On elevation and migration: a model for sandbank dynamics in sediment-scarce seas

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ABSTRACT: Tidal sandbanks are large-scale dynamic bedforms observed in shallow seas with varying sediment supply. Their dynamics have often been studied under the assumption that sediment supply is unrestricted. However, this is invalid for banks in sediment-scarce seas, like the Flemish and Norfolk banks in the North Sea. Here, we show using a process-based idealized model how sediment scarcity affects the cross-sectional shape and migration speed. We find that sediment scarcity reduces the height of sandbanks and changes bank asymmetry when a residual current is present. Furthermore, the migration rate of banks increases. Our findings are especially relevant in the context of continued sand extraction in sediment-scarce seas, and help understand sandwave dynamics around sandbanks.

1 INTRODUCTION

Tidal sandbanks are large-scale marine bedforms in shallow seas that migrate under asymmetric tidal forcing. They are frequently observed in conjunction with sandwaves. Due to their large size of ten of metres in height, tens of kilometres in length and kilometres in width (Dyer & Huntley, 1999, de Swart & Yuan, 2018), their dynamics determine the environmental conditions (e.g. water depth and flow characteristics) relevant for sand waves. They are also an attractive location for sand extraction and an important ecological habitat for marine species (Wyns et al., 2021).

Observations have identified that sandbanks are regularly located in sediment-scarce seas. For examples, the Flemish banks lie on top of a layer of hard clay, which is exposed in the troughs (Hademenos et al., 2019). Gravel has also been observed in the troughs between the Norfolk Banks (Caston, 1972). Sand extraction for coastal nourishments and industry will further reduce the sediment budget. Therefore, it is important to understand how tidal sandbank dynamics depend on the available sediment budget.

So far, sandbanks have often been studied under the assumption of infinite sediment supply. Under these conditions, process-based models have explained the initial growth of sandbanks as a free instability of the flat bed (Huthnance 1982a, Hulscher et al., 1993), and have shown that sandbanks may evolve towards static or dynamic equilibria (Roos et al., 2004, Yuan et al, 2017). Under asymmetrical forcing (e.g. residual current or M4-tide) sandbanks attain asymmetrical cross-sectional shapes and exhibit migration in the order of meters per year. However, these results come from models ignoring conditions of sediment scarcity.

Huthnance (1982ab) did consider the effects of sediment scarcity in his models of equilibrium cross-sections (1982a) and sandbank evolution (1982b). He concluded that sediment scarcity led to lower and narrower sandbanks. He also found that sediment scarcity was important for attaining equilibrium profiles, together with the presence of wind waves. However, his results were based on simplified hydro-dynamic conditions (no Coriolis effects and block flow). It is unclear whether his results hold under more complex tidal conditions.

