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Simulating Particle Erosion and Deposition in a Lagrangian Sand Transport Model

Natascia Pannozzo[1](✉), Stuart G. Pearson[1], Martin Meijer[2], Tim de Wilde[3],
Edwin Elias[3], and Bram C. Van Prooijen[1]

[1] Delft University of Technology, 2628 CN Delft, Netherlands
N.Pannozzo@tudelft.nl
[2] University of Twente, 7522 NB Enschede, Netherlands
[3] Deltares, Boussinesqweg. 1, 2629 HV Delft, Netherlands

Abstract. Employing Lagrangian particle tracking models for the study of coastal sediment transport dynamics is highly beneficial as they record the complete history of sediment transport pathways. Correctly simulating bed-particle interactions and its stochastic nature in Lagrangian models is essential to accurately estimate the direction and timescale of sediment transport. In this study we compare and assess the performance of two stochastic approaches for simulating particle erosion and deposition in Lagrangian sediment tracking models: 1) formulations proposed by Soulsby et al. (2011) that calculate probability of particles erosion and deposition from empirically-derived parameters and 2) newly-developed formulations that calculate probability of particles erosion and deposition from physical parameters. The two approaches are evaluated in the Lagrangian sediment tracking model SedTRAILS using a simulation of the dispersal of a pilot ebb-tidal delta nourishment in Ameland Inlet (Wadden Sea, Netherlands) as a case study. Our results show that the new physics-based approach represents the diffusive behavior of the nourished sediment better than the empirical approach. However, the new approach could not be fully validated yet, and the implementation of a slope term for bedload transport in the SedTRAILS transport formulations is necessary to further evaluate the new physics-based approach.

Keywords: Lagrangian · Particle Tracking · Sand Transport · Erosion · Deposition

1 Introduction

Lagrangian particle tracking models are valuable tools for investigating sediment transport dynamics in coastal settings, as modelling in a Lagrangian framework records the complete history of particle transport sources, sinks, and the pathways between them [1]. Correctly implementing erosion and depositional processes in sediment particle tracking models is essential to accurately simulate the direction and timescale of sediment transport. However, only a few Lagrangian sediment tracking models currently simulate the interaction between the sea-bed and sediment particles, either deterministically

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[2, 3] or stochastically [2, 4]. While a deterministic approach is easier to compute, the advantage of simulating bed-particle interactions stochastically is that such an approach takes into account the complexity of the natural interactions between the sea-bed and sediment particles [5]. Thus far, stochastic approaches have employed either physical [2] or empirically-derived [4] parameters.

In this study we aim to understand which approach (physical or empirical) is most effective for stochastically simulating erosion and depositional processes in Lagrangian sediment tracking models. To do so, we compare and assess the performance of 1) formulations proposed by Soulsby et al. (2011) that calculate probability of particles erosion and deposition from empirically-derived parameters and 2) newly-developed formulations that calculate probability of particles erosion and deposition from physical parameters. The two approaches are evaluated by computing them in the Lagrangian sediment tracking model SedTRAILS [6] and simulating the dispersal of a pilot ebb-tidal delta nourishment carried out in Ameland Inlet (Wadden Sea, Netherlands; Fig. 1) as a case study [7].

2 Methods

2.1 Computing Particle Erosion and Deposition

In the empirical approach of Soulsby et al. (2011), erosion (P_{er}) and deposition (P_{dep}) probability are calculated as follows:

$$P_{er} = a \cdot P_{mob} \tag{1}$$

$$P_{dep} = b \cdot P_{mob} \tag{2}$$

where

$$a = \gamma_e \cdot b/(1 - \gamma_e) \tag{3}$$

$$b = b_e \cdot \{1 - exp\,[-(\theta_{max} - \theta_{cr})/\theta_s]\} \tag{4}$$

$$P_{mob} = \{1 + [\frac{\pi}{6} \cdot \mu_d/(\theta_{max} - \theta_{cr})]^4\}^{-1/4} \tag{5}$$

where γ_e is the long-term equilibrium proportion of particles that are free (~ 0.01), b_e is the maximum free-to-trapped transition probability (~ $1.7 \cdot 10^{-3}$ s^{-1}), θ_{max} is the maximum value that the Shields parameter can take, θ_{cr} is the critical value for erosion of the Shields parameter, θ_s is the scale value that determines the distribution of residence times (~ 1.2), and μ_d is the dynamic friction coefficient (0.5).

