Nonlinear modeling of estuarine sand dunes: first results with unidirectional flow

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ABSTRACT: Estuarine sand dunes can be seen as intermediate bedforms between river dunes and marine sand waves. Past research has focused on understanding their growth in the linear regime. Here, we present a new morphodynamic model with lateral periodic boundary conditions to investigate estuarine sand dune dynamics in the nonlinear regime. Being still under development, we use the model in a riverine setting (unidirectional flow) and show flow properties (velocity, turbulent kinetic energy and excess pressure) as well as morphodynamic development. The model is capable of capturing lee-side effects and nonlinear morphodynamic interactions between bedform modes. Future work will be directed to extend the forcing to bi-directional flow to represent estuarine conditions.

1 INTRODUCTION

Sand dunes occur in shelf seas (known as tidal sand waves), rivers (river dunes) and estuaries (estuarine sand dunes). Depending on the environment, they have lengths on the order of tens of meters (rivers) or hundreds of meters (seas). They have been explained as free instabilities of the sandy bed subject to flow (Engelund, 1970). Modeling efforts have been directed to hindcast sand dunes (Krabbendam et al., 2021), and to understand the mechanisms that determine their size, shape and dynamics (e.g., the effect of wind waves, Campmans, 2017 and turbulence, Blondeaux & Vittori, 2005).

Such modelling efforts can roughly be divided into two groups: linear stability models and nonlinear models. Linear stability models linearize the sand-water system around a basic state (i.e. flow and sediment transport over a flat bed) to investigate the initial growth of bedforms. The strength of these models is that they are computationally cheap, allowing for systematic sensitivity analyses, and that they enable to disentangle the effects of different physical processes (e.g., the effect of bed-load from suspended load transport, Campmans, 2017). However, they cannot give information on shape and height of sand dunes in the finite-amplitude regime.

Nonlinear models, on the other hand, can model finite height and shape (although modeling bedform lengths in the finite amplitude regime is an ongoing quest, see also discussion). When the forcing is asymmetric (such as in rivers or estuaries, and to a lesser extent also in seas), dunes become asymmetric as well, giving rise to wake effects which become important at lee slopes larger than about 10 degrees (Lefebvre & Winter, 2016). In the past, the morphodynamic implications of lee side effects have been parameterized (Paarlberg et al., 2009), and more recently efforts have been made to resolve the flow field – also in the separation zone – in a morphodynamic model of smaller-scale bedforms (order of a meter, Doré et al., 2016), and on a larger scale (Doré et al., 2018). The model used in these two studies is capable of capturing lee-side effects because it is non-hydrostatic and uses a k-ω turbulence closure. However, the simulation times used (order of days) were not long enough to capture growth of large-scale bedforms towards equilibrium.

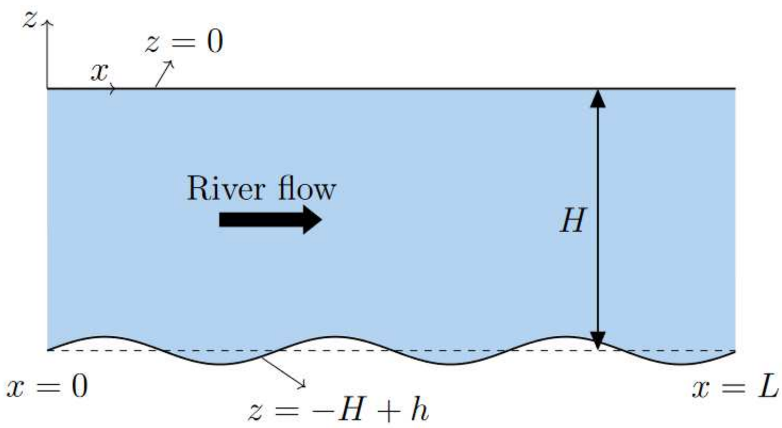

Figure 1. Overview of the 2DV model domain which represents a local portion of a river with domain length L, mean depth H and topography h, forced by river flow; the water surface is fixed (following from the rigid lid assumption).

