics, sediment transport, beach state, numerical modelling, Sand Motor

1. Introduction

Various researchers investigated the inter-relation between beach states and environmental conditions, since the typical rip-bar patterns can significantly affect hydrodynamics (i.e. rip currents). Wright & Short (1984) made a classification of dissipative to reflective beach states of which the occurrence was inter-related with the dimensionless fall velocity parameter. Changes in the beach state typically take place gradually when the beach becomes more reflective (i.e. downstate sequence) and very abruptly during storms (i.e. upstate sequences) which can completely wipe out the three dimensional morphology (Lippman & Holman, 1990). Typically, a change towards a higher state will coincide with erosion of the beach while accretion takes place during a downstate (Ranasinghe et al., 2004). This inter-relation between beach state changes and morphological changes, triggers the question whether the beach states itself influences the alongshore sediment transport. It is well known that the steepness of the beach affects the transport rates (Kamphuis, 1986; Mil-Homens, 2013), but still uninvestigated whether alongshore variability of the beach state contributes to net 'beach state averaged' transport. This research aims at exploring the potential impacts of beach states on alongshore sediment transport.

The potential impact of beach states may also be of relevance for the reshaping of large-scale coastline perturbations such as the large-scale nourishments such as the 'Sand Motor', which was constructed at the Holland coast (the Netherlands) from April to June 2011. Considerable alongshore variability in the bathymetry was observed at the Sand Motor (Radermacher et al., 2017a; Rutten et al., 2017) after the initial

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reshaping of the hook-shaped planform to a bell-shaped bathymetry (De Schipper et al., 2016). A transverse bar rip system (TBR) was present on the (erosive) peninsula in the first years after construction and more dissipative beach states such as Longshore bar trough (LBT), Transverse bar trough and Rhythmic bar beach (RBB) on both flanks (Radermacher et al., 2017a). It is envisaged that these beach states may therefore have affected the wave-driven alongshore transport rates.

2. Methodology

This research uses the Delft3D model (Lesser et al., 2004) to assess the potential impact of three specific beach states on net alongshore sediment transport. The approach consisted of the following steps

1. Derivation of realistic beach states from measured bathymetries.
2. The selection of realistic hydrodynamic conditions
3. Assessment of hydrodynamics and sediment transport rates
4. Evaluation of the relative impact of the beach state

2.1. *Bathymetry*

The planform design of the 'Sand Motor' comprised of a hook-shape with a dune lake and open lagoon on the landward side (Figure 1) with an alongshore extent of about 2.5km and a cross-shore width of about 1 km at the waterline. A volume of 21.5 million m^3 was applied at the coast and at two small foreshore nourishments (Stive et al., 2013; Luijendijk et al., 2017). The initial cross-shore profile slope at the center of the Sand Motor was about 1:30 which was considerably steeper than the reference profile, which is characterized by an initial slope of 1:50 in the surfzone (from MSL to MSL -4m) and milder slopes (1:80 to 1:400) in deeper water. The foot of the nourishment attaches to the natural bed at a depth of about 10 meters. Bathymetric changes after construction of the Sand Motor were monitored at 1 to 3 month intervals.

Figure 1 : Aerial photograph of the Sand Motor after completion (September 2011)

Three realistic beach states were derived from the August 2013 bathymetric survey by extracting a section of beach from the bathymetry at the Southern, Central and Northern side of the Sand Motor. The selected bathymetric sample sets extended from MSL +2m to MSL -6m which are depth-contours that smoothly follow the shape of the large-scale perturbation. A nearly uniform Longshore Bar Trough (LBT) was observed at the Southern flank and Transverse Bar Rip (TBR) bathymetries at the Northern flank and Central Section of the Sand Motor peninsula (see Figure 2). The TBR bathymetries differed in the respect that the rip-channel and transverse bar were much more pronounced for one TBR than for the other. The TBR at the peninsula and northern flank of the Sand Motor are referred to as TBR1 and TBR2 respectively. It is noted that the observed beach states at the Sand Motor are quite persistent over time even though the coast is constantly eroding. The TBR1 beach state does therefore not fully classify erosive TBR, which is considered a temporary feature during an upstate transition (Price et al., 2011). These observed beach states were then used to create bathymetries for the model (Figure 3). This was achieved by creating an alongshore repetition of each of the observed beach states (i.e. an ‘alongshore variable bathymetry’). An alongshore averaged bathymetry was also constructed for each of the beach states, which was used as a ‘reference bathymetry’. It is noted that this reference bathymetry was different for each of the three beach states.