In the new physics-based approach developed here, we calculate erosion (P_{er}) and deposition (P_{dep}) probability as follows:

$$P_{er} = E/(\phi \cdot \lambda) \tag{6}$$

$$P_{dep} = (w_s \cdot R)/h \tag{7}$$

where E (m s^{-1}) is the rate of erosion [8], ϕ [-] is the solid fraction of a sediment volume, λ (m) is the thickness of the active layer [9], w_s (m s^{-1}) is the settling velocity, R [-] is the Rouse number, and h (m) is the water depth derived from the hydrodynamic model.

A key assumption in both approaches is that short-term particle-bed interaction is taken into account (e.g., mixing at the surface of the bed or entrainment by ripples), but the effects of large-scale morphodynamic changes on particle burial and erosion is not.

SedTRAILS computes the position of sand particles using a 4th-order Runge Kutta algorithm to solve the following equation:

$$\frac{\partial \vec{x}}{\partial t} = F(t) \cdot [\vec{U}(\vec{x}, t) + D(\phi_{diff}) \cdot \vec{U}(\vec{x}, t)] \quad (8)$$

where $\overrightarrow{x}$ is the horizontal position of a particle, t is time, $F(t)$ is a "burial factor" determining if a particle is buried ($F = 0$) or active ($F = 1$), $D(\phi_{diff})$ is a random walk scaling factor to estimate the sediment diffusion in random direction ϕ_{diff}, and $\overrightarrow{U}$ is the spatiotemporally varying particle velocity derived from flow velocity fields [4]. F is determined stochastically for each particle at every timestep. In the physics based-approach, when a particle is buried ($F = 0$), if P_{er} is higher than a randomly generated number $0 \leq n \leq 1$, the particle erodes (F becomes 1), otherwise it stays buried; when a particle is active ($F = 1$), if P_{dep} is higher than a randomly generated number $0 \leq n \leq 1$, the particle deposits (F becomes 0), otherwise it says in suspension. In the empirical approach, the state of F changes based on whether a and b are higher or lower than the randomly generated number, while P_{mob} is a flow field-derived parameter that multiplies a and b in a separate computational step.

2.2 Simulation of Nourishment Dispersal

In order to assess the behavior of the two approaches in simulating the dispersal of the Ameland ebb-tidal delta nourishment, SedTRAILS simulations that employ the same bathymetric configuration and hydrodynamic forcings (flow-only; derived from a Delft3D model of Ameland Inlet [7]) are run using both the Soulsby et al. (2011) empirical approach and our new physics-based stochastic approach for the calculation of particle erosion and deposition probability. A sample of 500 representative sand particles ($D_{50} = 200$ μm) is randomly sourced within the nourishment area (Fig. 1) at the beginning of the simulation, with an initial $F = 1$ to characterize erodible nourishment sediment. For verification purposes, maps of particle positions are generated at different time steps of the SedTRAILS simulation for both approaches and compared with maps of sand spatial distribution derived from the Delft3D (Eulerian) simulation for 200 μm sand eroded from the nourishment area.