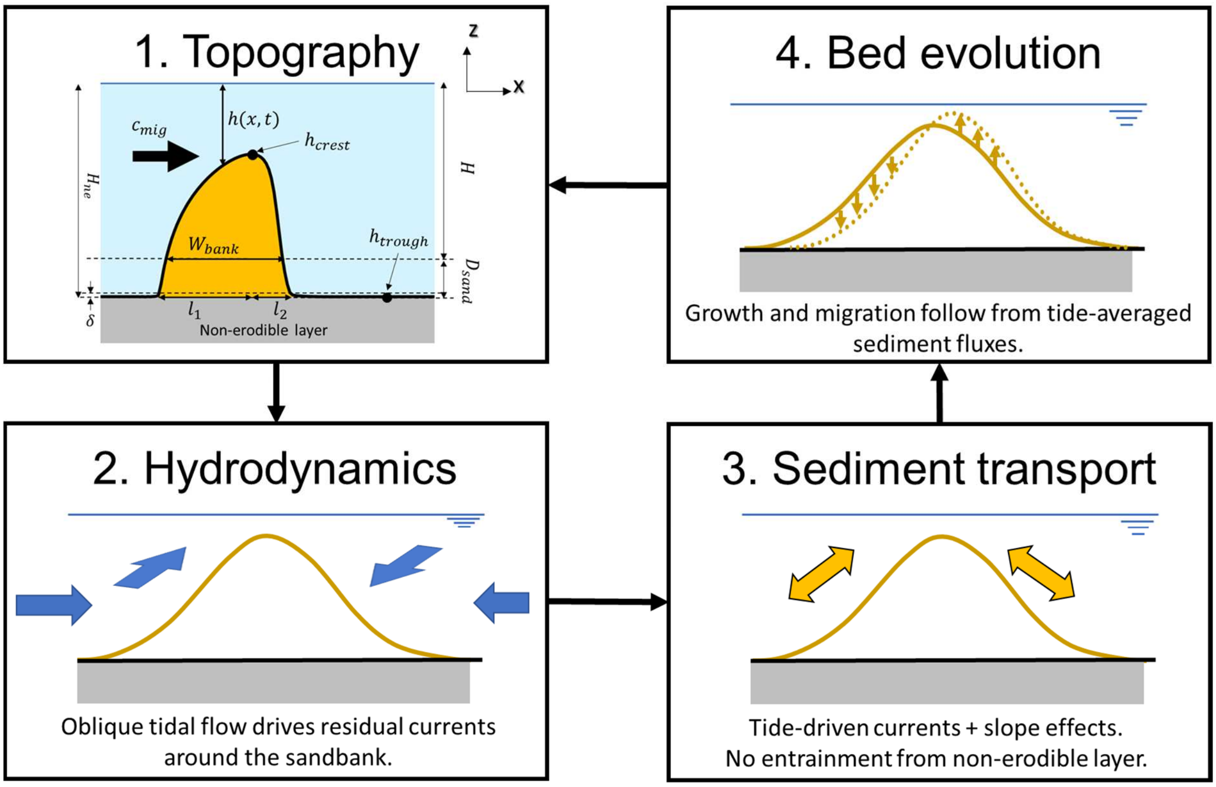

Figure 1. Schematisation of the four stages of the morphological loop in our process-based model. Stage 1 is the topography. The corresponding hydrodynamic solution given a tidal forcing is computed in stage 2. This leads to a solution for sediment transport in stage 3. Importantly, no sediment can be entrained from the non-erodible layer. Stage 4 solves the bed evolution based on the divergence of tide-averaged sediment transport. The evolved bed then serves as the new topography for the next iteration of the loop.

In order to overcome our limited understanding of sandbank dynamics under sediment scarcity, we present a process-based idealized model in which we restrict sediment availability via a non-erodible layer. We apply this model to study the cross-sectional shape and migration speed in sediment-scarce seas.

2 METHODS

Following previous models (Roos et al., 2004, Yuan et al, 2017, van Veelen et al, 2018), we keep our morphodynamic model as simple as possible, while still including the essential physics to understand tide-topography interactions and the resulting sediment transport. Our model includes tidal flow (including a residual current), and accounts for Coriolis effects, bottom friction, suspended sediment transport. We only consider the dynamics over the cross-section of the bank, as we focus on cross-sectional shapes in this study. Finally, all dynamics are depth-averaged, as bank evolution is driven by horizontal circulation cells (Huthnance, 1982a).

Sediment scarcity is included via a uniform non-erodible layer which limits the thickness of the sand layer (D_{sand}). Sand cannot be picked up where the non-erodible layer is exposed, but the non-erodible layer does not affect sediment transport when it is covered by sand.

We simulate the evolution of the topography $z = -h(x,t)$ over time based on the morphological loop (Fig. 1). The hydrodynamics are solved using the shallow water equations. Then, we compute sediment transport using the sediment advection-diffusion equation, given by

$$\frac{\partial c}{\partial t} + \frac{\partial (cu)}{\partial x} = \gamma(c_e - c). \qquad (1)$$

$c(x,t)$ is the depth-integrated sediment concentration. u is the flow velocity in cross-