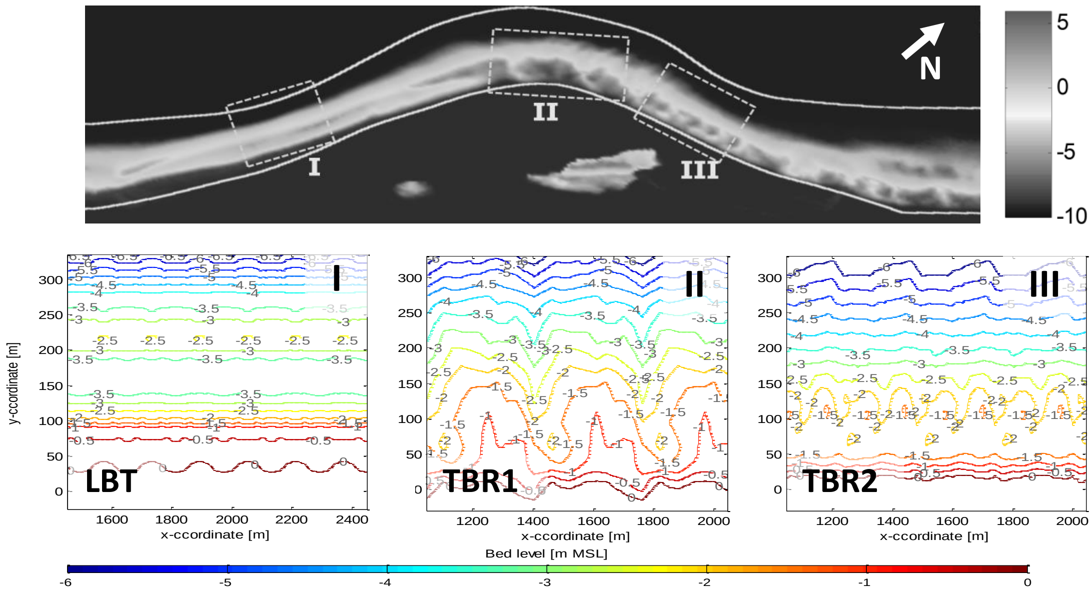

Figure 2 : Bathymetry of Sand Motor (top panel) and repeating pattern of the three selected beach states (lower panels).

2.2. *Hydrodynamic conditions*

The hydrodynamic conditions used in the numerical simulations mimic the conditions at the Southern Holland coast. The Holland coast wave climate is characterized by wind waves which originate either from the South-West (i.e. dominant wind direction) or the North-West (i.e. direction with largest fetch length). The wave climate is characterized by an average significant wave height (H_{m0}) of about 1 meter in summer and 1.7 meter in winter (Wijnberg, 2002) with typical winter storms with wave heights (H_{m0}) of 4 to 5 meter and a wave period of about 10 seconds (Sembiring et al., 2015). The most severe storms originate from the North-West and coincide with a storm surge of 0.5 to 2 meter. Offshore wave data at the Sand Motor are available at an offshore platform ('Europlatform') at 32 m water depth.

The horizontal tide at the Sand Motor is asymmetric with largest flow velocities towards the North during flood (about 0.7 m/s) and a longer period with ebb-flow in southern direction (about 0.5 m/s; Wijnberg, 2002). The tidal wave at this part of the North Sea is a progressive wave with largest flood velocities occurring just before high water. Tidal flow velocities at the Sand Motor are enhanced as a result of contraction of the flow (Radermacher et al., 2017b).

The current study applies a significant wave height (H_{m0}) of 1 m with a wave period (T_p) of 6 s, which covers the range of normal conditions. The wave direction was varied from -45 to +45 degree with respect to shore-normal. A selection of runs with a wave height (H_{m0}) of 1 m was also combined with tidal current velocities of 0.5 m/s. An average D_{50} of 278 μm was observed at the Sand Motor (Huisman et al., 2016) which was also applied in the model. The dimensionless fall velocity parameter ($\omega = H_b*T_p/w_s$) is about 5, which corresponds with a dissipative state according to Wright & Short (1984). With H_b the wave height at point of breaking [m], w_s the sediment fall velocity [m/s] and T_p the peak wave period [s].