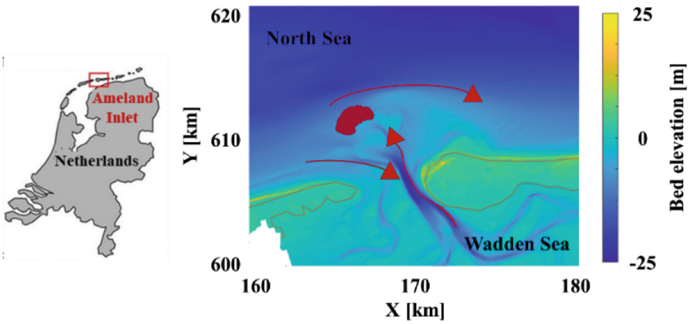

Fig. 1. Location (red rectangle) and bed elevation of the Ameland Inlet, release location of the sand parcels (red filled circles) at the ebb-tidal delta, and direction of observed net tidal transport [7] (red arrows). Island coastlines are indicated by thin brown lines.

3 Results

3.1 Erosion and Deposition Probabilities Across the Ameland Inlet

In both approaches, P_{er} is greater in magnitude within areas with higher bed shear stress (e.g., channels) at high and low tide, while it increases over other deep areas of the domain during flood and ebb phase. Its magnitude, however, is overall significantly higher in the physics-based approach. P_{dep}, on the other hand, displays completely different behavior depending on the approach used. In the empirical approach, P_{dep} mirrors the behavior of P_{er} over the different tidal stages. For the new physics-based approach, P_{dep} is highest over shallower areas (e.g., tidal flats) during flood and ebb phase and it increases over deeper areas of the domain at high and low tide. Again, its magnitude is overall significantly higher in the physics-based approach (Fig. 2).

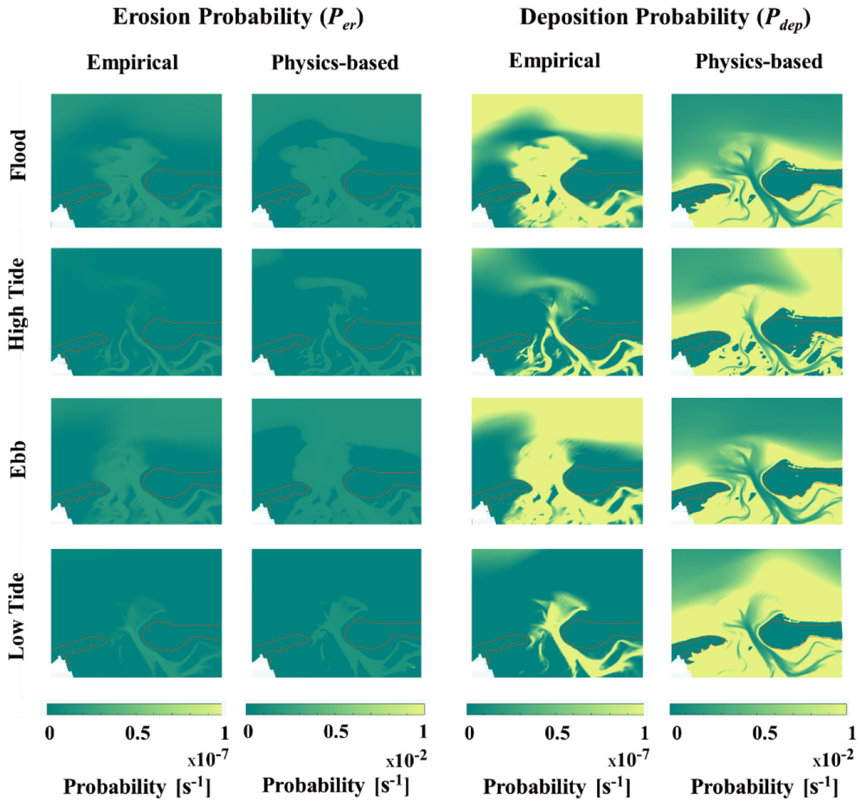

Fig. 2. Erosion probability (P_{er}) and deposition probability (P_{dep}) calculated across the Ameland Inlet using the empirical and the physics-based approach for different tidal stages. Island coastlines are indicated by thin brown lines.

