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Emergent Sediment-Sharing Cells in a Barrier Island-Lagoon System

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Abstract. Coastal sediment budgets are a foundational source of information for coastal management decision-making. To quantify these budgets, coastal systems are often divided into "cells" based on jurisdictional boundaries or topography. However, such divisions do not account for the pathways that water and sediment particles actually take. In this study we quantify cell boundaries that emerge from numerical simulations of sand and water pathways in a barrier island-lagoon system in the Netherlands (the Western Wadden Sea). By quantifying Lagrangian particle pathways as a network, we can derive internally well-connected but externally disconnected modules. Here we show that large (O(10 km)) coherent modules develop from flow patterns at tidal timescales (12.5 h), and are persistent through varying tide and weather conditions. Conversely, modules derived from 100 μm sand pathways are less coherent and highly spatially fragmented. The difference in patterns likely relates to the longer timescales associated with sediment transport. These emergent patterns could be used to better inform coastal and estuarine management by providing physics-based sediment cell boundaries.

Keywords: sediment connectivity · network analysis · modularity · barrier island · lagoon

1 Introduction

Coastal sediment budgets are a foundational source of information for coastal management decision-making. These budgets are often estimated based on bathymetric changes, and their internal boundaries or "cells" delimited based on jurisdictional boundaries or topography. However, such approaches neglect a key consideration: do these cell boundaries actually correspond to the pathways that water and sediment particles take? What are the internal boundaries that naturally emerge in coastal systems? To answer these questions, we apply a Lagrangian sediment transport model to the Western Wadden Sea, a barrier island-lagoon system in the Netherlands, and derive emergent sediment-sharing cells using the connectivity approach of Pearson et al. [1].

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2 Methodology

2.1 Hydrodynamic and Sediment Transport Modelling

We used a Delft3D-FM model of the Western Wadden Sea [2] to hindcast the hydrodynamic conditions at 30 min intervals from August 29th to October 9th, 2017. The model accounts for tidal and wind-driven forcing but not the effects of waves, focusing for now on larger-scale flow patterns. To estimate particle pathways, we use the Sed-TRAILS model [3]. We released particles on a uniform 667x667 m grid (9194 particles total) every 12.5 h (80 simulations total), and tracked their movement for 12.5 h (~1 tidal cycle). We first consider passive tracers (moving with depth-averaged velocity) as a baseline (Fig. 1a), and then 100 μm sand. The sediment velocity field was defined from bed shear stress and flow velocity using the method of Soulsby et al. [4]. Particle burial and mixing within the seabed are neglected to focus on sediment pathways of maximum potential lengths.

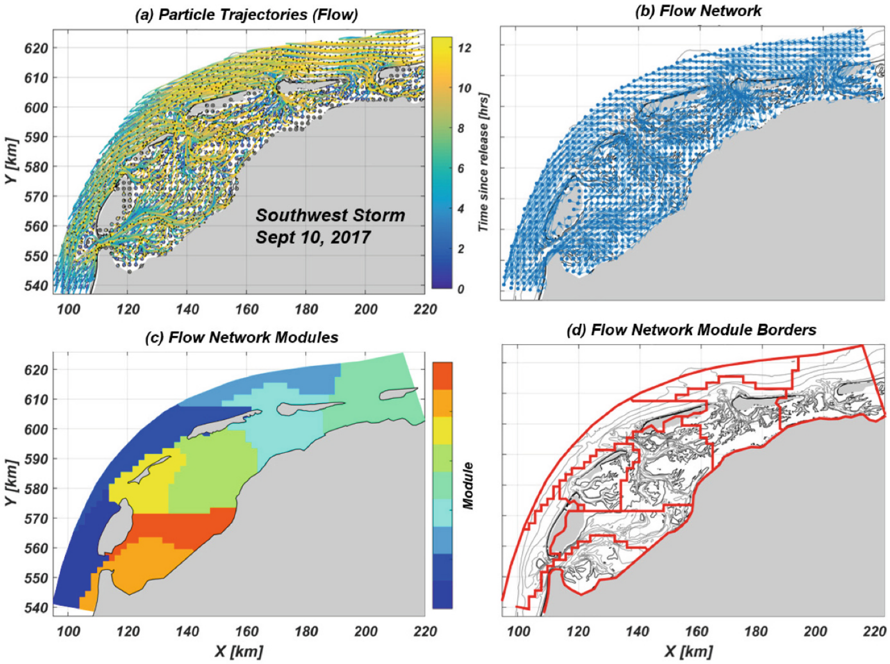

Fig. 1. Example workflow to derive network module borders, based on a single tidal cycle on September 10, 2017, during a storm with winds primarily from the southwest. **(a)** Passive particle trajectories advected by depth-averaged flow and coloured by time since release. **(b)** Network diagram indicating connections between each node. **(c)** Network modules, defined by high connectivity within modules and limited connectivity between modules. **(d)** Borders of network modules in panel (c). The identical procedure was repeated for 80 tidal cycles.