2.3. *Assessment of hydrodynamics and sediment transport rates*

A Delft3D numerical model (Lesser et al., 2004) was used to compute the hydrodynamics and sediment transports. The model uses the phase averaged wave transformation model SWAN (Booij et al., 1994) to compute wave transformation and breaking in the full domain. The current velocities are computed using the non-linear shallow water equations, which resolve the wave-driven alongshore current and residual circulations and rip-currents due to water level setup (Bowen and Inman, 1970; Dalrymple, 1975). A rectangular model with a length of 5.5 km, width of 600 m and a grid resolution of 5m was used for this purpose (see Figure 3). Wave and water-level conditions were applied at the seaward boundary of the model, while tidal currents were included as a water level gradient (i.e. Neumann type boundary) at the lateral boundaries. The roller model (Svendsen, 1984; Nairn et al, 1990; Roelvink, 1993; Stive and De Vriend, 1994) was applied to distribute turbulence of the breaking waves over the surfzone. Roller and viscosity settings were calibrated using the nearshore ADCP and wave measurement stations at the Sand Motor by Radermacher et al. (2017c) and also applied in this study. The TRANSPOR2004 formulation was used to compute sediment transport as a result of waves and currents (Van Rijn et al., 2004; Van Rijn, 2007a; Van Rijn, 2007b). No bed updating was applied in the model. The model was run for 12 hours which was sufficient to obtain a steady transport pattern throughout the whole domain.

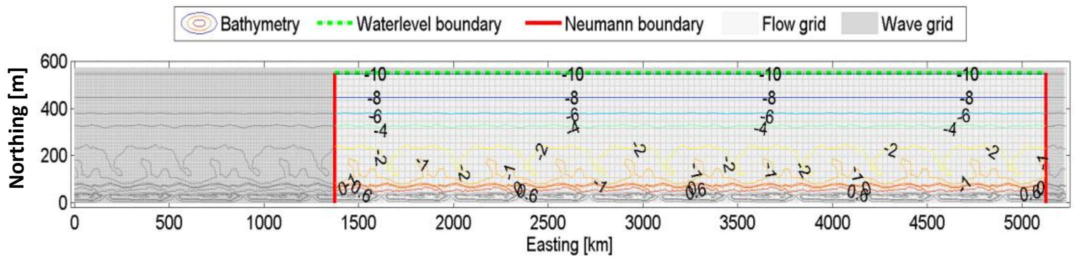

Figure 3 : Model grid and repetition of TBR beach state bathymetry for wave conditions from north-western sector. Note that wave grid was extended to the East for waves from the north-east.

2.4. *Evaluation of the relative impact of the beach state*

The impact of beach states on net alongshore transport was assessed by comparing the computed 'beach state averaged' alongshore transport rate of the 'alongshore variable' bathymetry ($Q_{S,AVG}$) and the net transport for the alongshore uniform 'reference bathymetry' ($Q_{S,uniform}$) for each of the considered beach states. For this purpose the alongshore component of the cross-shore integrated transport rate ($\overline{q}_{s,x}$) within the beach state is averaged over the length of exactly two beach states which are located in the middle of the computational domain.

$$Q_{S,AVG} = \frac{1}{2L} \int_{-L}^{L} \overline{q}_{s,x}(x)dx \quad (1)$$

Where x is the alongshore direction and L is the alongshore length of a beach state. $Q_{S,uniform}$ is computed in the same way as $Q_{S,AVG}$, but then for the alongshore uniform 'reference bathymetry'. The difference between $Q_{S,AVG}$ and $Q_{S,uniform}$ is considered a good proxy for the net impact of the beach state since it differentiates the impact of cross-shore profile shape from the effect of the 3D bathymetry.

