Primary Topic: Coastal sediment transport
Secondary Topic: Coastal nourishments and interventions

LAGRANGIAN SEDIMENT TRANSPORT MODELLING AS A TOOL FOR INVESTIGATING COASTAL CONNECTIVITY

S.G. Pearson[1,2], E.P. Elias[2], M. van Ormondt[2], F.E. Roelvink[2], P. Lambregts[1,2], Z.B. Wang[2,1], B.C. van Prooijen[1]
[1]Delft University of Technology, Department of Hydraulic Engineering, Delft, 2600GA, The Netherlands. s.g.pearson@tudelft.nl, paulamaria.lambregts@gmail.com, b.c.vanprooijen@tudelft.nl
[2]Deltares, Department of Applied Morphodynamics, Delft, 2600MH, The Netherlands
Edwin.elias@deltares.nl, maarten.vanormondt@deltares.nl, Floortje.roelvink@deltares.nl, Zheng.Wang@deltares.nl

1. Introduction

Estuaries and coasts can be conceptualized as connected networks of water and sediment fluxes. These dynamic geomorphic systems are governed by waves, tides, wind, and river input, and evolve according to complex nonlinear transport processes. To predict their evolution, we need to better understand the pathways that sediment takes from source through temporary storage areas to sink. Knowledge of these pathways is essential for predicting the response of such systems to climate change impacts or human interventions (e.g., dredging and nourishment). The conceptual framework of sediment connectivity has the potential to expand our system understanding and address practical coastal management problems (Pearson et al., 2020).

Connectivity provides a structured framework for analyzing these sediment pathways, schematizing the system as a series of geomorphic cells or nodes, and the sediment fluxes between those nodes as links (Heckmann et al., 2015). Once organized in this fashion, the resulting network can be expressed algebraically as an adjacency matrix: sediment moving from a given source to different receptors. There is a wealth of pre-existing statistical tools and techniques that can be used to interpret the data once it is in this form, drawing on developments in other scientific disciplines (Newman, 2018; Rubinov & Sporns, 2010). Lagrangian flow networks have been increasingly used to analyze flow and transport pathways in oceanographic and geophysical applications (Padberg-Gehle & Schneide, 2017; Reijnders et al., 2021; Ser-Giacomi et al., 2015). However, this approach has not yet been adopted to analyze coastal or estuarine sediment transport, and requires a multitude of field measurements or numerical model simulations.

Lagrangian particle tracking has been widely used to assess connectivity in the context of oceanography and marine ecology (Hufnagl et al., 2016; van Sebille et al., 2018), because the models record the complete history of a particle's trajectory, not only its start and end points. Particle tracking models are also relatively fast and lend themselves well to parallel computing (Paris et al., 2013). This approach thus permits a faster and more detailed analysis of sediment connectivity than existing Eulerian approaches (e.g., Pearson et al., (2020)). Although several Lagrangian sediment transport models have been developed (e.g., (MacDonald & Davies, 2007; Soulsby et al., 2011)), they have not been used to support connectivity studies. Hence, there is a need for Lagrangian sediment particle tracking tools tailored to predicting sediment transport pathways and determining connectivity of complex coastal systems.

To meet this need, we developed a Lagrangian sediment transport model, SedTRAILS (Sediment TRAnsport vIsualization & Lagrangian Simulator) and used it to develop a sediment connectivity network. Our approach provides new analytical techniques for distilling relevant patterns from the chaotic, spaghetti-like network of sediment pathways that often characterize estuarine and coastal systems. We demonstrate a proof of concept for our approach by applying it to a case study of Ameland Inlet in the Netherlands, and provide an outlook for future research opportunities using these tools.

2. Methodology

Our approach for determining sediment connectivity has four main steps: (1) Simulating hydrodynamics and (2) sediment transport with an Eulerian model; (3) Estimating Lagrangian sediment transport pathways using SedTRAILS; and (4) deriving a sediment connectivity network from those pathways.