2.2 Network Analysis

We then compiled the particle pathways from each SedTRAILS run into a connectivity network (Fig. 1b) as per [1]. Network nodes are spaced out on a uniform 2000x2000 m grid (963 total, containing ~ 9.5 particle sources each), and the connections between them are estimated based on the number of particles from a given source node that reach a given sink node. Using the Leicht & Newman algorithm for directed networks [5], we define groups of nodes ("modules") that have high within-group connectivity and low between-group connectivity (Fig. 1c). Following Thiemann et al. [6], we can define the borders of these modules (Fig. 1d). By linearly superimposing the borders corresponding to each tidal cycle, we can visualize which borders are more persistent through time.

3 Results

Here we first consider how the global network properties vary in time for both flow and 100μm sand networks. The flow network is better connected during windier storm events and spring tide, as quantified by network density (Fig. 2a,c). Overall system connectivity is persistently lower for sand, although it still varies with storms and spring-neap cycles.

This behaviour is further reflected in the networks' tendency to form separate modules, as quantified by modularity (Fig. 2c). Disconnected modules tend to join up into larger, more coherent modules during storms, leading to reduced modularity. Given the shorter transport pathways and reduced connectivity of the sand network, its nodes tend to cluster in smaller modules.

By considering an ensemble of module borders over the study period, we can better understand the persistent water- and sediment-sharing cells that emerge in the Western Wadden Sea (Fig. 3). Flows in the Western Wadden Sea exhibit a tendency to form large modules (O(10 km)) at tidal timescales (~12.5 h) that are persistent over the simulated 40-day period (Fig. 3a). Although geographic coordinates of each node in the network are not included in the modularity calculation, spatially coherent cells nevertheless emerge, indicating strong local connectivity and mixing. The persistent modules have a spatial scale closer to the mean excursion length ΣX travelled by particles (14.7 km) than to their net displacement ΔX (3.8 km) (Fig. 2d). Over a single tidal cycle, modules spanning the entire domain (O(100 km)) do not develop, even under the most energetic conditions.

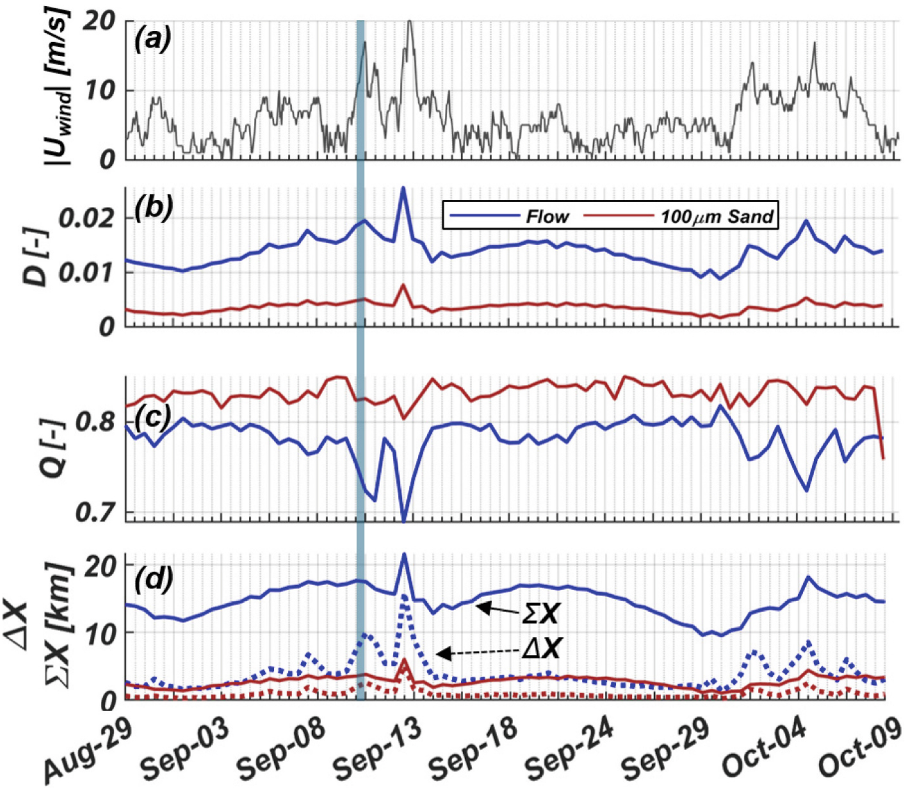

Fig. 2. **(a)** Windspeed magnitude measured at Terschelling (Hoorn). **(b)** Network density (D), which represents the fraction of actual connections out of all possible connections. **(c)** Network modularity (Q), where high values indicate a greater tendency to form separate modules. **(d)** Net particle displacement ΔX and particle excursion length ΣX, averaged across all particles in each simulation. Light blue vertical line corresponds to example in Fig. 1 from September 10, 2017.