Here, we will present a nonlinear morphodynamic sand dune model, which is capable of running long-term simulations to find (large-scale) sand dunes. Herein, we will focus (for now) on the riverine case by implementing unidirectional forcing. Results will show the equilibrium height and shape of these dunes, and the evolution thereto.

2 METHODS

2.1.1 Hydrodynamics

The model domain is outlined in Figure 1. The hydrodynamic module is solved with OpenFOAM, and solves the (non-hydrostatic) 2DV RANS equations with k-ω turbulence closure. At the surface we assume a rigid lid, and we impose a no-slip condition at the bed; the lateral boundaries are periodic. The model is forced by a constant barotropic pressure gradient, the magnitude of which is chosen such as to achieve a depth-averaged velocity of 1 m/s to the right at the beginning of the simulation, which aims to represent a riverine scenario.

2.2 Sediment transport and bed evolution

We use bed-load transport only (hence for now ignore suspended sediment transport). It is modelled as a power law of the bed shear stress τ (with coefficient α and power β), supplemented with a bed slope correction term (Bagnold, 1956; Lesser et al., 2004):

$$q = \alpha|\tau|^{\beta}\left(\frac{\tau}{|\tau|} - f_{\lambda}\right), \quad (1)$$

$$f_{\lambda} = 1 - \frac{\tan\Theta}{\cos\left(\arctan\left(\frac{\partial h}{\partial x}\right)\right)\left[\tan\Theta + \frac{\partial h}{\partial x}\frac{\tau}{|\tau|}\right]}. \quad (2)$$

Here, q is the bed-load sediment transport ($m^2\ s^{-1}$), and f_{λ} is the slope correction term, which acts stronger for larger bed slopes, with an asymptote at the angle of repose Θ. Furthermore, h is the bed level (superimposed on the mean bed level $z = -H$) and x the horizontal coordinate in our 2DV domain.

Lastly, the Exner equation links the divergence of sediment transport to the bed evolution:

$$(1-p)\frac{\partial h}{\partial t} = -\frac{\partial q}{\partial x}, \quad (3)$$

where p is the bed porosity.

