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The role of sediment transport processes in shaping offshore sand waves

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ABSTRACT

Sand waves, large scale dynamic bedforms, which are found on sandy, shallow seabeds worldwide, present an immediate risk to offshore structures, raising a pressing need for predicting related bed level dynamics on decadal timescales. Numerical models can help us understand and predict sand wave dynamics, but have shown difficulties with preserving sand wave shapes. Using the process-based Delft3D Flexible Mesh model, we have found that the choice of sediment transport formulation has a significant effect on the stability of sand wave shapes. The widely used Van Rijn (1993) sediment transport formulation predicts relatively high bed load transport rates, thereby raising a need for more dominant slope-induced transport. The simulations revealed that the Van Rijn (2007) formulation, which predicts relatively lower transport rates, and thus allows for lower bed slope-induced transports, is better capable of preserving the steep slopes of sand waves, while limiting sand wave growth. By considering various shape characteristics in our model assessment, more insight is gained about the improvements as well as adverse effects of changes in the parameterization of physical processes. These characteristics show that only with the less dominant bed slope-induced transport the crest levels are stable, while trough levels still lower slowly over time. This indicates that local processes are responsible for limiting the growth of sand waves and the importance of slope-induced transport has been overstated in previous works. With the adapted, non-upscaled set-up, the evolution of sand waves over multiyear timescales is represented well in the model compared to bathymetric field data for two contrasting sand wave field sites.

1. Introduction

The interest in marine and coastal zones is increasing at a rapid pace. These shallow offshore areas are highly suitable for various functions, such as the production of green energy, the transportation of goods and the mining of sand. Especially with the energy transition, population growth and climate change, expanding to these areas may offer solutions for the challenges we face in the future. For these purposes knowledge about the seabed, which is the foundation of all structures in these areas, is vital. The seabed is not flat, but covered with various dynamic bedforms, ranging from several centimetres up to kilometres in size, which may be a danger to our offshore constructions and shipping. Especially sand waves, which have wavelengths of several hundreds of metres, heights of several metres (Damen et al., 2018) and can migrate up to tens of metres per year (Van der Meijden et al., 2023), can be a risk for offshore activities (Morelissen et al., 2003). Sand waves, also known as marine dunes, are found throughout the world and show a large variation in characteristics and dynamics (e.g. Damen et al., 2018; Bao et al., 2014; Van Landeghem et al., 2009). Through data analysis and numerical modelling we are increasing our ability to understand these variations between different areas and over different periods in time. Data analysis shows that the maximum sand wave height can be related to water depth (Van Landeghem et al., 2009) and that sand wave shapes can be related to their migration rates (Knaapen, 2005). This sand wave migration is in turn driven by tidal asymmetry and residual currents, as is shown through data analysis (Van der Meijden et al., 2023) and numerical modelling (Besio et al., 2003, 2004). Numerical simulations have also shown that time-varying residual currents, such as wind- and density-driven currents, can cause significant variations in erosion and deposition rates in sand wave bathymetries over time (Overes et al., 2024).

Although these studies have provided vital insights into the nature and dynamics of the sand wave system, predicting future seabed levels in sand wave areas remains challenging. All the while the necessity of these predictions is growing due to, among others, major upscaling

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Table 1
Morphological settings in previous Delft3D sand wave models studies. For sediment transport formulations see: Van Rijn (1993), Van Rijn (2000) (adaptation of 1993) and Van Rijn (2007). Bed slope formulation and bed slope parameter based on Bagnold (1966), see Eq. (2).

Reference	Sediment transport formulation	Bed slope parameter α_{bs}
Liang et al. (2022)	Van Rijn 1993	2
Leenders et al. (2021)	Van Rijn 2007	3
Krabbendam et al. (2021)	Van Rijn 1993[a]	5
Damveld et al. (2020a) and (2020b)	Van Rijn 2007	3
Wang et al. (2019)	Van Rijn 2007	1–1.4
Van Gerwen et al. (2018)	Van Rijn 1993	3
Borsje et al. (2013) and (2014)	Van Rijn 1993	2.5
Tonnon et al. (2007)	Van Rijn 2007	1, 3, 5

[a] Slightly adapted version of the sediment transport formula is used.

of offshore wind energy. To fulfil this need data analysis is now commonly used to provide future bed levels and related uncertainties (e.g. Deltares, 2016). However, these methods are purely based on measured historic sand wave migration and cannot account for human interventions, environmental changes and extreme events.

Numerical models, on the other hand, can offer a more comprehensive way to understand and predict sand wave migration and changes in shape. Moreover, contrary to data analysis, these tools can predict the impact of environmental changes and human interventions. However, applying these numerical models to in-situ sand wave cases has proven to be difficult. Krabbendam et al. (2021) tried hindcasting sand wave migration at multiple locations in the North Sea using a calibrated Delft3D model. The model was calibrated for one location using a bed slope-induced transport parameter (α_{bs}) and a sediment transport multiplication factor. Combining a bed slope parameter (α_{bs}) of 5 with downscaling sediment transport by 50%, provided the lowest Root Mean Square Error (RMSE) between measured and modelled bed levels for the calibration transect. Although the calibrated model gave reasonable results for this transect, the predictions on other transects showed more deviations. Especially when sharp-crested sand waves were present, this combination of parameters resulted in reshaping of the sand waves through a reduction in sand wave crest height and slope steepness, while troughs deepened. Other studies where sand wave growth towards equilibrium is simulated (Van Gerwen et al., 2018; Damveld et al., 2020b), also show that although wave lengths match quite well, the ultimate shapes do not resemble any of the typical sand wave shapes found in observations (see for example Van Landeghem et al., 2009), which do not show broad flat troughs combined with rounded crests.

It is not surprising that sand wave shapes are not properly maintained in the state-of-the-art sand wave models (resulting in changes in slope steepness, height and crest and trough levels), since they have often been simplified (or idealized) in previous modelling studies. Instead, calibration and validation efforts have focused on sand wave heights and lengths (e.g. Campmans et al., 2022), and the morphological and sediment transport processes which shape these bedforms remain poorly understood. These processes can influence sand wave shapes by for example limiting the maximum slope or reducing sediment transport in certain areas. Sand wave shapes are thus directly affected by the basic representation of bed load rates and their slope-induced modifications in the model. For river dunes under unidirectional flow the representation of sediment transport has already shown to be instrumental for the resulting dune shape (Lokin et al., 2023). However, the importance of the choice of bed load and bed slope-induced transport formulations for tidal sand wave shapes remains undiscovered. An inventory of several state-of-the-art Delft3D sand wave models, shown in Table 1, reveals that the representation of these transport-related processes varies widely between studies. Different bed load transport formulations are used and especially the bed slope parameter (α_{bs}), which is known to influence sand wave growth (Borsje et al., 2014) and bed form steepness (Pessanha et al., 2023), varies widely between the studies. However, in none of these studies attention is given to the effects of these changes on sand wave shapes.

Representing sand wave shapes is of the essence to predict bed level changes on both short- and long-term. Since there is often a quick adaptation of the modelled bed levels to the imposed boundary conditions and physical parameterizations (Krabbendam et al., 2021), these bed level changes can drown out any short term adaptation due to actual physical processes. This complicates the assessment of for example single storm impact on sand waves, since these numerical adaptations are (at least) of the same order of magnitude as the actual response to a single storm. On the long term these numerically induced shape changes can complicate estimations of migration rates, due to the related horizontal position changes of crest and trough. When the slope of the sand wave becomes milder, this causes the crest and trough to be further apart, thereby inducing positional changes of these morphological points which are often used to assess true migration rates.

The misrepresentation of sand wave shapes in numerical models may easily be overlooked when using a single error statistic to judge the accuracy of the results. The RMSE, for example, is known to favour smooth results over those which represent bed forms well, but show a mismatch in migration rate (Bosboom and Reniers, 2014), thereby favouring an increase of diffusive processes, such as bed slope-induced transport. Instead of searching for the holy grail in terms of parameter settings, by optimizing for one error statistic, we should thus increase our understanding of the inner workings of these processes. By looking at various aspects of sand wave characteristics, such as height, slope and crest and trough level, simultaneously, we can gain insights into the interactions between sediment transport processes and these characteristics. Furthermore, we can then recognize parameterizations which may improve our representation of certain morphological aspects of the sand wave system, while having adverse effects on others. This can be the basis for a systematic exploration of what processes we might still be overlooking. Lastly, using this knowledge more informed decisions can be made for model calibration, significantly reducing the efforts needed.

The goal of this study is to understand the impact of the way we parameterize sediment transport processes on the development of sand wave shapes and thereby improve the ability of our morphological models to predict in-situ sand wave dynamics in different areas. To this end we will apply the 3D morphological model Delft3D Flexible Mesh (FM), in a non-upscaled manner (i.e. without morphological scaling), to test the ability of different parameterizations to reproduce sand wave morphology, particularly their shapes, at two contrasting field sites. The ability of the simulations to retain sand wave shapes will be assessed through various shape measures, which capture the various mismatches observed in previous studies.

2. Methods

2.1. Sand wave field sites

To allow for a wider understanding of the importance of sediment transport processes in shaping sand waves two field sites with contrasting sand wave shapes are chosen, both situated in the Dutch North Sea.

