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Important note
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Sediment Connectivity: A Framework for Analyzing Coastal Sediment Transport Pathways

Stuart G. Pearson[1,2] , Bram C. van Prooijen[1] , Edwin P. L. Elias[2], Sean Vitousek[3] , and Zheng Bing Wang[1,2]

[1]Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands, [2]Deltares, Delft, Netherlands, [3]Pacific Coastal and Marine Science Center, U.S. Geological Survey, Santa Cruz, CA, USA

Abstract Connectivity provides a framework for analyzing coastal sediment transport pathways, building on conceptual advances in graph theory from other scientific disciplines. Connectivity schematizes sediment pathways as a directed graph (i.e., a set of nodes and links). This study presents a novel application of graph theory and connectivity metrics like modularity and centrality to coastal sediment dynamics, exemplified here using Ameland Inlet in the Netherlands. We divide the study site into geomorphic cells (i.e., nodes) and then quantify sediment transport between these cells (i.e., links) using a numerical model. The system of cells and fluxes between them is then schematized in a network described by an adjacency matrix. Network metrics like link density, asymmetry, and modularity quantify system-wide connectivity. The degree, strength, and centrality of individual nodes identify key locations and pathways throughout the system. For instance, these metrics indicate that under strictly tidal forcing, sand originating near shore predominantly bypasses Ameland Inlet via the inlet channels, whereas sand on the deeper foreshore mainly bypasses the inlet via the outer delta shoals. Connectivity analysis can also inform practical management decisions about where to place sand nourishments, the fate of nourishment sand, or how to monitor locations vulnerable to perturbations. There are still open challenges associated with quantifying connectivity at varying space and time scales and the development of connectivity metrics specific to coastal systems. Nonetheless, connectivity provides a promising technique for predicting the response of our coasts to climate change and the human adaptations it provokes.

Plain Language Summary The pathways that sand takes as it moves along coasts and estuaries are determined by a complex combination of waves, tides, geology, and other environmental or human factors. These pathways can be challenging to analyze and predict using existing approaches, so we turn to the concept of connectivity. Connectivity represents the pathways that sediment takes as a series of nodes and links, much like in a subway or metro map. This approach is well used in other scientific fields, but in this study we apply these techniques to a new research field: coastal sediment dynamics. To demonstrate the sediment connectivity approach, we use it to map sediment pathways at a coastal site in the Netherlands. The statistics computed using connectivity let us quantify and visualize these sediment pathways, revealing new insights into the coastal system. We can also use this approach to address practical engineering questions, such as where to place sand nourishments for coastal protection. Sediment connectivity thus provides a promising technique for predicting the response of our coasts to climate change and the human adaptations it provokes.

1. Introduction

1.1. Challenges Posed by Coastal Sediment Transport

Coasts and estuaries are complex geomorphic systems formed by connected fluxes of water and sediment. Tides, wind, and waves steer the development of coastal systems, and nonlinear transport processes shape them. Tight feedback loops between morphology and hydrodynamic processes lead to dynamic landscapes in a wide range of coastal environments, from sandy beaches (Masselink et al., 2006) to coral atolls (Barry et al., 2007) or mudflats (Friedrichs, 2012). Sediment transport pathways become particularly dynamic and convoluted in the vicinity of tidal inlets or estuaries (Barnard, Erikson, et al., 2013; Elias et al., 2006; Hayes, 1980; Kana et al., 1999; Oertel, 1972; Sha, 1989), as indicated conceptually in Figure 1. Sediment may be exchanged between the lagoon or estuary and the adjacent coastlines. For example, it may bypass the inlet via bar migration on an outer (ebb-tidal) delta (Elias et al., 2019; FitzGerald, 1982; Gaudiano &
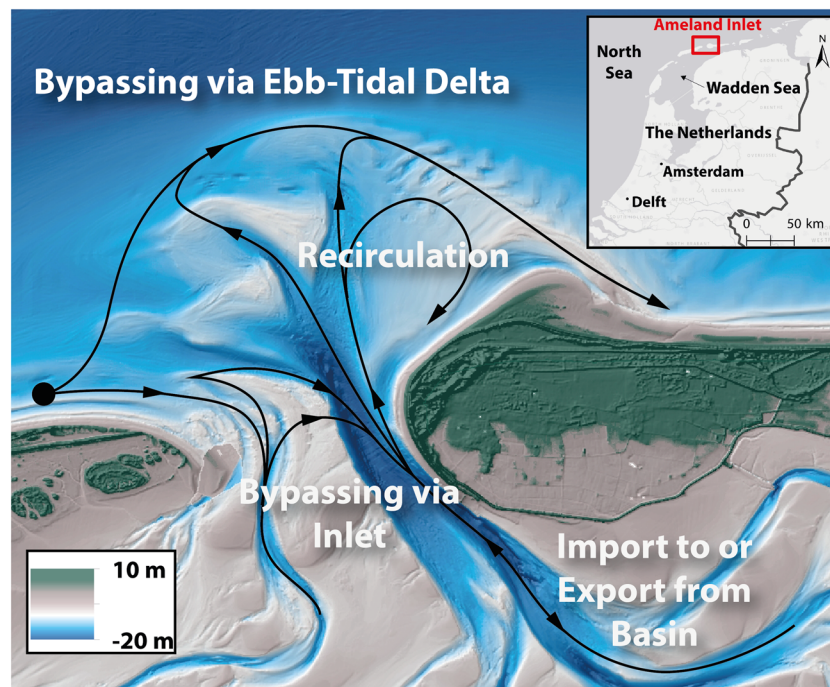
Figure 1. Conceptual diagram identifying key questions about sediment transport pathways, using Ameland Inlet as an example. 1. Via which pathways (black arrows) does sediment from a given origin (black dot) bypass the inlet? 2. Is there a net import or export of sediment to/from the basin? 3. Are there strong recirculations or opposing gross transports, or are transports largely unidirectional? 4. Where is the optimal location for a sand nourishment? 5. How do these patterns change with grain size? 6. Can the domain be grouped into distinct sediment-sharing cells? The inset map indicates the location of Ameland within the Netherlands. Bathymetry (circa 2017) and topography source: Rijkswaterstaat.