3. Results

The Delft3D model was used to compute wave transformation on the bathymetry, alongshore currents (due to wave-driven processes and water-level setup) and subsequent transport. The nearshore waves and currents for a condition with 10° obliquely incident waves (from 350 °N) are shown in Figure 4, which is considered a condition which shows evidence of the most relevant hydrodynamic processes that are (sometimes to a lesser extent) also present for other wave incidence angles and wave heights. The wave transformation of the wave with H_{m0}=1m and dir=350°N shows a small increase of the wave height between y=100 to y=300 m, as a result of shoaling of the waves, after which a decrease is observed as a result of depth induced breaking. The wave dissipation for the LBT takes place mainly at the shoreline (i.e. gradient in wave height in Figure 4), while a more diffuse pattern of wave dissipation is observed on the transverse bar of the TBR beach states. Wave height is also found to be reduced in the rip channel for TBR1, which relates to the local refraction of the waves.

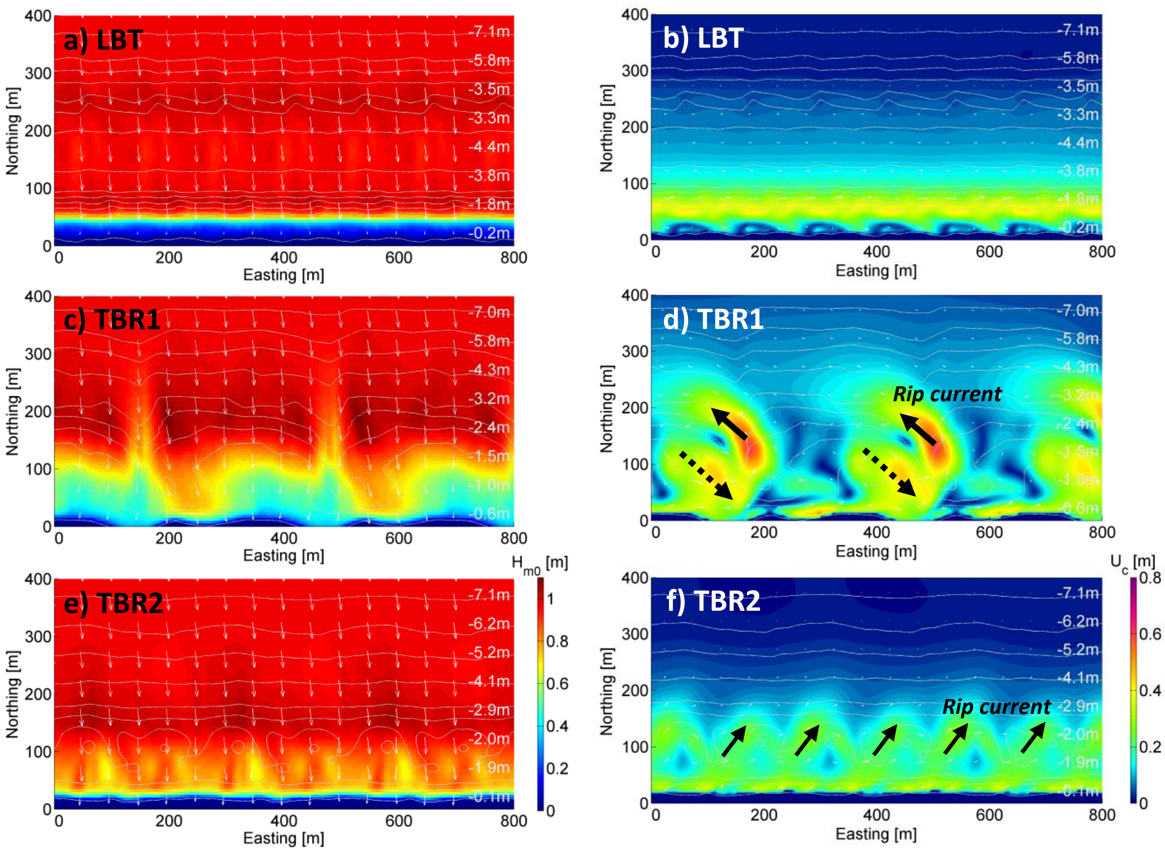

Figure 4 : Hydrodynamic conditions for the LBT, TBR1 and TBR2 beach states for a moderate wave condition (Hs=1m, Tp=6s and θ=350°N). Depth contours of the bathymetry are shown in gray. Left panels: Significant wave height; Right panels: Velocity magnitude.