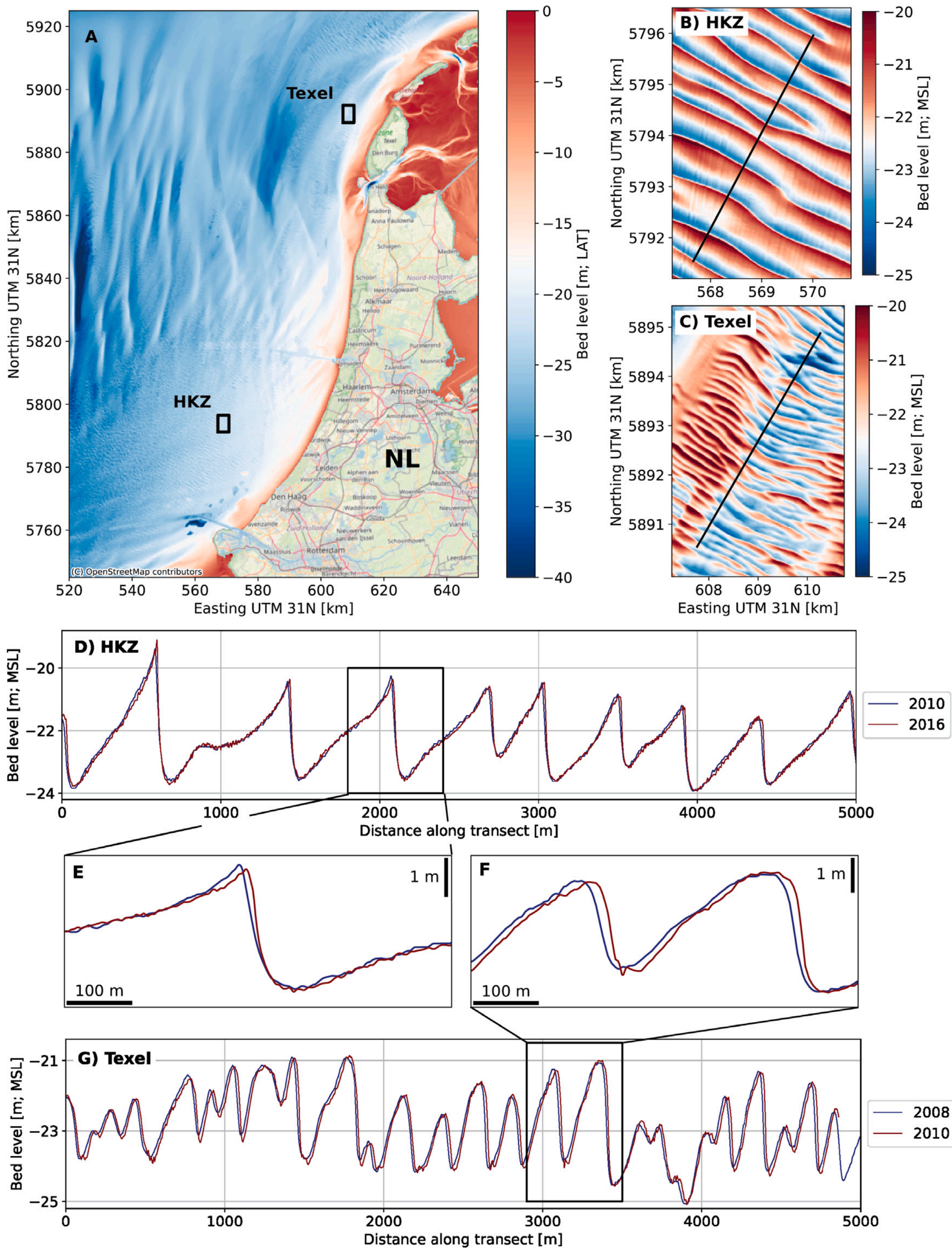

Fig. 1. (A) Locations of the two study sites with respect to the Netherlands (NL), (B) 2012 bathymetry measurement at the HKZ site, including chosen transect, (C) 2008 bathymetry measurement at the Texel site, including chosen transect, (D) measured sand wave bathymetry profile along the HKZ transect, (E) zoom of HKZ transect bathymetry, (F) zoom of Texel transect bathymetry and (G) measured sand wave bathymetry profile along the Texel transect.

The study sites are based on Overes et al. (2024). Fig. 1 shows the locations of these sites as well as the measured bed levels. The first site is located in the HKZ wind farm zone and includes highly asymmetrical, saw-tooth shape sand waves. The sand waves retain their shape over the years, although some steepening can be observed. The mean slope steepness increases from 0.036 m/m to 0.039 m/m (2.0° to 2.2°), while the maximum slope steepness increases from on average 0.091 m/m to 0.129 m/m (5.2° to 7.4°). The sand waves are highly asymmetric, with an asymmetry index (see Supplementary Materials for definition) of on average 0.7. The migration rate is generally low and estimated at 1–2 m per year (Van der Meijden et al., 2023). The second site is located near the island of Texel and includes more rounded, moderately asymmetrical sand waves. The data shows that the sand waves retain their shape while migrating at a significant speed of around 10 m per year. Here, the mean slope steepness increases from 0.031 m/m to 0.033 m/m (1.8° to 1.9°), while the maximum slope steepness increases from on average 0.078 m/m to 0.097 m/m (4.5° to 5.6°). The sand waves are moderately asymmetric, with an asymmetry index of on average 0.5.

At both study sites Multibeam Echosounder (MBES) bathymetry data is available from the Netherlands Hydrographic Office of the Royal Dutch Navy (NLHO). The data from NLHO can be accessed via Deltares (2017) and has a horizontal resolution of 5 m. For the HKZ site, MBES data is available through this source for 2012. This data is supplemented with a dataset from 2016, which was measured to aid wind farm development and has a resolution of 1 m (Fugro and Deltares, 2018). This data is available at RVO (2018). At the Texel site NLHO provides MBES data from 2008, which is supplemented with 2010 MBES data from Rijkswaterstaat. The Rijkswaterstaat dataset showed a vertical offset relative to the NLHO data. The magnitude offset differed per MBES survey line. Since the survey is measured in approximately the same direction as the model transect, the 2010 bathymetry data is corrected with the averaged offset over this transect, by lowering it with 16.6 cm. Additionally, ADCP measurements have been carried out at a location along the HKZ transect over the period between June 2016 and June 2018. These measurements have been used by Overes et al. (2024) to validate the currents and waterlevels in a 2DV sand wave model, which has the same hydrodynamic setup as the models applied in this study.

2.2. Modelling software

The Delft3D Flexible Mesh (FM) model software (Deltares, 2025) is used to simulate hydrodynamics and morphodynamics in the sand wave areas in this study. The Delft3D FM model has recently been developed as the successor of Delft3D (version 4) which is extensively applied for sand wave research (see Table 1). The main advantages of Delft3D FM over Delft3D-4 are the ability to use unstructured grids (flexible meshes) and to carry out parallel simulations on multiple computational nodes. These improvements allow for more efficient model runs. In the models used in this study this results in a 13 times speedup of the simulation, relative to Delft3D-4. The physical basis remains the same between the models and is briefly described in the following sections. For a more detailed description of the model reference is made to the user manual (Deltares, 2025). For this research the 2023-03 release of the software was used.

2.2.1. Hydrodynamics

To solve the hydrodynamics the Delft3D FM model applies the shallow water equations, which include a continuity equation and momentum equations in three directions. The horizontal scales are assumed to be much larger than the vertical one, thus allowing for reducing the vertical momentum balance to the hydrostatic pressure. To include sub-grid turbulence processes the $k-\epsilon$ turbulence closure model is included. This set of equations is solved using a finite volume solver, which is applied on a staggered grid. The time integration is done explicitly, apart from the water levels, leading to the need of a Courant limitation based on flow velocities for the timestep, which is implemented automatically based on a user defined Courant number.

2.2.2. Sediment transport

To compute the bed load transport resulting from near bed currents different sediment transport formulations are available in Delft3D FM. Especially the Van Rijn transport formulations are widely used in sand wave modelling (see Table 1). This can be explained by the fact that these formulations meet the following three requirements for simulating sediment transport in sand wave environments. Firstly, these formulations compute bed load and suspended load transport separately, which is necessary due to their contrasting effects on sand waves (Borsje et al., 2014). Secondly, they use the bed shear stress to compute sediment transport rates, thereby capturing the effect of the sand waves on the near bed velocities. Lastly, these formulations have been validated for the type of sediments and environmental conditions similar to those found in offshore sand wave areas. A review of the 16 available sediment transport formulations in Delft3D FM showed that only the Van Rijn equations (Van Rijn 1984, 1993, 2007 and Soulsby–Van Rijn, see Deltares, 2025) meet these three requirements (Van Rijn, 1984; Van Rijn, 1993, 2007; Soulsby, 1997). It should be noted that other sediment transport formulations (not implemented in Delft3D FM) may also meet these requirements. Moreover, sediment transport formulations which do not meet these requirements may still be able to simulate sand wave dynamics in specific conditions or with limited accuracy.