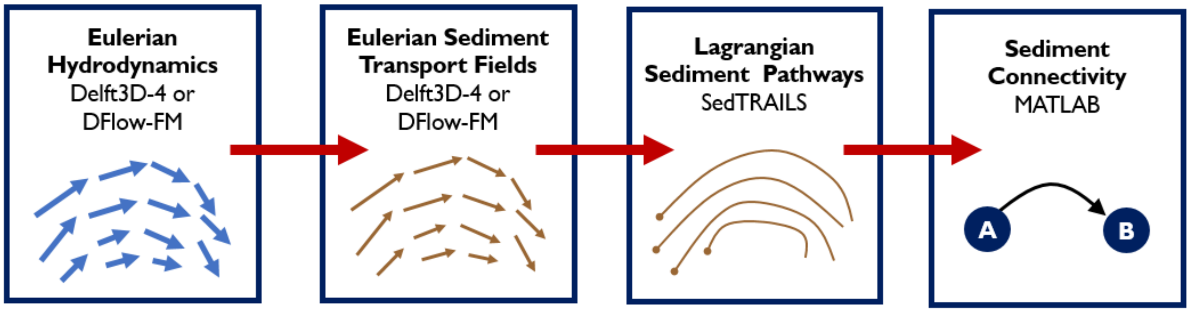

Figure 1. Flow chart of the modelling methodology, beginning with an Eulerian hydrodynamic and sediment transport model. Lagrangian sediment pathways are then computed using SedTRAILS, which can then be used as input for connectivity analysis.

2.1. Eulerian Model

A 2D hydrodynamic and morphostatic sediment transport Delft3D model (Lesser et al., 2004) formed the basis of our analysis. The model domain was centered on Ameland Inlet and extends to the adjacent Vlie and Frisian Inlets to capture inter-basin flows within the Wadden Sea. The grid resolution ranges from 50 m in Ameland Inlet to 350 m at the boundaries. The bathymetry was based on surveys from 2017, with data from 2008-2017 used to fill gaps. The model forcing was derived from tides, wind, and wave measurements spanning the entire year 2017. A more detailed description of the model set up is provided in Nederhoff et al. (2019).

To advect particles, we derived sediment velocity fields from suspended and bed load flux fields divided by a constant scaling factor. Diffusion was incorporated using a random displacement at each timestep. Precomputing the sediment transport velocity fields to decouple them from the sediment trajectory computation led to efficient run times.

2.2. Lagrangian Model

We adapted the Lagrangian model described by Storlazzi et al. (2017) to advect particles using sediment transport velocities computed in the previous step. Five-hundred geomorphic cells were defined using a *k*-means algorithm to cluster the bathymetry, weighted by XY position and bed elevation. This ensured that cells were distributed evenly throughout the domain, in a way that prioritizes higher density for areas with larger gradients in bathymetry (Figure 2a). The centroids of these cells were used as the initial sources for the SedTRAILS simulations. Particles trajectories were then computed for each source using forcing corresponding to the entire year 2017.

2.3. Derivation and Analysis of Connectivity

To estimate connectivity and compile the results into a graphical network, we started by considering the trajectory of particles from a single source (i). The position of every particle was recorded at each subsequent timestep of the model (t_{total}). A given particle may pass through several other receptor cells (j) during the simulation, and the number of timesteps it spends in each of those cells is effectively a "residence time" ($t_{r,j}$). The connectivity between a given source (i) and a given receptor (j) was thus calculated as $C_{ij} = t_{r,j}/t_{total}$. For example, the sediment pathways and resulting connectivity for a single source are depicted in Figure 2b and c. This calculation was then repeated for each of the 500 sources.