A wave-driven alongshore current is generated (U_c of 0.2 to 0.4 m/s) near to the shoreline for each of the beach states (Figure 4b, 4d and 4f) as well as at the seaward edge of the transverse bars (Figure 4d and 4f), which is the result of the obliquely incoming waves. Noticeable is that the alongshore current at TBR2 is relatively well distributed along the seaward edge of the transverse bar, while the more pronounced TBR1 generates a local longshore current at the landward side of the obliquely oriented rip channel (see dashed arrow in Figure 4d). Additionally, a strong rip current of about 0.6 m/s is generated at the most pronounced transverse bar configuration (TBR1; see arrows in Figure 4d), while a much smaller rip current (~0.3 m/s) is generated at TBR2 (Figure 4f). It is noted that the residual circulations (and rip currents) are generally small compared to the alongshore current, but become relatively more important for waves with a small inclination from the shore-normal (i.e. less than 10°) for the more pronounced TBR1 beach state.

Sediment transport at the three considered beach states is primarily generated in the areas with wave dissipation (i.e. gradients in the wave height pattern in Figure 4) which are located near to the shoreline as well as at the seaward edge of the transverse bar (Figure 5a to 5c). It is noted that the TBR1 configuration especially shows local longshore transport at the landward side of the rip channel during conditions with relatively shore-normal wave incidence (Figure 5b), which was also depicted in Figure 4d as a region with a strong longshore current. Transports at the 'updrift' side of the transverse bar are, however, relatively small which is the result of a locally smaller angle of wave incidence and subsequent smaller local current velocities (Figure 4b).

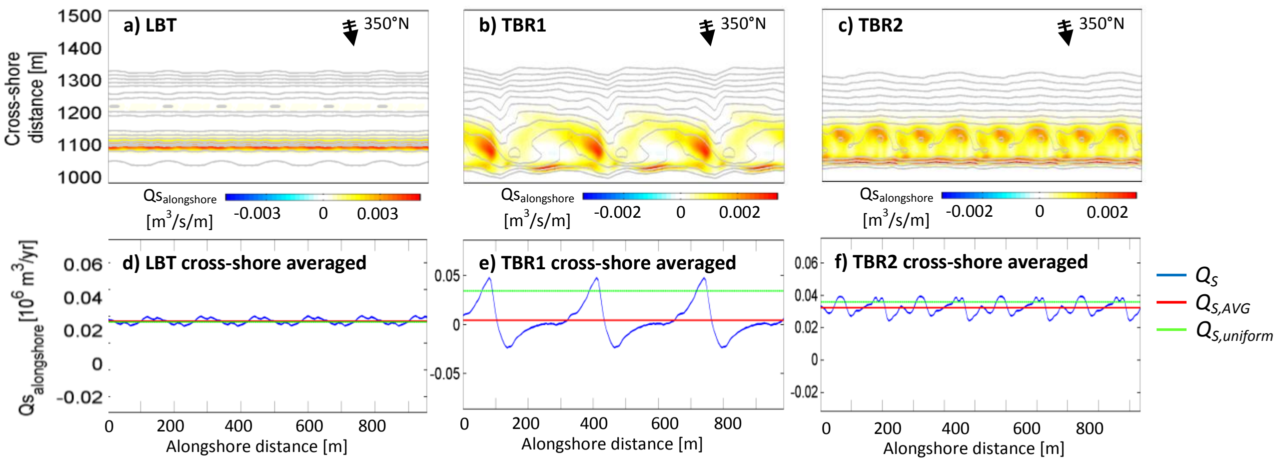

Figure 5 : Computed transport rates for the LBT, TBR1 and TBR2 bathymetries for a moderate wave condition (Hs=1m, Tp=6s and θ=350°N). Upper panel: spatial transport field (positive towards the East). Lower panel: Cross-shore integrated alongshore transport of the complex beach state (blue line), beach state averaged transport (red line) and alongshore uniform bathymetry (green line).