To get insight into the effects of alternative sediment transport formulations on sand wave characteristics and dynamics, we will thus compare the results of two Van Rijn transport formulations, which are widely used in sand wave modelling. For this comparison we have chosen the latest transport formulation: Van Rijn 2007 (VR2007) (Van Rijn, 2007) and its predecessor: Van Rijn 1993 (VR1993) (Van Rijn, 1993), both of which have been applied in numerous sand wave modelling studies (see Table 1). The Van Rijn 1993 bed load transport formulation (when excluding waves) implemented in Delft3D FM uses slightly different tuning parameter values than the original formulation, based on additional research by Van Rijn (2000), see Supplementary Materials for the details. The VR2007 transport formulation assumes a lower bed friction for sediment transport, relative to VR1993. Moreover, in this transport formulation the threshold bed shear stress for sediment transport includes bed slope effects and is lowered when the modelled shear stress is close to this threshold. The latter is done to allow for limited transport in these cases based on measurements by Paintal (1971). The combined lower bed friction, added bed slope effects and lowered threshold of motion for VR2007 result in lower transport volumes and a higher threshold velocity relative to VR1993 on a flat bed (see Van Rijn et al., 2004), although for VR2007 both are now dependent on the bed slope. The formula schemes for the transport formulations used in this study are included in the Supplementary Materials.

Bed load transport is the dominant transport mode at the field sites, as is demonstrated by the local Rouse number, which varies between 3.5 and 6 for spring and neap tidal conditions respectively (Fredsøe and Deigaard, 1992). Moreover, this is corroborated by the presence of sand waves, which are dampened by suspended sediment transport (Borsje et al., 2014). For simplicity suspended sediment transport is thus excluded from the simulations. The bed load transport is scaled to account for bed slope effects using the α_s factor as follows:

$$\vec{S}_b = \alpha_s \vec{S}'_b \tag{1}$$

Where $\vec{S}_b$ is the scaled bed load transport and $\vec{S}'_b$ is the unscaled bed load transport following one of the transport formulations (see Supplementary materials). α_s is calculated using:

$$\alpha_s = 1 + \alpha_{bs}\left(\frac{\tan(\phi)}{\cos\left(\tan^{-1}\left(\frac{\partial z}{\partial s}\right)\right)\left(\tan(\phi)+\frac{\partial z}{\partial s}\right)} - 1\right) \tag{2}$$

Where ϕ is the angle of repose of the sediment, which is set at 30° and $\frac{\partial z}{\partial s}$ is the slope of the bed in the transport direction. This calculation is based on (Bagnold, 1966) and includes a possibility for scaling using the user-defined α_{bs} factor. In Delft3D FM the default value for the α_{bs} factor is 1, which reduces the formula to the original equation as proposed by Bagnold (1966). For higher values of α_{bs} the effect of bed slope-induced transport increases. The development of the bed level due the calculated bed load sediment transport is solved using the Exner equation:

$$\left(1-\varepsilon_p\right)\frac{\partial z_b}{\partial t} + \frac{\partial S_{b,x}}{\partial x} + \frac{\partial S_{b,y}}{\partial y} = 0 \tag{3}$$

Where ε_p is the porosity of the bed, which is assumed to be 0.4, and $\frac{\partial z_b}{\partial t}$ is the derivative of the bed level to time. This bed level derivative is balanced with the change in sediment transport over the horizontal dimension.

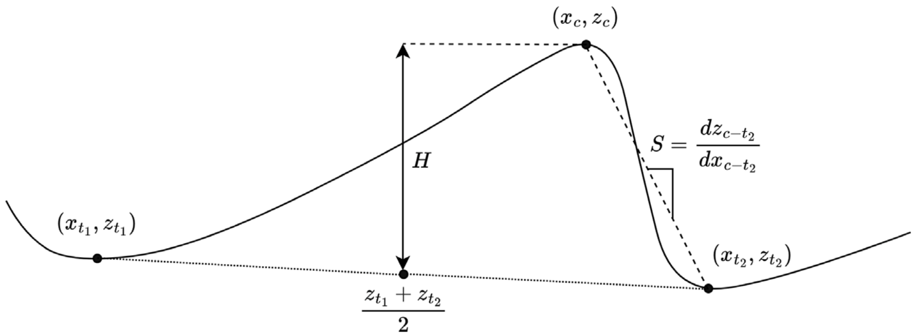

Fig. 2. Sand wave shape characteristics used for assessment: height (H) and average slope (S), based horizontal distance along transect (x) and bed level (z) for the one crest (c) and two trough (t) points (trough points numbered in migration direction)

2.3. Sand wave model set-up

2.3.1. Computational mesh and bathymetry

At the two study sites sand wave models are set up. Since the along crest currents and bathymetric variations are limited at the chosen locations (see Fig. 1 and Overes et al., 2024), the along crest direction is left out of the model to reduce computational efforts. The horizontal x direction is aligned with the direction of the maximum tidal currents which is approximately perpendicular to the sand wave crests. This horizontal direction also aligns with the migration direction of the sand waves (Deltares, 2016). Since the model includes vertical layers, which are needed to accurately simulate the influence of the sand waves on the hydrodynamics, the models have a 2 Dimensional Vertical, or 2DV, setup. The lateral boundaries are closed. At the far ends of the 16 km long domain two open boundaries are included. Here the hydrodynamics are forced through offline coupling with the Dutch Continental Shelf Model (DCSM) (Deltares, 2018).

In the central region of the domain, sand waves are included over a length of 7 kilometres. At the edges of the domain these sand waves are dampened out towards the large scale bathymetry from the DCSM. In this way the water depth matches between the models at the boundaries and the effect of the sand waves on the hydrodynamics is built up gradually. The sand waves in the initial bathymetry are based on MBES measurements from 2012 at the HKZ site and 2008 at the Texel site. In the 7 km long sand wave domain the HKZ and Texel site models include 8 and 16 full size sand waves respectively (see Supplementary materials). To remove the superimposed megaripples, which cannot be represented accurately due to the chosen model resolution, a one dimensional highpass Fourier filtering is applied, based on a wavelength of 15 m.

Due to the presence of steep slopes in the sand wave bathymetry (as illustrated in Fig. 1), a horizontal grid resolution of 2 metres is adopted within the sand wave zone, in accordance with Van Gerwen et al. (2018). Toward the boundaries, outside the sand wave domain, the grid resolution increases to nearly 400 m, growing with a factor 1.1 per cell from the original 2 metre resolution. The vertical grid comprises of 40 sigma layers, with layer thickness increasing exponentially from 0.1% of the water column at the bed to 11.4% at the surface. Detailed layouts of both horizontal and vertical grids are provided in the Supplementary Materials.

2.3.2. Hydrodynamic forcing conditions

To allow for morphological validation of model results a hindcast is performed, where the simulation runs from one bathymetry measurement to the next. The imposed hydrodynamic forcing is obtained through a hindcast run of the regional Dutch Continental Shelf Model (DCSM), spanning 2012–2016 at the HKZ site and 2008–2010 at the Texel site. This regional model is widely validated using measured hydrodynamics (see Deltares, 2018). The 2DV sand wave model is forced using a velocity timeseries at the inflow boundary of the dominant tidal current (SW at both sites) and a waterlevel timeseries at the opposite side (NE). This setup is based on Overes et al. (2024), who validated the hydrodynamics using ADCP measurements. This validation showed a good match for velocities and waterlevels. Although the ADCP measurements were not available for the time period considered in this study, the hydrodynamics in the 2DV models are compared to those from the regional DCSM, which shows a good match for both water levels and current velocities (see Supplementary Materials).

2.3.3. Parameter settings

The vertical turbulent eddy viscosity is determined using the k-epsilon turbulence model, following Borsje et al. (2013). A background horizontal eddy viscosity of 0.1 m^2s^{-1} is adopted. . The maximum flow Courant number, which dictates the timestep, is set at 0.7. A uniform sediment size is assumed, which consist of a single fraction, with a log-uniform distribution. A median grainsize d_{n50} of 350 μm is selected for both study sites, based on local measurement data, see Damen et al. (2018). The bed roughness is characterized using a Nikuradse roughness height of 0.03 m. This roughness height is based on the presence of ripples, with an average length (λ_r) of 0.17 m (as observed by Damveld et al., 2018) and an average ripple height (Δ_r) of 0.017 m, assuming a steepness (H/L) for current ripples of 0.1 (Van Rijn, 1993). The ripple roughness is calculated using the formula proposed by Van Rijn (1993) ($k_{s,r} = 20\gamma_r\Delta_r(\Delta_r/\lambda_r)$) and combined with the grain roughness ($k_{s,grain} = 3d_{90}$, $d_{90} = 1.5d_{50}$). A quick sensitivity test showed only marginal sensitivity of the morphological results to the bed roughness for both sediment transport formulations. Table 2 provides an overview of the main model parameter settings. Morphological scaling is not employed (i.e., a morphological scale factor of 1), following Overes et al. (2024), which means that in these non-upscaled simulations the hydro- and morpho-dynamics are calculated using the same timescales. Runs are performed with both the Van Rijn 1993 (VR1993) and the Van Rijn 2007 (VR2007) transport formulation (for details see the Supplementary materials). Different values are used for the bed slope correction parameter, based on previous sand wave models (see Table 1). We included the following values in the simulations: α_{bs} = 0.5, 1, 2, 3, 4 and 5.

Table 2
Overview of model characteristics and parameter settings.