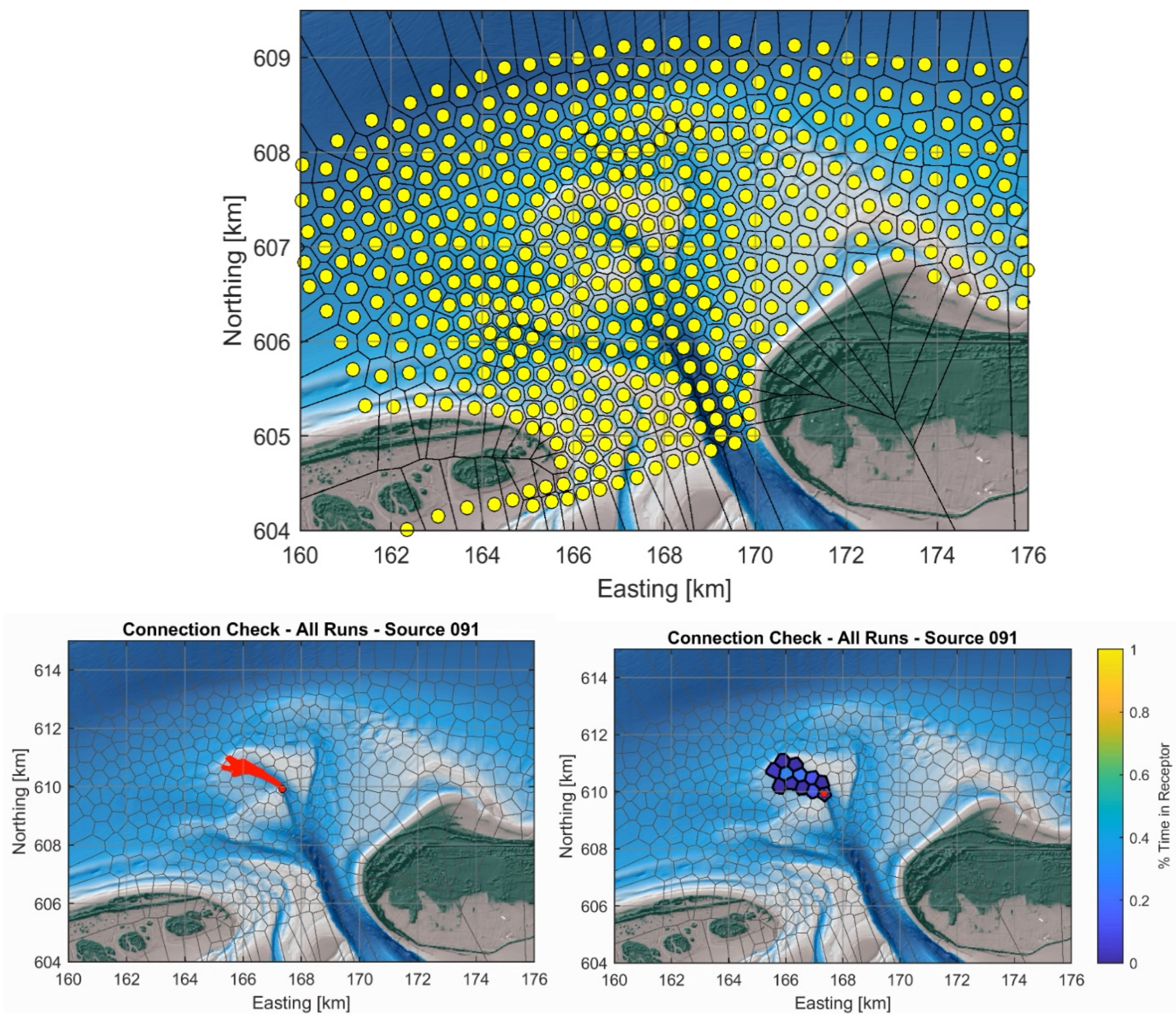

Figure 2. (a) Source locations for all particles, as determined via *k*-means cluster analysis of the bathymetry. (b) Example of particle positions computed by SedTRAILS for Source 091. Particles originate at the large red and black circle, then travel in a northwesterly direction to the outer lobe of the ebb-tidal delta, passing through several geomorphic cells on its way. (c) Example of tabulated connectivity between Source 091 and its receptors. The number of particles $t_{r,j}$ in each receptor cell j is counted and divided by the total number of particles t_{total} under consideration. Since a single particle is released at the start of the simulation and its position stored at each timestep, the colour of each receptor cell thus corresponds to the percentage of a given particle's total lifespan spent in each cell. For example, if a particle spends 25 out of 500 timesteps in a cell, that receptor cell will have a connectivity C_{ij} of 0.05.