Cross-shore averaged transport rates were computed for each of the considered beach states (blue line in Figure 5d to 5f) which results in repetitive pattern of net longshore transport with local enhancement and reduction of the transport at the location of the rip channel. The 'beach state averaged' transport (red line) of the transverse bar rip configurations was found to be smaller than the transport of the alongshore uniform bathymetry of the considered beach state (green line), while the LBT configuration provides similar transport rates as the alongshore uniform bathymetry. These results show that the net beach state averaged alongshore transport rates can be affected considerably by the alongshore variability of the beach state as present at TBR1 and TBR2 (see Figure 5e and 5f).

A reduction of the transport is also shown for waves from a larger angle of incidence for TBR1 (Figure 6a and 6d), which is expected to be related to the spreading of wave energy on the platform of the transverse bar which is located between MSL-2m and MSL-1m. A net transport in the direction of the rip channel may even occur for shore-normal incident waves at TBR1 (Figure 6b and 6e). Tests with a higher wave height (H_S=1.5m) gave similar transport patterns, but then with a slightly enhanced reduction of the net transport (Figure 6c and 6f). Noticeable is that most of the transport is generated at the western side of the rip-channel (towards the East) and at the entrance of the rip-channel (in westward direction).

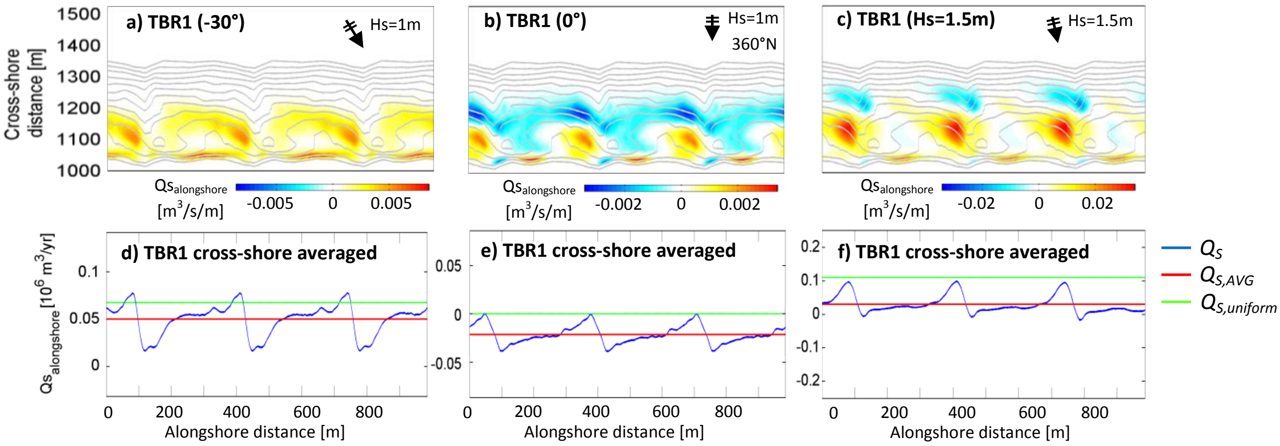

Figure 6 : Computed transport rates for the TBR1 bathymetry for an oblique wave condition (Hs=1m, Tp=6s and θ=330°N), shore-normal condition (Hs=1m, Tp=6s and θ=360°N) and somewhat more energetic wave condition (Hs=1.5m, Tp=6s and θ=350°N). Upper panels: spatial transport field (positive towards the East). Lower panel: Cross-shore integrated transport of the complex beach state (blue line), beach state averaged transport (red line) and alongshore uniform bathymetry (green line).

The relative impact on the net 'beach state averaged' alongshore transport can be summarized for each of the considered beach states with a relation between the incident wave angle and the net 'beach state averaged' transport ($Q_{S,AVG;}$ Figure 7) which can be compared to the transport rate for a uniform beach profile ($Q_{S,uniform}$).