3.2 Nourishment Dispersal Analysis

The sand spatial distributions derived from the Eulerian simulation show sand diffusing from the nourishment area in the first 3 days of the simulation and roughly staying within the same area of the domain for the rest of the simulation. The SedTRAILS simulation, when the empirical approach is employed, results in sand particles clustering together for the whole duration of the simulation and quickly moving eastwards in the direction of the tidal flow, until they leave the domain. The particle movement in this case does not reflect at all the behavior displayed by the sand in the Eulerian simulation. When the physics-based approach is employed, the particles are more spread across the domain. Some of the particles spread around the nourishment area in the first 3 days of the simulation and their position remains roughly constant for the rest of the simulation, reflecting in part the behavior displayed by the sand in the Eulerian simulation. The remaining particles, however, still move eastwards in the direction of the tidal flow (Fig. 3).

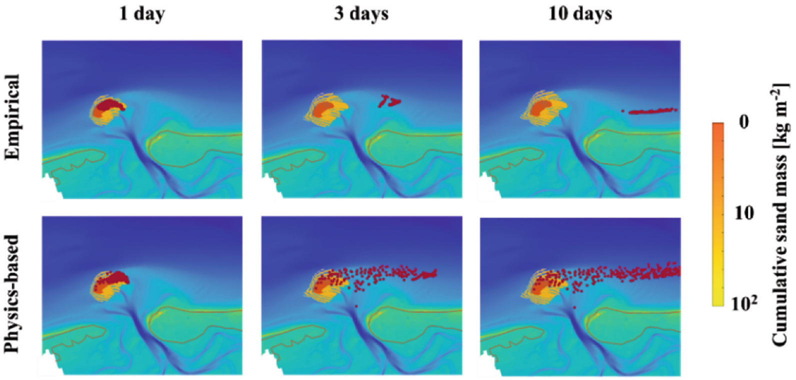

Fig. 3. Position of the 200 μm sand particles (red filled circles) after 1, 3, 10 and 30 days from the beginning of the SedTRAILS simulation performed using the empirical and the physics-based approach compared with cumulative (bedload + suspended) sand mass derived after 1, 3, 10 and 30 days from the beginning of the Delft3D simulation for the 200 μm sand eroded from the nourishment area. Island coastlines are indicated by thin brown lines.

4 Discussion and Conclusions

All particles released in the nourishment area have an initial $F = 1$, such that they are free to erode at the beginning of the simulation. The empirical approach estimated erosion and deposition probabilities with very small magnitudes ($O(10^{-7}\ s^{-1})$) and produced no areas of net deposition, as particles are able to change state only above a critical threshold of motion ($\theta_{max} > \theta_{cr}$), neglecting low-energy areas. This means that the probability for particles to deposit and bury across the system is minimal, and the particles tend to be mostly transported by the tidal flow away from the domain. The physics-based approach estimated higher probabilities of state changes ($O(10^{-2}\ s^{-1})$) and produced distinct areas of net erosion and deposition, which allowed a more frequent switch of F between "active" and "buried" states. This prevented the particles from being completely transported away from the domain and allowed more spreading of particles across the system, producing more diffusive patterns which resemble in part the spreading displayed by the sand in the Eulerian simulation.

This study showed that the physics-based approach represents the diffusive behavior of the nourished sediment better than the empirical approach. There is, however, still a mismatch between the Eulerian and Lagrangian results even when the physics-based approach is employed (i.e., many of the particles are still carried eastwards by the tidal flow). There is high likelihood that the discrepancy is due to some limitations of the transport formulations currently employed in SedTRAILS (e.g., the lack of a slope term for bedload transport [10], which may be important around the relatively steep bathymetric features of the nourishment and ebb-tidal delta) or to the definition of the active layer thickness. Further development of SedTRAILS and sensitivity tests are therefore necessary to further evaluate the physics-based approach developed here.

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