The matrix given by C_{ij} for all *i* and *j* is known as the adjacency matrix (Figure 4a). A column *j* in the matrix corresponds to all the different sources *i* contributing to a particular receptor *j*. For example, sediment originating in Cell 91 ($C_{091,j}$) and travelling to all connected receptors j is indicated by the red dots in Figure 4a.

This matrix can also be represented as a network diagram, where each source or receptor becomes a point on a map connected to one another by links. For example, we can visualize the connections from Node 91 to its receptors (given by the red dots in Figure 4a) as a series of red arrows in Figure 4b. By drawing the connections originating from all 500 nodes in the network, we arrived at the complete network diagram in Figure 4b. Once the network was compiled, we used connectivity metrics such as degree and strength to describe individual nodes, as well as shortest-pathway analysis to characterize transport across the entire system (Pearson et al., 2020).

3. Results

3.1. Sediment Pathways

We first considered the transport pathways of sediment originating from each of the 500 sourc es across the ebb-tidal delta (Figure 3). Key patterns included (i) bypassing via the inlet; (ii) trans port along the outer delta; (iii) pathways along the main ebb channel; (iv) recirculation at several locations. To unravel key patterns in the spaghetti-like trajectories, we then computed connectivit y.

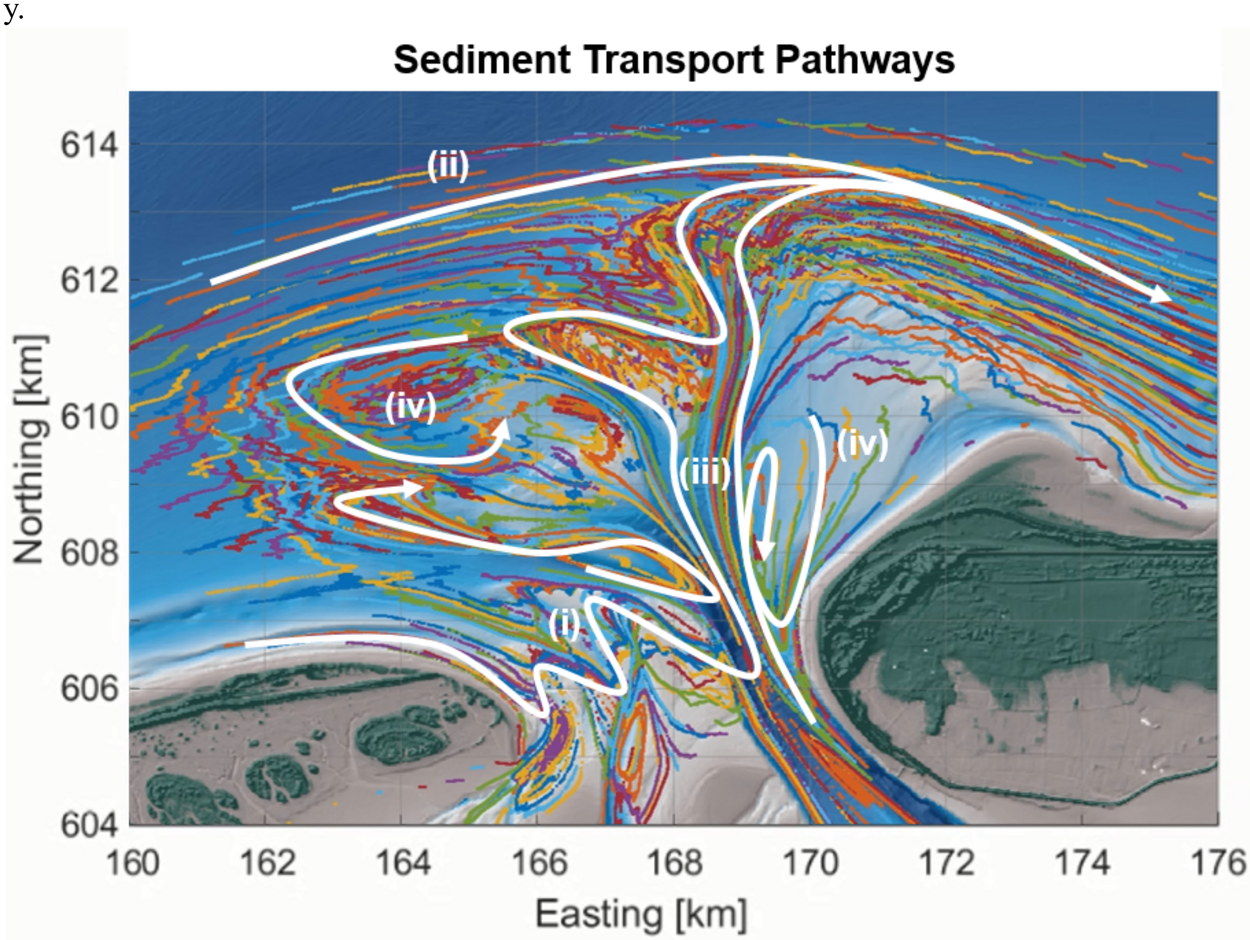