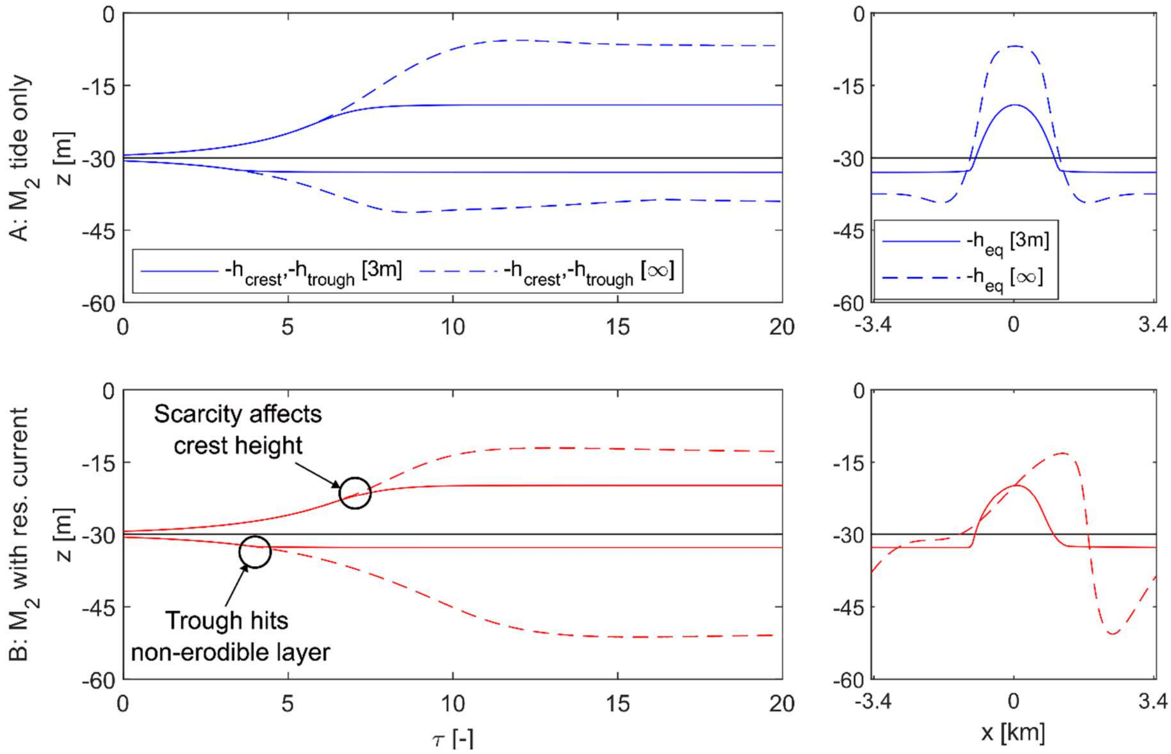

Figure 2. Left: Evolution of crest height and trough depth over morphological time τ with sand layer thickness of 3m and ∞ (denoted between square brackets). Every τ-unit is approximately 280 years. Some conditions ran for longer than $\tau = 20$ to reach equilibrium. Right: Equilibrium cross-sectional profiles for D_{sand} = 3m and D_{sand} = ∞ under conditions A (top) and B (bottom). All plots show mean water depth $z = -H$ as a solid black line.

bank direction, γ is a deposition coefficient, and

$$c_e = \alpha_s \mu_s (u^2 + v^2) \quad (2)$$

is the entrainment concentration with sediment transport coefficient α_s, sediment limiter μ_s, and velocities in cross-bank and along-bank directions u and v. $\mu_s(h)$ is 0 when the non-erodible layer is exposed ($h = H_{ne}$), ranges between 0 and 1 in the buffer layer ($H_{ne} - \delta \leq h \leq H_{ne}$), and is 1 when sufficient sand is available. Finally, the bed evolution is obtained via Exner's equation.

The solution method is pseudo-spectral in space and time. The initial topography is given by a sinusoidal bank with amplitude $0.02H$ and with a wavelength and orientation in accordance with the fastest growing mode from linear theory (e.g., Hulscher et al., 1993). The simulation continues until a morphodynamic equilibrium is reached.

3 RESULTS

3.1 Overview of simulations

We run our model for two types of conditions. Condition A is forced by an M_2-tidal flow with an amplitude of 0.6 m/s. Condition B is characterized by an M_2-tidal flow amplitude of 0.57 m/s and a residual current of 0.03 m/s. Furthermore, both conditions have a mean water depth of H = 30 m, and are located at a latitude of 52°N. Each condition is repeated with a sand layer thickness varying between 1.5 m and infinity (i.e., non-erodible layer not present).

3.2 Evolution towards equilibrium

The evolution towards a morphodynamic equilibrium for both conditions with D_{sand} = 3 m and ∞ is shown in Figure 2. Sediment scarcity affects bank evolution from the moment that the non-erodible layer is exposed in the trough. The trough cannot