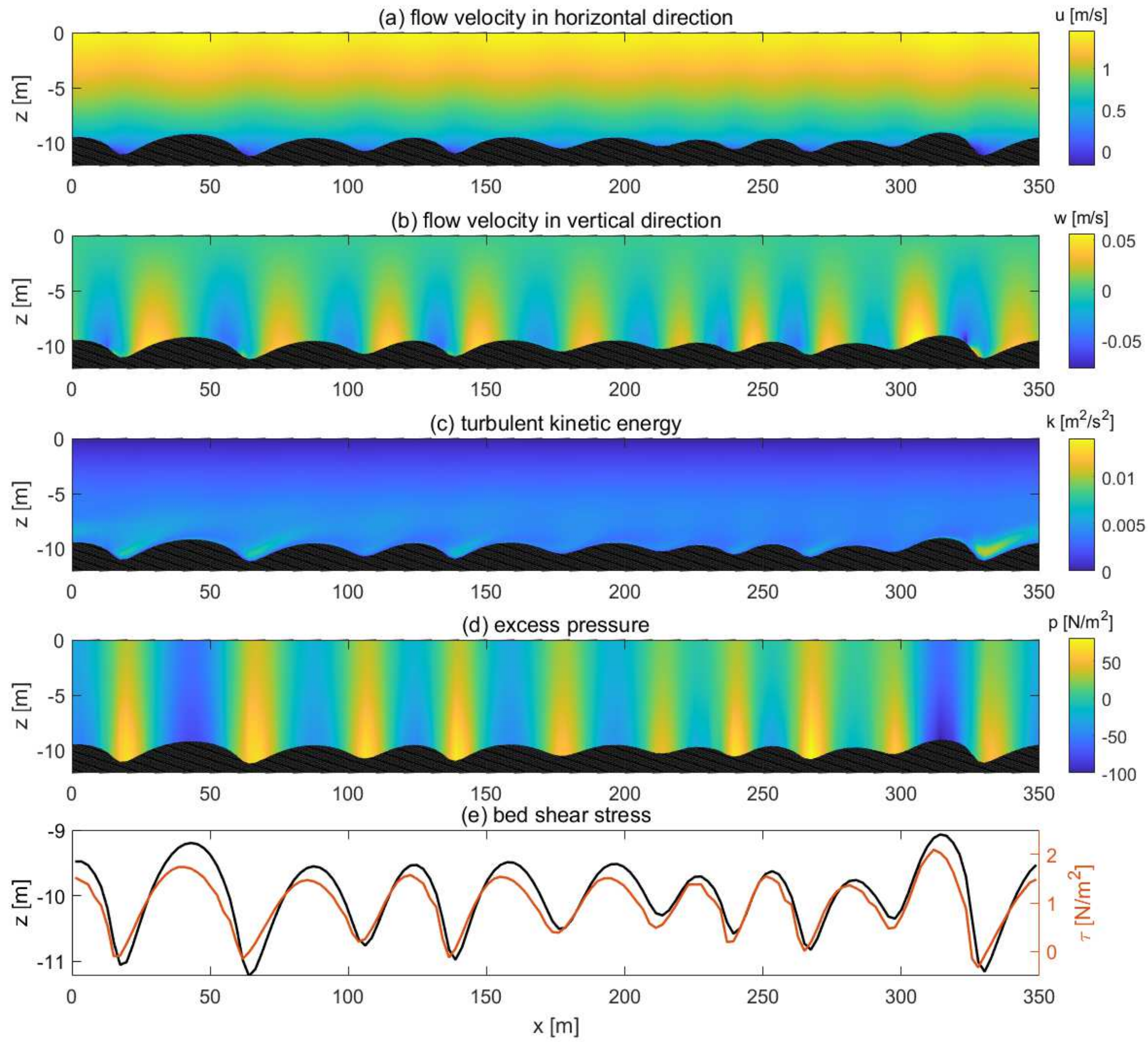

Figure 2. Flow properties over multiple dunes in a periodic domain. From top to bottom: (a) horizontal and (b) vertical flow, (c) turbulent kinetic energy, (d) excess pressure (difference between actual pressure and hydrostatic pressure), and (e) the bed level (left axis) and in orange the bed shear stress (right axis).

3 RESULTS

3.1 Hydrodynamics

We show flow properties over multiple bedforms in a periodic domain with a domain length of $L = 350$ m. The dunes shown have actually been generated by our morphodynamic model, which is further addressed in Section 3.2. Figure 2 shows the bed pattern in all subfigures, and contains the horizontal and vertical flow velocity, turbulent kinetic energy, (excess) pressure and bed shear stress. The excess pressure p is defined as the actual pressure minus the hydrostatic pressure.

The model is, by construction, capable of handling lee-side effects, which can be seen by the flow reversal in the wake around $x =$ 325 m. Lee-side effects give rise to increased turbulent kinetic energy in the wake region. Excess pressure mainly varies in the horizontal direction, although it should be noted that smaller excess pressure variations in the vertical are responsible for wake effects.

Bed shear stress drops in the lee-side, supporting the parameterization used by Paarlberg et al. (2009) for bed shear stress in the flow separation zone.

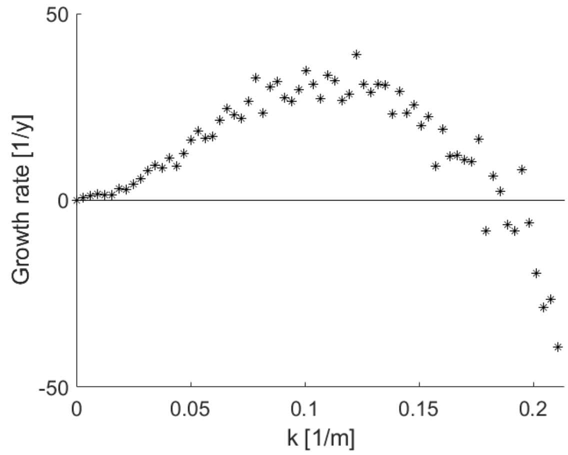

Figure 3. Growth curve as obtained by the morphodynamic model in the linear (initial) phase. Here, k is the topographic wavenumber.