Figure 3. Sediment pathways derived from SedTRAILS. Each colour indicates a sediment transport pathway originating from a different source. Main pathways include (i) inlet bypassing, (ii) transport along the outer delta, (iii) transport through the main ebb channel, and (iv) recirculation.

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3.2. Network Analysis

Within the transport network (Figure 4b), the same patterns visible in the SedTRAILS trajectories were also evident. In addition to the patterns visible in the SedTRAILS trajectories (Figure 3), the transport network (Figure 4b) makes several trends apparent:

A. The network is most densely connected on the ebb shoals, Boschplaat, and tip of the main ebb channel (Akkepollegat). These are areas with strong tidal currents and/or strong wave forcing.
B. The network shows a general eastward direction in its connections, which matches what we expect from our understanding of both the forcing and historical changes to the inlet (Elias et al., 2019; Pearson, van Prooijen, et al., 2021; Pearson, Verney, et al., 2021).
C. Sheltered areas on the Bornrif platform and on the Wadden Sea side of Terschelling, or deeper areas in the offshore corners of the domain are completely disconnected from the rest of the system. The low connectivity of this morphologically active region (c.f. Elias et al. (2019)) is likely explained by the model schematization, forcing, and timescale applied here.
D. There appears to be little cross-channel connectivity in the main Borndiep channel, although this may be partly a limitation of the 2D model.