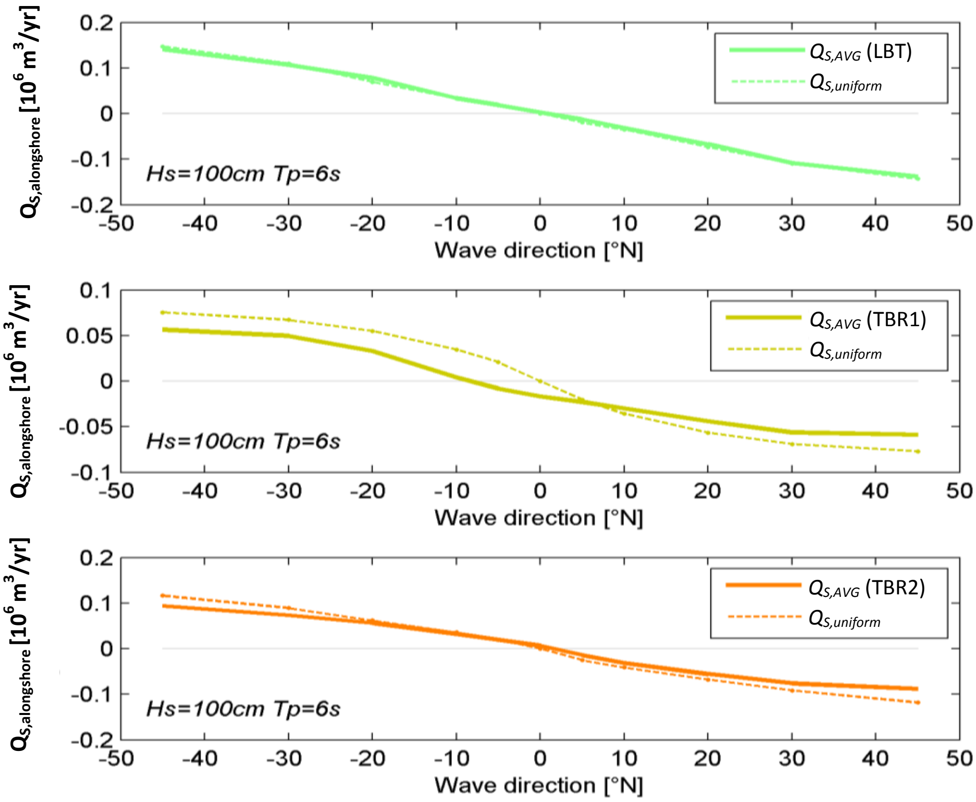

Figure 7 : Relation between relative wave incidence angle and net 'beach state averaged' alongshore sediment transport for the LBT (upper panel), TBR1 (middle panel) and TBR2 (lower panel).

The overview in Figure 7 shows that the 'beach state averaged' alongshore transport ($Q_{S,AVG}$) is reduced considerably for the alongshore variable TBR1 configuration, while a much smaller impact is observed for the less pronounced TBR2 configuration and no impact for the LBT. The reduction of the transport at TBR1 is especially relevant for smaller wave angles (i.e. within 10° from the equilibrium angle), where even a reversal of the direction of the net transport may take place. Residual circulations and rip currents are expected to be the cause of the change in net transport at smaller wave angles. The reduction of the transport rates for TBR1 at larger wave angles (i.e. 20° or more from shore-normal) is expected to relate to the attenuation and refraction of the waves on the submerged part of the transverse bar which effectively results in a wider area with wave breaking (i.e. similar to a milder sloped beach). In summary, it is observed that net alongshore transport can be impacted considerably for bathymetries with large alongshore variability.

4. Discussion

The strongly alongshore variable Transverse Bar Rip (TBR) bathymetry at the peninsula of the Sand Motor was found to have a large impact on net sediment transport rates, while the other bathymetries had a very small impact. This suggests that the precise configuration of the bathymetry is of relevance for triggering a mechanism that reduces or enhances alongshore transport rates. Based on the findings from the current model it is expected that the mechanism which enhances (or decreases) the net transport at the transverse bar rip configurations is the related to 1) the oblique orientation of the rip-channel for the considered TBR1 configuration as well as to 2) a more diffusive pattern of the wave breaking and refraction on the spatial variable bathymetry. In the first case, a partially alongshore directed rip-current is generated during conditions with a relatively shore-normal wave incidence angle. The velocities of the rip-current can be of similar order of magnitude or even equal to the alongshore current, thus generating a transport in direction of the (obliquely oriented) rip channel, which was the case for TBR1. The second situation relates to more obliquely incident waves (i.e. more than 10° with respect to shore-normal) which are reduced as a result of a spreading of the wave energy over the considered beach state (i.e. more distributed area with wave breaking) resulting in a decrease of the maximum transport rates. Additionally, the alongshore current velocities at the seaward edge of the transverse bar may be reduced as a result of the time and space it takes for the current to accelerate.