Parameter	Symbol	Value	Unit
Horizontal grid size	Δx	2	m
Nikuradse bed roughness	k_s	0.03	m
Horizontal eddy viscosity	ν_H	0.1	m^2s^{-1}
Maximum Courant number	–	0.7	–
Median sediment grain size	$d_{n,50}$	350	μm
Bed slope parameter	α_{bs}	0.5–5	–

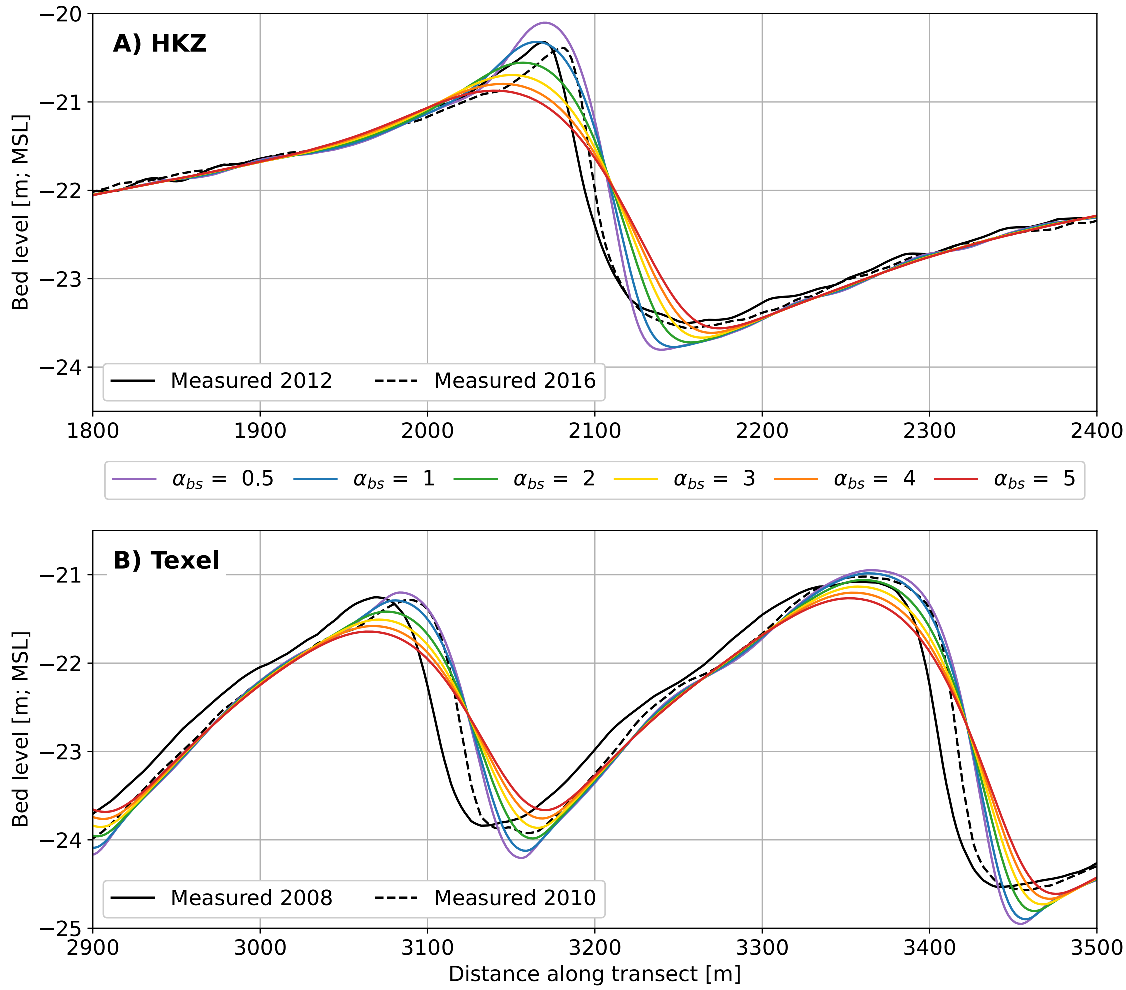

Fig. 3. Measured and modelled bed levels at the end of the simulation period (2016 for HKZ and 2010 for Texel) using the VR2007 sediment transport formulation, combined with a varying value for α_{bs}. The initial measurement is used as the starting bathymetry for the model. Megaripples are filtered from the measurements.

2.4. Method for assessment of model results

To avoid biases of specific error statistics and to properly assess the different aspects of sand wave shapes for which mismatches have been observed in previous model studies (e.g. Krabbendam et al., 2021 and Overes, 2021), various metrics are used to judge the model skill. The most important mismatches found in previous studies are a reduction of the slope steepness of the steep slope, changes in crest and trough level and a mismatch of height. To assess these characteristics, the following sand wave shape measures are chosen: height, average slope steepness of the steep slope and crest and trough level. At the considered locations the steep slopes of the sand waves are found on the side towards which the sand waves migrate, which is north-east for both locations (right in the plots). The chosen metrics are assessed for each full sand wave in the model transect. The individual sand waves are defined between two sand wave troughs: local minima with a distance of one wavelength in between. The crest of the sand wave is the highest point in between these two troughs. To arrive at assessment criteria for sand wave shapes, firstly the height (H) of the sand wave is calculated as the average vertical distance between the crest and the two troughs, see Fig. 2. Since this quantity does not discern between trough and crest changes also the variations in these specific levels (z_c and z_t) are tracked. The steeper slopes of the sand waves are found facing the ebb current in both transects. At these slopes sedimentation occurs due to migration of the sand waves in flood direction. Especially at these steep slopes often shape changes are observed in previous modelling studies (Krabbendam et al., 2021). To assess the ability of the model to maintain these slopes an average slope steepness (S) is included in the assessment criteria, see Fig. 2. The offset correction applied to the 2010 bathymetry data at the Texel site does not influence the calculated height and slope. The asymmetry of the sand waves is intrinsically captured in the height and the slope steepness of the steep slope, since the wavelength of the sand waves is quite stable over the considered time periods. Namely, a reduction in height with an unchanged slope or a increase in slope with an unchanged height will directly lead to increased asymmetry. We have included the definition of, and results for this metric in the Supplementary Materials.

3. Results

To assess the influence of changing the sediment transport formulation and the dominance of bed slope-induced transport on the representation of sand wave shapes, simulations are run for the period between two measurements (2 and 4 years for Texel and HKZ respectively). The final computed sand wave characteristics are then compared with measured characteristics. The simulations combine either the VR1993 or VR2007 sediment transport formulations with 6 different values of the bed slope parameter (0.5, 1, 2, 3, 4 and 5) at the two sites. The combination of VR1993 with a bed slope parameter of less than 2 at the HKZ site or less than 1 at the Texel site resulted in unstable morphological behaviour. Hence, these runs are omitted in further analyses. For visual purposes only one or two sand waves along each transect are included in the bed level figures. In the comparison of the heights and slopes, all full sized sand waves in the transects are included (8 at the HKZ site and 16 at the Texel site).