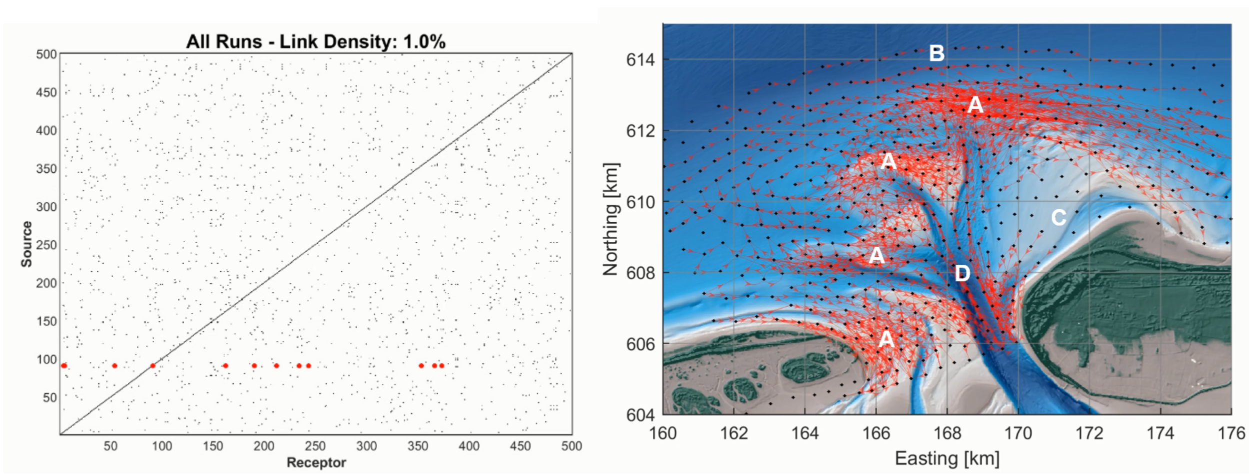

Figure 4. (a) Adjacency matrix for all timesteps of all 2017 scenarios. Each point on the plot is representative of a connection from source i to receptor j. The central diagonal denotes self-self interactions, which are particles that remain in or return to their source. As a demonstration, connections from Source 091 to all other receptors are highlighted in red. Link Density indicates the fraction of actual connections out of all possible connections. (b) Network diagram for all connections in the network. Red lines indicate the connection between two nodes, with their thickness implying the strength of the connection, and the arrow indicating the direction.

3.3. Individual Node Analysis

The characteristics of individual nodes in the network provide useful information about local sediment transport behavior. First we considered degree, which is the number of nodes that a given node is connected to, in a binary fashion, irrespective of how many particles are passing through (Figure 5a). As such, degree highlights nodes that have a more diverse range of connections than the strength plot (Figure 5b). Degree can be considered as an indicator of mixing, comparable to the Finite-Time Lyapunov Exponent (FTLE) (Ser-Giacomi et al., 2015). The main channels may be “busier”, but the distal end of the ebb shoals have a higher degree because particles reaching the end of the shoals come from many different origins: particles from upstream in the channel and beyond, locally resuspended material from more immediate neighbours, and also material being bypassed from updrift. It is thus a convergent zone of intense sediment mixing from many different sources.

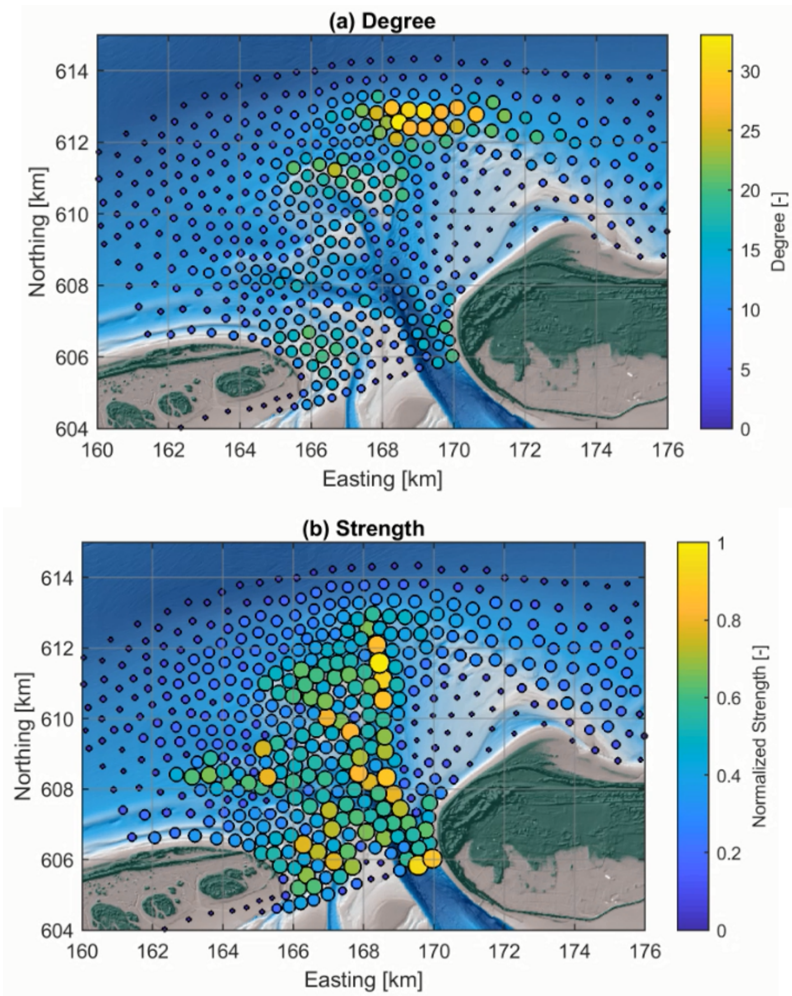

Figure 5. (a) Degree of each node in the network. Lighter colours and larger dots indicate that more other nodes are connected to a given node, either as sources or receptors. (b) Strength of each node in the network. Lighter colours and larger dots indicate that more particles are passing into or out of a given node.