3.2 Morphodynamics

Firstly, we use the initial morphodynamic evolution resulting from our model to find a growth curve which allows comparison to the outcome of linear stability models (Figure 3). It is obtained by starting with a random bed perturbation of small amplitude, the evolution of which reveals the growth rates of all topographic modes involved. The growth rates we find are of similar order of magnitude as those resulting from linear stability models (e.g. Van der Sande et al., 2021). The wavenumber of the fastest growing mode resembles those of river dunes (Lokin et al., 2022). The scatter in Figure 3 is

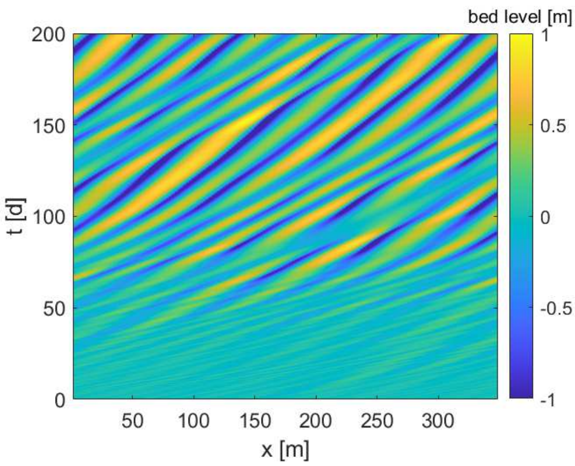

Figure 4. Time stack plot of morphodynamic development during 200 days. The bed profile at $t = 200$ d is the same as shown in Figure 2.

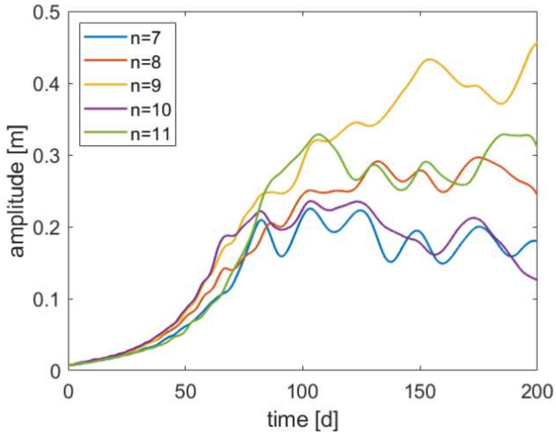

Figure 5. Development of the most dominant modes during the simulation. Herein, the amplitude in meters is defined as follows: $h_n = \hat{h}_n \cos(2n\pi x/L - \phi_n)$, with n the mode and L the domain length (350 meters).

similar as found in an earlier similar study (Campmans et al., 2018), and is likely due to numerical inaccuracies.

Furthermore, we show a time stack plot of dune evolution from an initially perturbed bed, which also includes bed evolution in the nonlinear regime (Figure 4). From this plot, pattern formation as well as migration rates and merging behavior can be discerned.

The development of the most dominant bedform modes corresponding to Figure 4 is shown in Figure 5. Initially, the bedforms show exponential growth (as following from linear stability analyses). After roughly 50 to 100 days, the evolution of the modes starts to deviate from this.

3.3 Feedback of morphodynamics on hydrodynamics: roughness

Due to non-hydrostatic effects of dunes on the flow, the flow field experiences an increased roughness as dunes grow in our morphodynamic model. Figure 6 shows deceleration of the domain-averaged horizontal flow velocity as dunes develop from a flat bed, akin to found by Lefebvre (2013), although here we show the change in domain-averaged flow velocity as dunes develop.