Kana, 2001; Sexton & Hayes, 1982) or recirculate at the mouth (Herrling & Winter, 2018; Hicks et al., 1999; Smith & FitzGerald, 1994; Son et al., 2011). The net import or export of sediment through the inlet system and changes to the ebb-tidal delta can have a profound influence on the morphological evolution of the adjacent coastline (Elias & Van Der Spek, 2006; FitzGerald, 1984; Hansen et al., 2013; Ranasinghe et al., 2012; Warrick et al., 2019).

Effective management of coastal sediment is vital for sustainable protection against flooding and erosion (Hanley et al., 2014; Mulder et al., 2011; Van Wesenbeeck et al., 2014). In order to reliably predict coastal evolution, improved understanding of sediment transport pathways is necessary at multiple scales (Ruggiero et al., 2016; Vitousek et al., 2017). Interruptions to the flow of sediment may degrade coastal systems, causing socioeconomic and ecological damage (Roelvink, 2015). Furthermore, human interventions such as nourishments, protective structures, or basin closures can also affect coastal sediment transport pathways by interrupting existing paths, or by creating new ones (Davis & Barnard, 2000; Eelkema et al., 2013; Elias et al., 2012; Fontolan et al., 2007; Luijendijk et al., 2017; Wang et al., 2015, 2018). Understanding how human interventions change sediment pathways is important for gauging the effectiveness of the intervention, predicting potential consequences of that intervention, or assessing its environmental impact (Hendriks et al., 2020).