Secondly, we considered node strength, which in our case corresponded to the number of particles passing in and out of a given receptor – highlighting the “busiest” receptors (Figure 5). In general, these areas corresponded to the channels and tips of shoals.

3.4. Dominant Bypassing Pathways

One of the most valuable features of network theory is that it allows us to consider connected pathways across a network as a whole. Let us consider the distance between two nodes to be the inverse of its weight (a higher weight indicates a larger flux and stronger connection, so the “distance” between those points is shorter). We can then derive a matrix of the shortest (although not necessarily fastest) path along the network between any two nodes. This matrix can then be queried to find relevant pathways, such as the main bypassing routes across or around the inlet.

Here we consider the shortest bypassing routes from a transect seaward of Terschelling to a point on Ameland (Figure 6). This map was produced using the network and does not show actual particle trajectories (none of the particles ever travelled the entire width of the inlet during the simulation; rather, it shows the most efficient paths through the network by linking all of the particle trajectories together). The patterns here are similar to those presented in Pearson et al. (2020), but with 500 nodes rather than 25, so the detail of the pathways is much greater.

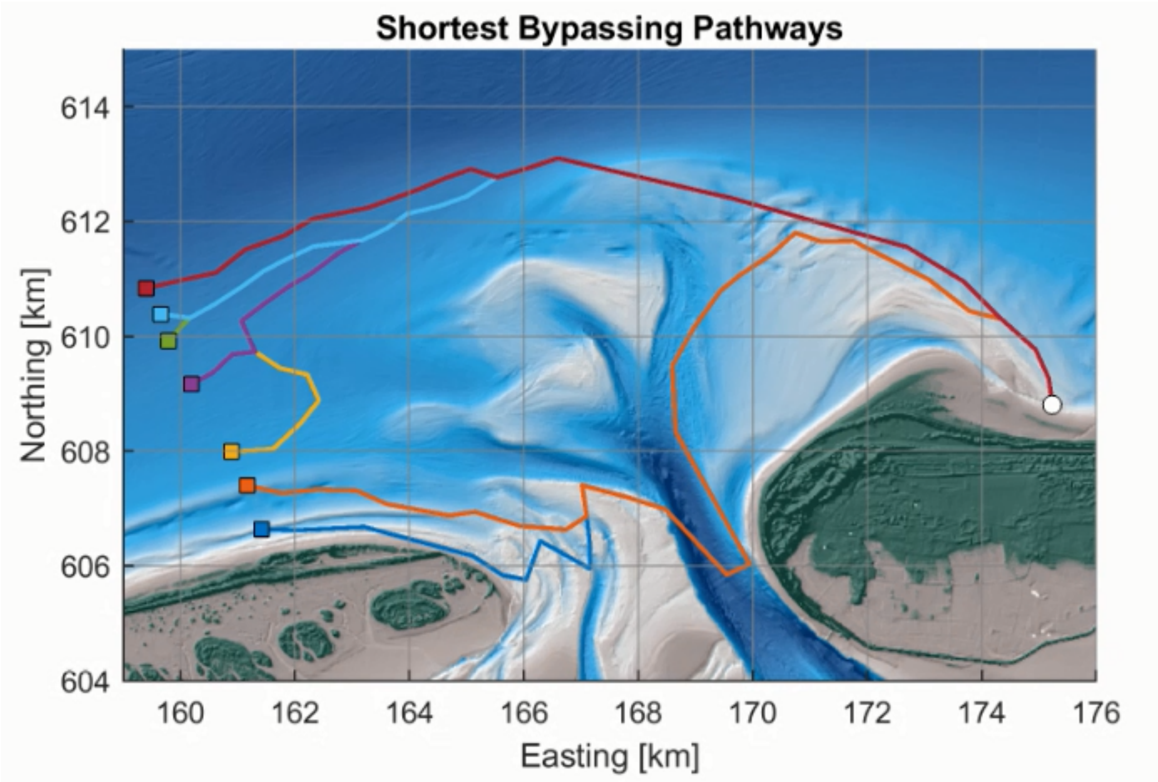

Figure 6. Shortest (dominant) bypassing pathways from 7 nodes offshore of Terschelling (the updrift side of the inlet) to a single point on the (downdrift) coast of Ameland.

Closer to shore, "channel bypassing" via the inlet dominates, whereas sediment originating seaward of the outer bar bypasses via the outer delta. Presumably, tidal currents are driving at least the first half of this journey, although it is likely that waves play a greater role on the shallower platform to the east. Notably, the shortest pathways avoid the morphodynamically active shoals on the western side of the delta, since the particle trajectories there are more convoluted and feature prominent recirculation zones (Figure 3).

4. Discussion

SedTRAILS enables the fast, high-resolution mapping of sediment transport pathways and connectivity in coastal environments. This approach provides new quantitative and qualitative insights into sediment pathways in complex settings like tidal inlets. The visualizations produced improve our understanding of the system dynamics and provide us with new tools for comparing models and measured data. The connectivity patterns derived here are consistent with previous studies of Ameland Inlet (Elias et al., 2019; Pearson et al., 2020) and with modelled and measured pathways observed at other similar sites (Herrling & Winter, 2018; Son et al., 2011). Furthermore, these metrics can be used to address practical coastal management questions. For instance, the path-finding approach is useful for planning a nourishment or trying to determine the potential for sand to reach a specific location.