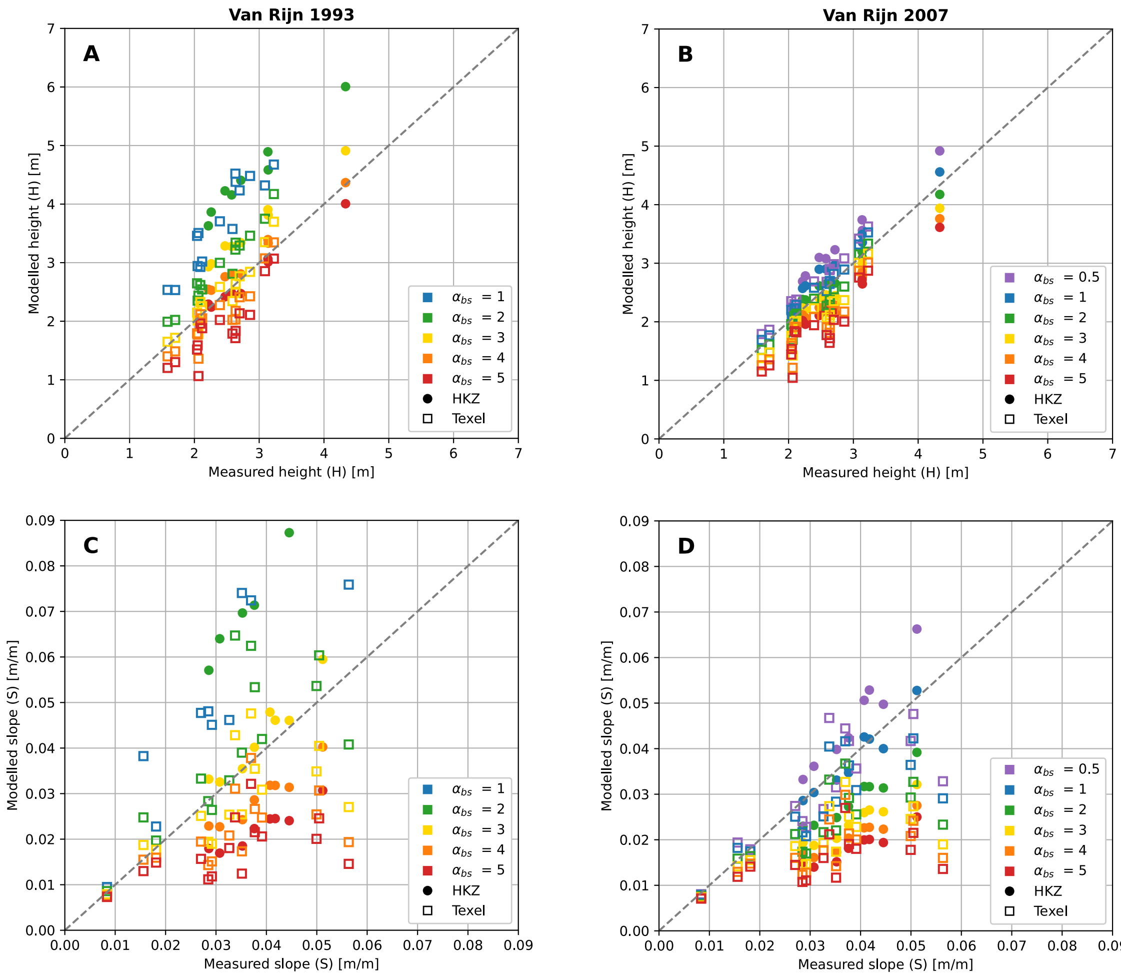

Fig. 4. Comparison of modelled and measured sand wave heights (A, B) and slopes (C, D) obtained with the VR1993 (A, C) and VR2007 (B, D) sediment transport formulations. Note: the runs combining VR1993 with an α_{bs} of 0.5 and 1 at HKZ and α_{bs} of 0.5 at Texel are excluded due to unstable morphological behaviour.

3.1. Influence of bed slope effects

Adjusting the bed slope effects has a considerable effect on sand wave shapes, see Fig. 3. Higher bed slope parameter values (α_{bs}) lead to dampening of the sand waves at both sites, which is manifested as a reduction of slope steepness and sand wave height. When a low bed slope parameter is applied, the crest levels are quite accurately modelled, although the trough levels become slightly deeper. Increasing the bed slope parameter ($\alpha_b s$) counteracts the lowering of the trough, but simultaneously leads to lowering of the sand wave crest height. Due to the reshaping of sand waves for higher values of α_{bs} the migration of the crests (in flood direction) decreases relatively, while the troughs migrate faster. The migration direction of the crest may even become opposite the overall flood directed migration of the sand waves. The average migration of the steep slope is however not significantly influenced by the bed slope effects, due to the opposing behaviour of crest and trough. At both sites the final bathymetries show a sort of pivot point on the steep slope, where all runs predict the same bed level.

3.2. Behaviour of sand wave height and slope

To compare both the effects of the bed slope parameter and sediment transport formulation on all sand waves in the transects (8 at HKZ and 16 at Texel), the shapes are captured in two assessment criteria: height (H) and steep slope angle (S) (see Section 2.4). Fig. 4 shows a comparison of these criteria between the final measurements and the final bed levels of the different simulations for each sand wave in the transect. We again observe that the bed slope parameter ($\alpha_b s$) has an considerable influence on both the sand wave heights (in the upper panel) and sand wave slopes (in the lower panel). Especially when applying the VR1993 sediment transport formulation a large spread is observed for the different parameter settings. Fig. 4A shows that to maintain the height of the sand waves while applying VR1993, a bed slope parameter of around 3–5 should be applied. The sand waves at the HKZ site require a higher bed slope parameter to maintain their height, and the modelled heights are more sensitive to varying dominance of this process. However, if bed slope parameter ($\alpha_b s$) of 3–5 is adopted, the averaged slope steepness may reduce significantly as is shown in Fig. 4C. For lower values of the bed slope parameter, the slopes increase rapidly and the models may even become unstable.

When applying the VR2007 transport formulation (see Fig. 4B and D) the sand wave heights and slopes show less sensitivity to the bed slope effects. This is evident from the limited spread in the simulated heights and slopes. A value of α_{bs} of around 1–2 shows the best match for modelled sand wave heights with observations. For the sand wave slopes a similar value of the bed slope parameter of around 1 leads to a good representation. Interestingly, these effects are similar for the two sites. The results also show that the models may have a tendency to underestimate sand wave heights and slope steepness when bed slope effects are more dominant. These results are also reflected in the asymmetry index, which is included in the Supplementary Materials.

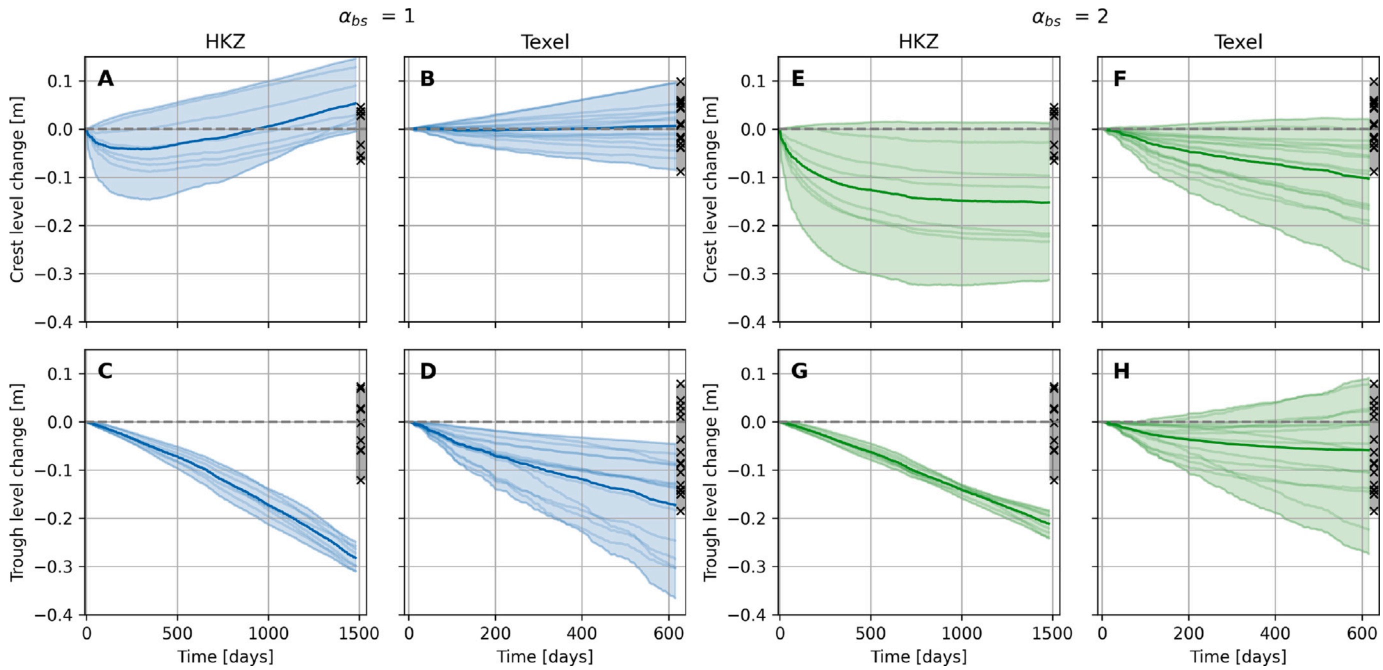

Fig. 5. Crest (upper) and trough (lower) bed level change over time for the model combining the VR2007 transport formulation with an α_{bs} of 1 (left) and 2 (right) at the HKZ and Texel site. Thick line shows the average of the individual sand waves (8 at HKZ and 16 at Texel), faded lines represent the individual crest and trough developments and the shaded area shows the spread. Crosses and grey area indicate crest and trough changes from measurements.

3.3. Impact on crest and trough levels

When looking at the trough and crest levels separately, instead of combining them in the total sand wave height, interesting behaviour is exposed. The development of these levels over time shows whether developments observed in the model are expected to continue if the simulation period is extended. The measurements reveal that in reality the crest and trough levels are more or less stable over time, see black crosses in Fig. 5. The average crest and trough level changes are below 1 cm, except for the troughs at Texel, which have lowered with close to 7 cm on average. The maximum changes are in the order of 1–2 decimetres, which is within the expected variability range due to superimposed smaller bed forms. From Fig. 4 it is clear that the combination of VR2007 with an α_{bs} of 1 results in a good match with observations for both sand wave height and slope steepness at both areas. With these settings the crest levels are more or less stable at both sites, with maximum changes of around 10–15 cm within the modelled period (Fig. 5A and B). At the HKZ transect first a quick lowering of the crest levels is observed, followed by a slow, but steady increase in crest level. At the end of the simulation the average crest level changes exceed those from measurements, which show relatively stable crest levels. At the Texel transect the developments of the crest levels are more constant over time, with individual sand waves which slowly heighten, lower or stay at a stable level, and on average the crest level is stable over the transect. Contrary to the HKZ transect, the crests at Texel thus show opposing behaviour (lowering versus heightening). This variation in crest level development and the resulting spread in change rate does match well with the observations at the Texel transect.