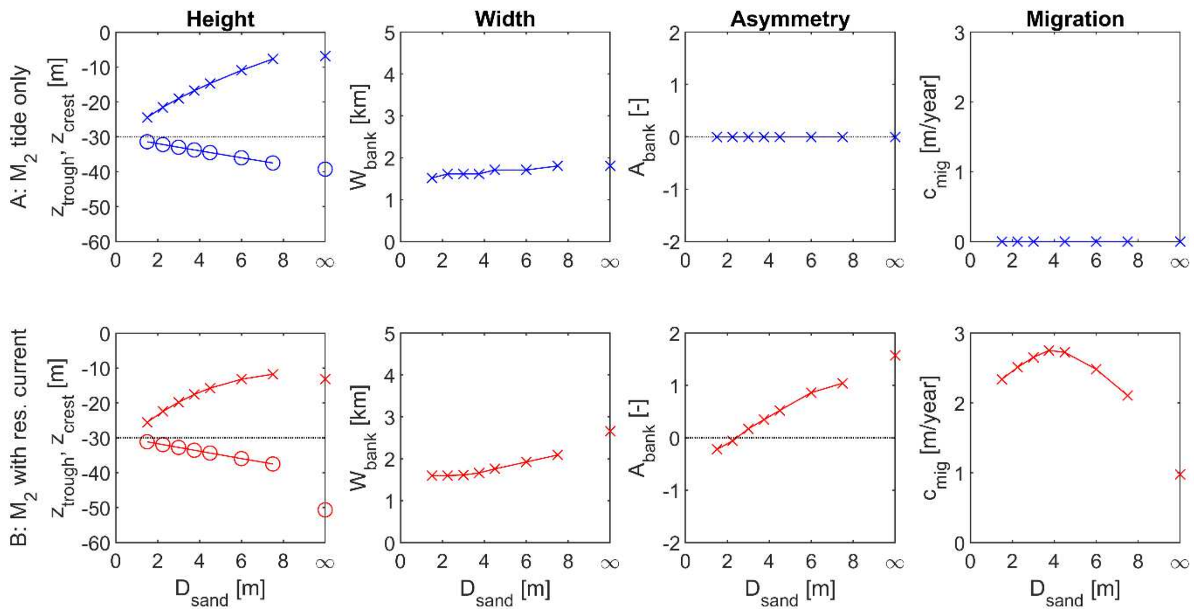

Figure 3. Influence of sand layer thickness D_{sand} on various properties of the equilibrium bank shape: crest and trough elevation z_{crest} and z_{trough}, bank width W_{bank}, bank asymmetry A_{bank}, migration speed c_{mig}.

erode beyond the non-erodible layer. As shown in Fig.2, the crest height is not affected until much later in the simulation. Importantly, the equilibrium crest height and trough depth are both of lower amplitude when sediment is scarce.

3.3 Cross-sectional equilibrium shape

The relation between sand scarcity and shape parameters z_{crest} and z_{trough}, width W_{bank}, and asymmetry $A_{bank} = \log(l_1/l_2)$ (see Fig. 1) is presented in Figure 3. The height is much more sensitive to scarcity than width. Our results indicate that equilibrium profiles become lower rather than narrower when sediment supply reduces.

When a residual current is present (conditions B), the asymmetry is affected by the scarcity. The lee side flattens with a thinner sand layer, as also shown by the equilibrium cross-sections in Figure 2 (bottom right). When sand is very scarce (here $D_{sand} < 2.5$m), the asymmetry may even flip. This means that the stoss side is steeper than the lee side rather than the other way around as is observed when $D_{sand} = \infty$.

3.4 Migration

Our results show that sandbanks migrate faster when a non-erodible layer is present (Fig. 3d). All our runs with a non-erodible layer exhibit higher migration rates than when sediment supply is unlimited. There is a maximum: highest migration rates are obtained with $D_{sand} = 3.75$ m under the conditions studied here. The migration rate reduces when the sand layer is either thinner or thicker. Note that migration can only occur when the tidal flow is asymmetric (i.e. condition B).

4 CONCLUSIONS

Tidal sandbanks are large-scale bedforms, whose dynamics affect the flow characteristics for sandwaves and other bedforms. Here, we have included a non-erodible layer in a process-based idealised model in order to study how sediment scarcity affects the cross-sectional shape and migration speed.

Our results show that the equilibrium values of the crest height and trough depth reduce when sediment becomes scarcer, whereas the width of the banks is less sensitive to scarcity. During the development process, the trough depth is immediately affected when the non-erodible layer is exposed, whereas the crest height will not be affected by scarcity until much later in our simulation.

The migration rate increases under sediment-scarce conditions. Our results suggest that there exists a sand layer thickness for which the migration rate reaches a maximum. It is recommended that this is further explored in future research.

5 ACKNOWLEDGEMENT

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