It should, however, be accounted for in the interpretation of the results that alongshore variable bathymetries will adapt to the prevailing conditions (i.e. due to morphological changes), which means that an impact on net alongshore transport of a complex beach state may change over time. Typically, it is expected that morphological changes as a result of obliquely incoming waves will reduce the alongshore variability of the beach, although this morphological aspect was not investigated explicitly in this study. Morphological changes are, however, expected to take place at a longer time-scale (days to months) than the changes in hydrodynamic conditions which may take place within a few hours. The reduced or enhanced transport conditions can therefore also be considered to be inheritance of the previous conditions which shaped the alongshore variable bathymetry. The preceding condition, which generated the rip-bar patterns, can be a situation with relatively shore-normal wave incidence (Reniers et al., 2004a) but may also be the result of tidal contraction or eddies at the Sand Motor (Radermacher et al., 2017b).

It is expected that the alongshore variability of the bathymetric configuration has a considerable influence on the impact of the beach state on net transport rates, which is shown from the lower impact of the TBR2 bathymetry. The results for a given bathymetry were, however, not very sensitive to the wave and water-level conditions and model settings. The influence of the representation of the hydrodynamics was investigated both with and without the roller model, which resulted in a similar pattern of changes, although more pronounced impacts were found using the roller model which is considered the most accurate method. The precise influence of the roller on bed shear stresses, concentrations in the water column and vertical distribution of the roller energy (Reniers et al., 2004b) and infra-gravity motions (Reniers et al., 2006) was not investigated in this research and can be considered of relevance for future research. Tide was not included in the models, but a preliminary simulation with a constant alongshore current of 0.5 m/s has shown that a similar (relative) reduction in transport rate is achieved for the TBR1 for a situation with a small wave angle. It is envisaged that a more somewhat more smooth spatial transport pattern will be present for situations with tidal forcing, since more capacity is available to suspend and transport the sediment reducing the relative importance of waves for the total alongshore transport.

Spatial variation of the bed sediment composition at rip-bar cells (Gallagher et al., 2011) may also have an effect on the transport rates, since a local coarsening of the bed may for example reduce the transport in the rip-channel to some extent. A clear coarsening of the bed of the rip-channel was, however, not observed in the measurements of bed composition at the Sand Motor (Huisman et al., 2016), which is expected to relate to the strong erosive gradients which prevent a coarser top-layer from developing.

Implications of the findings on the potential impact of beach states are that alongshore sediment transport at beaches with very pronounced beach states may be enhanced or reduced compared to the assumption of an alongshore uniform beach profile. This is especially relevant in view of the typical tendency of process-based area models to flatten out the beach bathymetry and sub-tidal bars (e.g. Van Duin et al, 2004).

5. Conclusions

Impact of spatial variability in the nearshore bathymetry on net sediment transport rates has been investigated for a selection of observed beach states at the Dutch coast. The beach states comprise a longshore bar trough and two transverse bar rip configurations. These observed bathymetric features were then applied multiple times next to each other along a longer stretch of coast to obtain a repeating pattern of the considered beach state. Sediment transport rates along the beach state were computed with the Delft3D model.

The present study shows that net sediment transport rates can be impacted considerably by the alongshore variability of the beach bathymetry, which was especially the case for the Transverse Bar Rip (TBR) at the center of Sand Motor nourishment. Impact on net sediment transport rates is largest for situations with low-angle waves (i.e. less than 10° from shore-normal), but a decrease in transport rates is also found for conditions from larger angles of wave incidence (i.e. 30 to 45° from shore-normal). The impact of the bathymetries of longshore bar trough and the less pronounced transverse bar trough on net sediment transport rates is much smaller.

The potential impact of a complex beach state (with a pronounced rip-bar configuration) on the net alongshore transport for situations with obliquely incident waves should be regarded as a temporary state, since obliquely incident waves will affect the morphology of the beach.

The actual cause for the enhancement (or decrease) of the net transport for the transverse bar rip configuration is expected to be related to 1) the oblique orientation of the rip-channel for the considered configuration as well as to 2) a more diffusive pattern of the wave breaking as a result of the spatially variable bathymetry and refraction of the waves on the transverse bar.

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