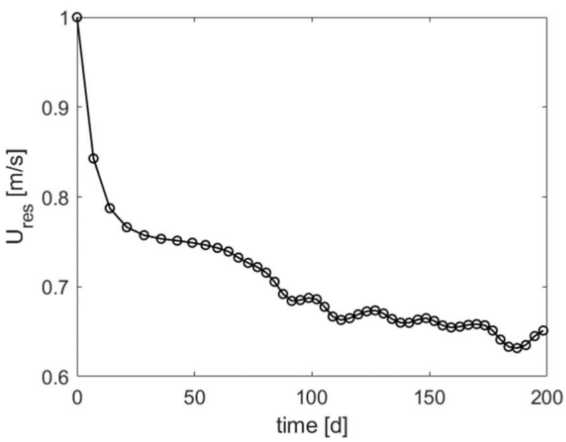

Figure 6. Domain-averaged horizontal flow velocity over time as dunes develop.

4 DISCUSSION

4.1 Dunes as linear instability

Some studies (e.g., Doré et al., 2016; Fourrière et al., 2010) contest that dunes are formed by a linear stability mechanism, and instead argue that dunes form because of amalgamation of smaller scale bedforms (i.e. ripples). The growth curve (Figure 3), nonlinear development of dunes resulting from our model (Figure 4) suggest that these two mechanisms are not mutually exclusive. Instead, the linear instability mechanism allows dunes to initiate and persist while they grow further through amalgamation.

4.2 Equilibrium dune length

From the preliminary runs carried out with our model, we could not find a stable equilibrium of more than one dune in our model domain. This is a defect encountered in many nonlinear bedform models with spatially periodic boundary conditions, which has been pragmatically dealt with in the past by setting the domain length equal to the expected wavelength (e.g. as resulting from linear stability analysis). Laboratory experiments (Bacik et al., 2021) suggest that a combination of suspended sediment transport and turbulence (in their words: “sand trapping efficiency” and “turbulence intensity”) ensure the stable coexistence of two bedforms in a circular flume. An earlier linear study suggested that suspended sediment transport dampens long wavelengths (Borsje et al., 2014). Hence, the omission of suspended sediment transport in our model might be the cause that small wavenumbers continue growing throughout the simulation. This is also suggested by the results of Doré et al. (2016), who included suspended sediment transport and found multiple dunes on a periodic domain. However, their simulation time (order of hours) was not long enough to ensure an equilibrium condition.

Another hypothesis (instead of limited merging) is that dune length is limited through dune splitting. Warmink et al. (2014) showed instances of dune splitting in laboratory experiments, and presented a nonlinear model with a parameterization for dune splitting which yields realistic equilibrium bedform lengths.

4.3 Future research directions

Here, we used a unidirectional forcing, which represents a riverine scenario. In the future, we will also include time-periodic forcing to better represent a marine or estuarine setting, and will build upon past research on estuarine sand dunes (Van der Sande et al., 2021, Van der Sande et al., in press) to include the effects of salinity gradients (through for instance gravitational circulation).

Our model uses a k-ω turbulence closure, which has been shown to be more accurate for flows with adverse pressure gradients (e.g. flow separation) than the widely used k-ϵ closure (Bardina et al., 1997). Hence, our model setup enables accurate calculations of the flow field over asymmetric dunes. Regardless, our model would benefit from validation against data to improve on the chosen (Nikuradse) skin roughness length, and on the choice of the wall function for ω.

The presented model is based on the RANS-equations (i.e. averaged over a turbulent timescale), which, by construction, is not capable of simulating phenomena such as ‘wake-flapping’ (Kostaschuk, 2000; Kwoll et al., 2017; Omidyeganeh & Piomelli, 2011). This phenomenon has been shown to be important for suspended sediment transport (Shugar et al., 2010; Yuill et al., 2020). To describe this effect in a morphodynamic model as presented here, one would need to resort to large-eddy simulations, or find parameterizations to represent it in RANS-based models.

5 CONCLUSIONS

We have presented a newly developed nonlinear morphodynamic model for estuarine sand dunes. Currently, it is capable of capturing river dune dynamics forced by a unidirectional current in the finite amplitude regime. Results show that the hydrodynamic module is capable of capturing lee-side effects as amply described in the literature.

Furthermore, the morphodynamic module shows initially linear growth of sand dunes from a slightly perturbed bed, and later nonlinear interactions between modes, reflecting behavior such as merging of dunes.

In the future, the model will be extended to include bi-directional flow and analysis will be extended to determine roughness coefficients over time as dunes develop.

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