Although many of these borders coincide with topographically-defined tidal watersheds between adjacent inlets (the most persistent borders occur around the Eierlandse Gat sub-basin and Terschelling watershed), they are quite variable depending on weather conditions (Fig. 3a). Furthermore, the Marsdiep and Vlie basins feature several persistent sub-modules. Equally relevant as the barriers are the areas without any barriers (e.g., Ameland basin), suggesting areas of strong internal mixing.

Conversely, the 100 μm sand network shows a much weaker spatial coherence, forming many smaller (O(1 km)) and more spatially-fragmented nodes (Fig. 3b). As with flows, persistent sand modules have a spatial scale similar to the mean sand excursion length (2.7 km). The "fuzzy" module borders of the sand network also indicate that module connections are not as temporally consistent as in the flow network. This is supported by the weak trend in sand modularity through time in Fig. 2c. The landward side of Ameland basin in Fig. 3b shows a sharp border at the edge of quiescent intertidal areas where sand is less frequently mobilized.

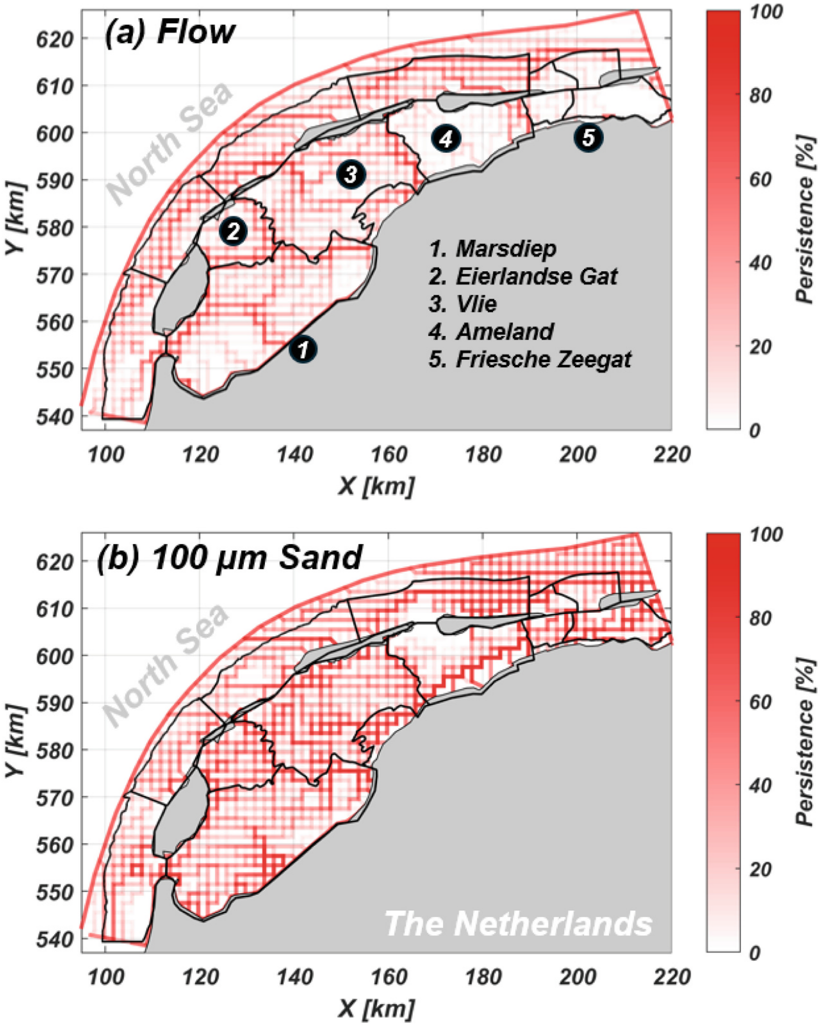

Fig. 3. Module borders for **(a)** flow and **(b)** 100μm sand networks. Borders from each 12.5 h period are linearly superimposed on each other, with darker red lines representing more persistent borders. Black lines indicate management boundaries based largely on topography, used by Elias & Wang [7] to derive sediment budgets.

4 Discussion

Coherent modules emerge from flow patterns in the Western Wadden Sea, while sediment transport produces much more fragmented modules at similar timescales. Unlike passive water particles, sand particles are limited by their critical threshold of motion, and respond nonlinearly to flows. This explains why some areas (e.g., tidal inlets where velocities are strong) are well-connected with more coherent modules, while other areas (e.g. within the Wadden Sea) show limited motion, low connectivity, and fragmented modules (Fig. 3b). While 12.5 h is apparently a sufficiently long time to generate coherent modules in the flow network, we hypothesize that longer simulation times may be needed to produce similar patterns in sediment networks. The relationship between module size and particle path length suggests that module properties also vary as a function of grain size.

Our findings point to the need for a deeper examination of the spatiotemporal evolution of marine connectivity. This approach could be used to better delineate sediment cells for coastal management and sediment budgets, bridging between small and large spatiotemporal scales. Future research will focus on the influence of longer simulation periods, higher spatial resolution, and varying grain sizes (including fine sediment).

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