The trough levels do show more change over time compared to the crest levels (Fig. 5C and D). At both sites the trough levels are lowering steadily, with no clear signs of stabilizing towards the end of the simulation. Especially in the HKZ transect the different sand wave troughs show very similar development. After 4 years the troughs have lowered with approximately 0.3 m at the HKZ site (relative to a sand wave height of around 3 m). The spread in this lowering of the trough at the HKZ site is only a few cm, while the sand wave heights vary between 2 and 4 m. Therefore, the modelled change rate of the trough level is not directly related to the total height of the sand wave. At the Texel site more variation in the trough development is seen. The average rate of change of the trough levels is higher at the Texel transect (note the different timescales). This increased rate of change is in line with the overall larger natural morphological changes over time at the Texel site, reflected by the higher sand wave migration rates as shown in Fig. 1. At both transects the lowering trend from the model is not reflected in the measured developments of the trough levels.

When the bed slope-induced transport is increased by applying an α_{bs} of 2, the crest and trough developments show moderate changes, see Fig. 5E–H. At both sites the crest levels lower during the model run. At the HKZ site the crest lowers quickly at first, but stabilizes after around 700 days. At the Texel site the crest levels are not yet stabilizing at the end of the run, after 600 days. The spread in crest level development, between the sand waves in the transect, significantly increases when applying an α_{bs} of 2 instead of 1. This indicates that although for some sand waves the crest levels are more stable in this run, most sand waves show significantly increased deviations. This increased spread and the remaining lowering trend are not reflected in the measured crest level behaviour at both sites. The trough levels at the HKZ site (Fig. 5G) show very similar behaviour with the increased bed slope effects. All the troughs are lowering at a steady rate, which is a bit lower than the rate found with an α_{bs} of 1. This behaviour does not match with the observed on average steady trough levels. At the Texel site the spread in the trough development is still high, even slightly increased, with an α_{bs} of 2 (see Fig. 5H). However, since some trough levels increase and others decrease, on average the change in trough level is limited. For the Texel site, this spread in, and on average slightly lowering trend of the trough levels matches well with the observations. However, although the match for the trough levels at Texel improved with a higher bed slope parameter, the trough levels at HKZ still show an unnatural lowering trend an the match for the crest level development has worsened.

Through investigation of instantaneous bed load transport rates it is found that the erosion of the trough happens during flood flow, see Fig. 6. During peak flood flow there is a phase difference between minimum bed load transport and the minimum bed level (the trough),

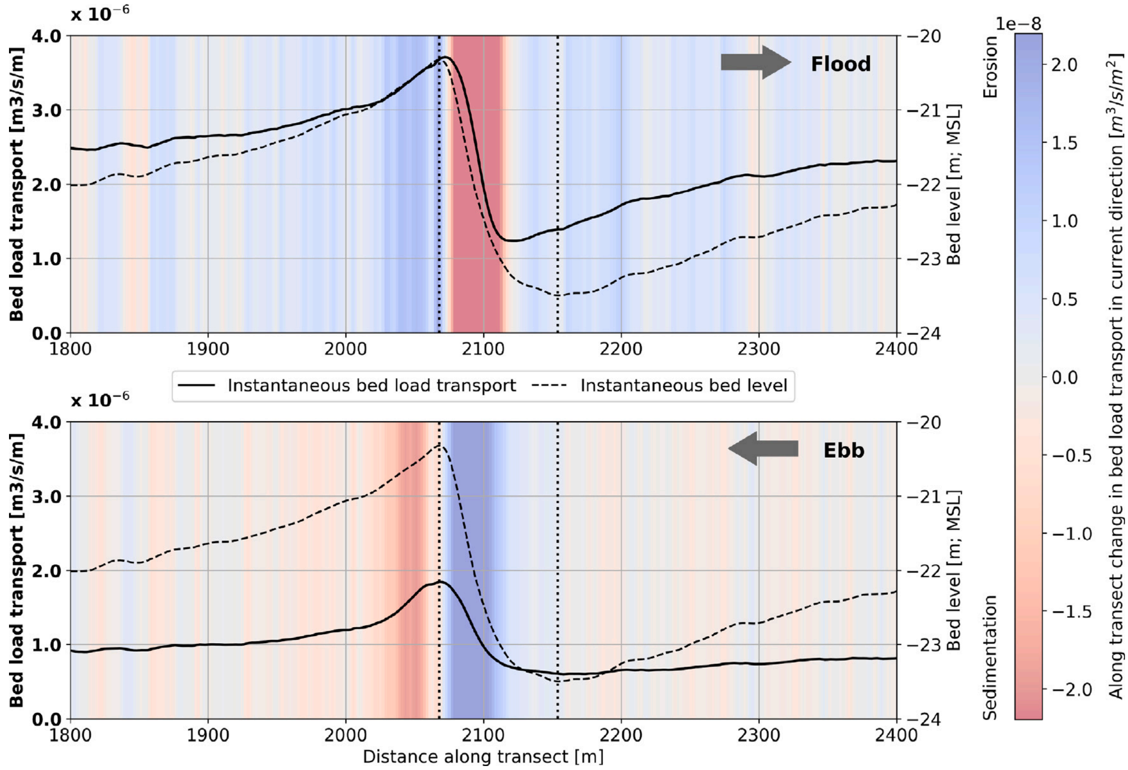

Fig. 6. Instantaneous bed load transport magnitude during spring peak flood (upper) and peak ebb (lower) flow for the VR2007, α_{bs} = 1 simulation at HKZ. The bed level is included (scale to the right), as well as the crest and trough locations (vertical dotted lines). The background colours represent the change in bed load transport in current direction, thereby showing the locations of sedimentation (red) and erosion (blue). For visual purposes the maximum and minimum change exceed the limits of the colour scale.

causing the sediment transport to increase at the location of the trough. This increase in sediment transport causes a slow, but steady erosion. This phase difference is also observed in the near bed velocities, which increase at the trough location. During peak ebb flow the location of minimum transport and the trough coincide, leading to steady trough depths during this phase of the tide. The phase difference during flood is observed for all sand waves in both the HKZ and Texel transect, but reduces with a higher bed slope parameter.

3.4. Effect of adapting bed slope dominance

The shape criteria have demonstrated that the different sediment transport formulations need a varying dominance of bed slope-induced transport to reproduce the steep sand wave slopes found in-situ. Based on the relations shown in Fig. 4, modelling results for two model setups are used to further demonstrate the effect of varying bed slope dominance. The two setups are VR1993 and VR2007 with a bed slope parameter of 3 and 1 respectively. The former settings are much alike those used in various previous sand wave modelling studies (see Table 1). In the VR1993 run, the higher sediment transport rates predicted by the formulation, are balanced by the increase of slope-induced transport. Although this balancing is able to counteract sand wave growth, while maintaining the slope steepness, still adverse effects can be observed (Fig. 7). At both locations this setting shows an increased migration rate of the steep slope, leading to a further overestimation of the observed sand wave migration. Moreover, the reduction of trough levels is accelerated in this run and the pointy crest at the HKZ transect broadens due to the diffusive effects of the increased slope-induced transport.

By combining the VR2007 transport formulation with a bed slope parameter (α_{bs}) of 1, the evolution and shape of the sand waves is reproduced well in the model (Fig. 7). Especially the migration of the gentle slope is well predicted in the simulation. On the other side some deviations can be observed in the amount of sedimentation of the steeper slope and the amount of erosion of the sand wave trough. However, overall the results are satisfying, considering that they span a period of multiple years. These model runs show that although some balancing mechanisms can be used to improve shape representation in numerical models, the suitability of sediment transport models for reproducing sand wave evolution may still vary.

4. Discussion

In this study we have shown the influence of the choice of sediment transport formulation and bed slope parameter on the development of the shape of numerically simulated sand waves and found those to be significant. The robustness of model results vary widely, depending on which transport formulation is chosen. When lower sediment transport rates are predicted, bed slope-induced transport becomes less important for maintaining sand wave heights. With a lowering of the bed slope-induced transport the sand wave shapes, specifically the steepness, are better preserved. With these model settings the sand waves show a slight growth over time, specifically through a lowering of trough levels. However, an increase in slope-induced transport is unable to counteract these effects. By adapting the dominance of bed load and slope-induced transport, the representation of sand wave shapes, for both sharp crested and rounded sand waves, can be improved significantly. Moreover, with the adapted model set-up, the evolution of sand waves over multiyear timescales is reproduced well in the model.