Having successfully demonstrated a proof of concept for SedTRAILS here, the door is now open to many new possible analyses and improvements. The most essential next step is to improve the transport velocity formulations used to advect particles. SedTRAILS in its present form visualizes potential sediment trajectories but does not directly estimate volumes transported or the timescales of transport. The sediment transport velocity can be better derived from a correction based on sediment concentration (e.g., Soulsby et al. (2011)). Processes like burial and re-emergence are also not accounted for. After these features are implemented, validation using sediment tracers (Pearson, van Prooijen, et al., 2021) or geochronology approaches like Optically Stimulated Luminescence (Reimann et al., 2015) will be used to achieve realistic sediment migration speeds.

The Lagrangian nature of SedTRAILS permits the analysis of chaotic stirring and Lagrangian coherent structures (LCS), both of which determine mixing and barriers to transport in the context of coastal hydrodynamics (Kuitenbrouwer et al., 2018; Ridderinkhof & Zimmerman, 1992). In conjunction with the development of new connectivity metrics, this sets the stage for a suite of new quantitative analysis techniques for sediment transport pathways. The speed of our approach also lends itself well to sensitivity testing and ensemble modelling to quantify predictive uncertainty, if a schematized wave climate and morphological tide are used. SedTRAILS has already been applied in this manner to sites in the Netherlands (Bult, 2021; Lambregts, 2021) and USA (Stevens et al., 2020), and can easily be expanded to other locations.

5. Conclusions

We used a Lagrangian sediment transport model and visualization tool (SedTRAILS) to estimate sediment transport pathways and populate a connectivity network at Ameland inlet in the Netherlands. This model enables the efficient and high-resolution computation of sediment transport pathways, which makes it ideally suited for the development of connectivity networks. Network-derived metrics like node degree and strength give insight into critical locations for sediment exchange. We can also determine the dominant transport pathways in the system by considering the network as a whole and not just individual particle paths. Together, these tools improve our understanding of complex coastal and estuarine systems and can be used to address practical coastal management questions. This approach also opens the door to a variety of analytical techniques (e.g., LCS analysis) which can be used to better quantify coastal sediment pathways in future studies.

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