By evaluating the model results based on different sand wave characteristics, the precise effects of changes in process formulations can be better understood. By tracking specific characteristics, such as crest and trough levels, improvements as well as adverse effects can be recognized more easily, than through combined factors such as the shape factor applied in Perillo et al. (2014). In the meantime shortcomings of overall error statistics, such as the 'double penalty effect' related to the RMSE, are avoided (Bosboom and Reniers, 2014). These error statistics may favour certain solutions, such as those which are more smoothened

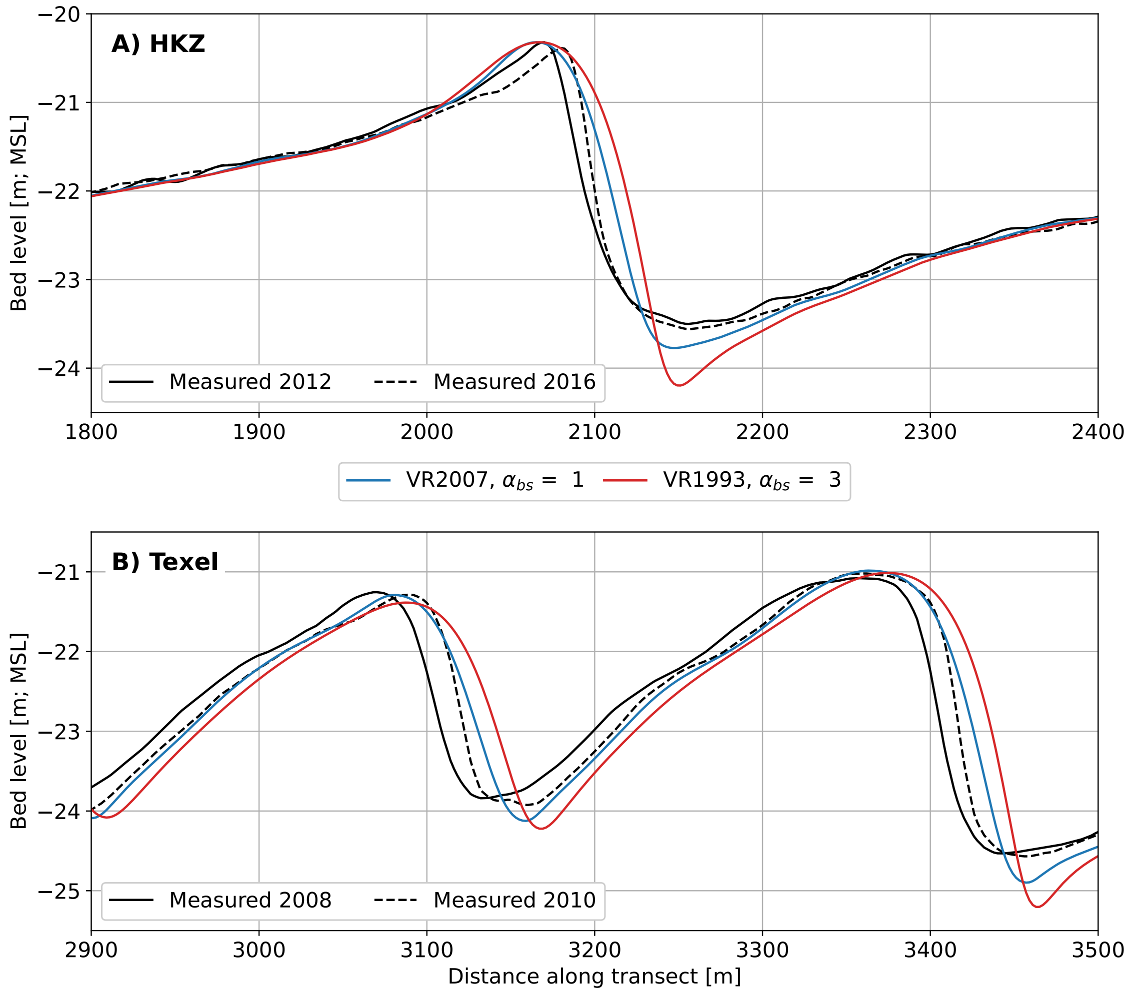

Fig. 7. Measured and modelled bed levels at the end of the simulation period (2016 for HKZ and 2010 for Texel) for the state-of-the-art setup, using VR1993 and an α_{bs} of 3, and the improved setup, using VR2007 and an α_{bs} of 1. The initial measurement is used as the starting bathymetry for the model. Megaripples are filtered from the measurements.

or show less change, over results which represent many processes well but, for example, mismatch migration rate. Moreover, these error statistics do not give any insight on the influence of the 'snapshot' in time, between two measurements, used to validate the simulation results. Model parameters may be adapted to fit this snapshot, but this gives no certainty about the development when the model period is extended. The insights gained in this study support knowledge based improvements of sand wave simulations, thereby omitting the need for blindly calibrating certain parameter settings.

4.1. Sediment transport formulation

We have tested two versions of the widely applied Van Rijn sediment transport formulations. The results show that the latest sediment transport formulation (VR2007) is more robust, both numerically and physically, than an earlier version (VR1993). The VR1993 transport formulation predicts higher sediment transport rates and a lower threshold for sediment transport relative to the VR2007 model. Van Rijn et al. (2004) noted that both the original VR1993 transport formulation and the adapted version based on Van Rijn (2000) (used in this study) seem to overpredict the measured transport rates for current only cases (no waves) from observations of several riverine and estuarine stations (see Van Rijn, 2000). All the while the VR2007 transport formulation is in good agreement with these measurements. Higher sediment transport rates lead to a higher growth rate and equilibrium sand wave height as well as quicker migration of the sand waves. This may explain the overestimation of equilibrium sand wave heights, which is often observed in sand wave models (e.g. Van Gerwen et al., 2018 and Campmans et al., 2022). Moreover, in this study overestimation of the sand wave migration rate is observed, especially when applying the VR1993 transport formulation (see Fig. 7B). Similar effects were not mentioned in the validation of a sand wave model by Krabbendam et al. (2021), where the VR1993 transport formulation was applied. However, the mismatch in modelled growth and migration rates was probably counteracted by reducing the sediment transport rate by over 50% through the use of a 'sand transport factor' (f) of 0.45, thereby limiting both mechanisms. Still, solving these deficits in this way is not recommended since the mismatch in sediment transport rates is not linear. Based on the results of this study and the validation by Van Rijn et al. (2004), we recommend the use of the VR2007 transport formulation and dissuade the use of the VR1993 transport formulation (both the original and adapted version) for sand wave simulations, for both the widely used Delft3D FM and Delft3D models. Using the VR2007 sediment transport formulation good agreement is found between the predicted and measured sand wave evolution for two locations with contrasting sand wave characteristics and dynamics.

4.2. Dominance of slope-induced transport

The need for bed slope-induced transport is closely related to the chosen sediment transport formulation as well as other model equations. This transport mode is an intrinsically diffusive process, which can therefore be used to dampen instabilities in morphological models. Depending on the stability of the applied spatial discretizations and the

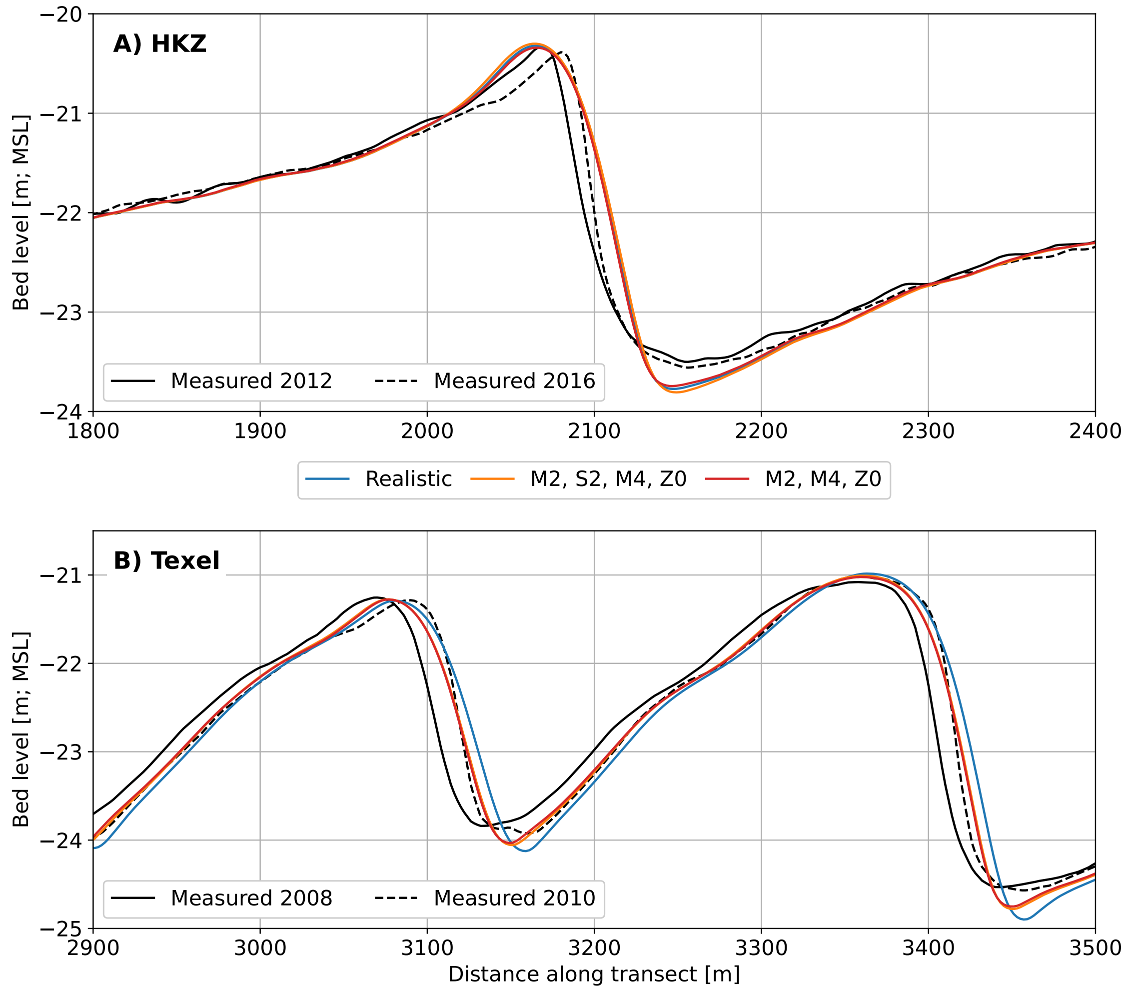

Fig. 8. Measured and modelled bed levels at the end of the simulation period (2016 for HKZ and 2010 for Texel) with VR2007 and $\alpha_{bs} = 1$, using realistic hydrodynamic forcing (including non-tidal, time-varying currents used throughout this study) and two kinds of simplified tidal forcing combining several tidal components (M2, M4, S2) with a constant residual current (Z0), see Overes et al. (2024) for details. The initial measurement is used as the starting bathymetry for the model simulations. Megaripples are filtered from the measurements.

inclusion of other diffusive processes the need for bed slope-induced transport for stable results may thus change (Volp et al., 2016). An example of such a process is suspended sediment transport, which is not expected to lead to significant morphological changes at the sites included in this study, due to the local dominance of bed load transport (Damen et al., 2018). However, when sediment grain sizes reduce this process may lead to diffusion of sediment and thereby dampen the sand waves (Borsje et al., 2014), affecting both the height and slope steepness. Moreover, Tritthart et al. (2024) have shown that the artificially increased diffusion from transverse bed slope transport may be used to compensate for model inadequacies, such as inadequate mesh resolution and orientation. A similar reasoning can of course be applied to longitudinal slope-induced transport which are affected by the α_{bs}. These kind of model limitations are unrelated to the physical process the bed slope-induced transport formulation is supposed to capture. The results have shown that when using the VR1993 transport formulation, increasing the bed slope parameter will indeed lead to stable results. However, this increase of slope-induced transport is not necessary when applying the VR2007 sediment transport formulation. In this case the default value for the bed slope parameter (α_{bs}) of 1, which reduces the formula to the original derivation by Bagnold (1966), allows the model to maintain the steep slopes of the sand waves, while remaining stable. This may be partially attributed to the inclusion of slope effects on the threshold for sediment transport in the VR2007 formula, which are missing from the VR1993 formulation. Tritthart et al. (2024) have shown that this correction may significantly affect the need for scaling slope-induced transport. The importance of bed slope-induced transport may thus have been overestimated in previous modelling studies, in which often a bed slope parameter (α_{bs}) of 2–5 is applied.

Instead of bed slope-induced transport, other processes might be leading in limiting equilibrium sand wave heights. When the bed slope parameter (α_{bs}) is adapted for reproducing sand wave slopes, minor but steady growth of the sand waves is observed at both model sites. This growth is mainly caused by a lowering of the trough level as was also observed in Krabbendam et al. (2021), while crest levels were more or less stable. Increasing the bed slope-induced transport is found not to be an effective measure to counteract this process. This local erosion of the trough might be caused by the exclusion of certain physical processes, such as non-hydrostatic pressures. When these are included in the simulation, the turbulent wake behind the steep sand wave slope can lead to locally reduced near bed velocities as shown by Lefebvre and Cisneros (2023). However, these effects are only expected to be present within a range of several metres from the steepest slopes of the sand waves. Alternatively, spatial variations in geophysical, sedimentological and morphological characteristics may have a significant influence on sand wave dynamics. Vertical differences in sediment characteristics and packing density, which origin from the geological history of the bed, may cause significant differences in erodibility between crest and trough. Furthermore, studies have shown that sediment sorting processes can lead to either coarsening or fining of the sand wave troughs, depending on the mobility of the coarser sediment grains (see Damveld et al., 2020b and Van Oyen et al., 2013). These sorting processes affect both the threshold for sediment transport and the bed roughness and can thereby lead to locally reduced sediment transport rates, for example when armouring occurs. Moreover, video observations of the seabed by Damveld et al. (2018) show that ripple dimensions as well as biota density can vary widely between the crest and trough of a sand wave. These variations can alter the local hydrodynamics as well as sediment characteristics and morphology. The presence of shells in the sand wave troughs can for example further increase the threshold velocity for sediment transport locally (Cheng et al., 2021). By further lowering the sediment transport close to the sand wave troughs these variations can counteract the observed erosion of the troughs.

4.3. Importance of time-varying, non-tidal currents

For the simulations in this study a realistic hydrodynamic forcing is applied, which includes a varying residual current from several sources, such as wind and atmospheric pressures, superimposed on the tidal hydrodynamics. This setup is based on (Overes et al., 2024) who showed that the time variations of non-tidal currents can cause significant changes in (average and instantaneous) sedimentation rates of the steep slope of the sand waves. These changes are not captured when applying a constant residual current. However, it is common practice in sand wave modelling to simplify these hydrodynamics to tidal currents and a constant residual current. This is done to make the forcing periodical, and thereby offer opportunities for morphological upscaling. Fig. 8 shows a comparison between the final bed levels with simplified and realistic hydrodynamics for the two sites. The relevance of time-varying, non-tidal currents for sand wave morphology clearly differs between the sites. At the HKZ transect the final bed levels with the different forcing are much alike, with only minor differences in the areas close to the crest and trough. At the Texel transect including these non-tidal, time-varying currents clearly leads to an increase of the migration rate, combined with a more pronounced lowering of the trough, compared to the cases with simplified hydrodynamics. The latter may be explained by the increased sediment transport rates when including non-tidal, time-varying currents, see Overes et al. (2024), causing an acceleration of the steady lowering of the trough shown in Fig. 5. Time-varying, non-tidal currents may thus be of importance to reproduce decadal sand wave evolution. Depending on the local hydrodynamics, the mobility of the bed and the timescale of the simulation, the inclusion of these currents can lead to significant differences in the predicted bed levels. The contrast between the sites included here are in line with the observations by Overes et al. (2024), who concluded that the absolute effect of these currents was largest at the Texel site.

4.4. Practical implications

The morphological results from this study supply a good basis for further exploration of the influence of physical processes on sand wave dynamics. With the improved settings steep slopes are well preserved and initial sand wave shape adaptation (also called 'morphological spin-up' in Krabbendam et al., 2021) is limited. This allows for physical processes to be studied in more detail and opens the door for short-term sand wave simulations, which for example include the impact of a single storm. In these cases the effects of an overestimation of the bed slope effects are of the same order as the expected physical changes in the sand wave bathymetry over the simulation period. On the other side of the spectrum, the limited influence of non-tidal time-varying currents at the HKZ site offer opportunities for long term simulations. There a simplified setup, including only tidal currents and a constant residual, can easily be combined with upscaling methods, such as morphological scaling with the morfac (Ranasinghe et al., 2011), as long as intrinsic limitations of the methods are considered. In this way further decrease of run times can be achieved, offering opportunities for simulating sand wave evolution over longer timescales and larger spatial scales, thereby further opening the door for 3D sand wave simulations in areas where the along crest bathymetry is not uniform. This could be the case for sand waves superimposed on sand banks, with changing crest direction, short crested or bifurcating sand waves or when human interventions have taken place. Especially in the latter case numerical simulations are essential, since these human interventions are not included in historical data. By applying a hybrid approach the strengths of both methods, namely the simplicity and speed of data-analysis and the process representation and flexibility of numerical models, can be optimally utilized. The numerical models can then fill gaps in the data, caused for example by lack in temporal resolution or measurement uncertainties, while data-analyses provides a quick understanding of the basic system. Together these methods can thus aid our understanding of the physical processes as well as our ability to predict future sand wave evolution.

5. Conclusions

By assessing various sand wave characteristics, we show that the way bed load and slope-induced sediment transport are represented in numerical models has a significant effect on sand wave shapes. These characteristics are average slope steepness of the steep slope, sand wave height and crest and trough level. We found that, in order to retain sand wave height, a need for more pronounced bed slope-induced transport can arise due to overestimation of sediment transport rates. However, to reproduce the steep slopes of sand waves observed in-situ, the magnitude of the bed slope-induced transport should remain limited. By combining the Van Rijn 2007 (VR2007) sediment transport formulation, with a reduced bed slope-induced transport ($\alpha_{bs} = 1$), our Delft3D FM model is able to preserve sand wave shapes and adequately predict their migration over multiyear timescales for two contrasting sites in the North Sea. The sand waves show a slight growth, through a steady lowering of the trough levels, but increasing the bed slope-induced transport does not lead to improvements in the stability of these crest and trough levels. These model results show that the role of bed slope-induced transport for limiting sand wave heights has been overstated in the past. Specifically, the developments of the trough levels signal that local processes, such as spatial variations in sedimentology, may be leading in limiting sand wave growth. The improved model settings show the ability to preserve sand wave shapes and reproduce sand wave migration more accurately. This offers opportunities to assess the impact of environmental changes and human interventions on sand wave dynamics, which cannot be done using data analysis. Moreover, these simulations offer insights for bed level evolution in data scarce areas.

CRediT authorship contribution statement

Pauline H.P. Overes: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bas W. Borsje:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Arjen P. Luijendijk:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Johan Reyns:** Writing – review & editing, Software. **Suzanne J.M.H. Hulscher:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.csr.2025.105513.

Data availability

The input files and results of the numerical simulations are available via https://doi.org/10.4121/ac09ebb7-df66-41f5-9fe1-eaafeb9bd6d0. The measurement data underlying the models can be accessed via Deltares (2017) and RVO (2018).

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