Where does the sediment from a given location go to? Furthermore, where does the sediment at that same location come from? These two questions are fundamental to sediment transport. Yet rarely, if ever, are answers to these questions available, owing to the complexity of coastal sediment transport dynamics. Numerical models begin to answer these questions: At a given location, sediment goes to and comes from neighboring grid cells over a single time step. However, sediment transport pathways over large spatiotemporal scales are observed. Hence, the framework of sediment connectivity is critical to bridging the gap between geomorphic coupling among neighboring regions (e.g., Harvey, 2001) and system-wide
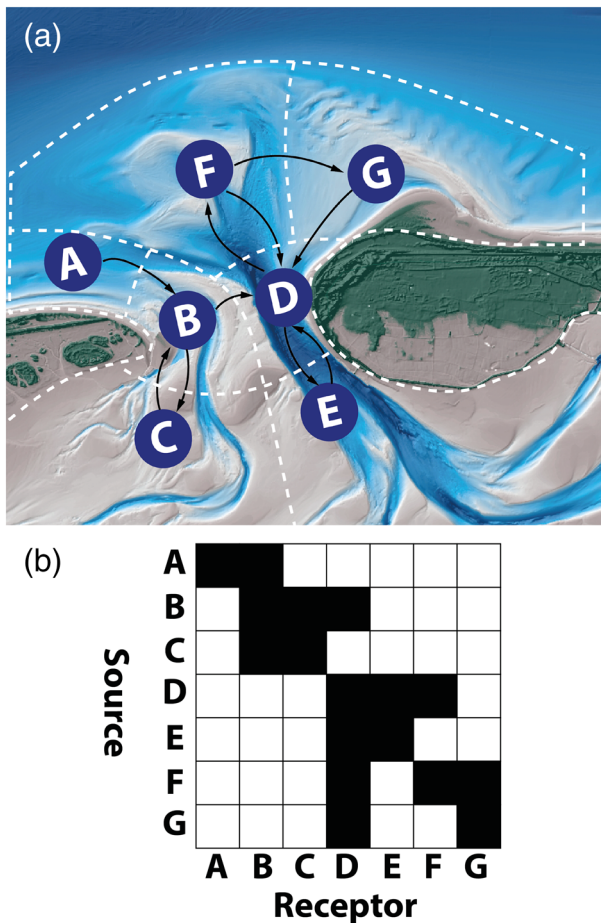
Figure 2. Conceptual diagrams explaining how graph theory can be used to quantify sediment connectivity. (a) Hypothetical sediment pathways at Ameland Inlet, represented as an unweighted, directed network diagram. Blue nodes (A–G) are representative of the geomorphic cells defined with white dashed borders. Black arrows represent links or fluxes between the nodes. (b) An unweighted, directed adjacency matrix A, the algebraic representation of the network graph presented in (a). Black squares (represented numerically as a "1") indicate the existence of a pathway from a given source node i to a given receptor node j, while decoupled pairs of nodes are white (represented numerically as a "0"). For instance, Row B shows that Node B acts as a source for Nodes C and D, while Column B shows that Node B receives sediment from Node A and Node C. The main diagonal of the matrix corresponds to self-self connections, that is, sediment that stays in or returns to the node where it originated.

connections. In this study we show that connectivity is a useful framework for analyzing sediment transport pathways in coastal environments and for addressing challenges in sediment management.

1.2. Connectivity: A Transformative Concept

In its most general sense, connectivity is a framework for representing the connections and flows between the different parts of a system. It has been widely adopted in other fields such as neurology (Honey et al., 2007; Rubinov & Sporns, 2010), biology (Maslov & Sneppen, 2002), epidemiology (Read et al., 2008), computer science (Bassett et al., 2010), transportation (Derrible & Kennedy, 2009; Sperry et al., 2017), ecology (Cantwell & Forman, 1993; Urban et al., 2009), and sociology (Scott, 2011; Krause et al., 2007). Connectivity has proven itself to be a "transformative concept" for describing and understanding complex dynamic systems in these disciplines (Turnbull et al., 2018). Wohl et al. (2019) identifies the value of connectivity in geomorphology, since it can illuminate interactions between seemingly disparate and/or distant components of a system. Keesstra et al. (2018) argue that connectivity is useful for designing better measurement and modeling schemes for water and sediment dynamics.

Increasing attention has been paid to the topic of sediment connectivity in recent years, although the concept has seen limited application in coastal sediment transport contexts (Anthony & Aagaard, 2020; Passalacqua, 2017; Tejedor et al., 2015a, 2015b). On the other hand, advances made in noncoastal fields like neurology and hillslope geomorphology have led to the development of techniques for assessing connectivity using graph theory and network analysis (Csárdi & Nepusz, 2006; Franz et al., 2016; Newman, 2003; Phillips et al., 2015; Rubinov & Sporns, 2010).

The major advance in connectivity analysis in recent years has been the adoption of techniques from network science, a broad field concerned with the analysis of complex systems. Within network science, graph theory conceptualizes a complex system as a series of nodes and the links between them, referred to as a graph (Newman, 2003; Phillips et al., 2015). The terms "network" and "graph" are often referred to synonymously in literature (Newman, 2018). Graph theory provides a strong mathematical framework for analyzing geomorphic systems and quantifying sediment connectivity (Heckmann & Schwanghart, 2013). With this approach, sources and receptors of sediment are defined as a series of n nodes interconnected by m links (Figure 2a). These links can have both magnitude (i.e., a weighted graph) and direction (i.e., a directed graph). They can represent fluxes between nodes (e.g., sediment transport rates) or some other spatial relationship (e.g., distance).

Nodes and links can be compiled into an $n \times n$ adjacency matrix, A, with sources i and receptors j (Figure 2b). The matrix entry a_{ij} indicates the presence or absence of a connection (1 or 0, respectively), or alternatively, a probability, or the magnitude of the flux. The adjacency matrix lies at the heart of network analysis, since many different algebraic techniques can be applied to it. In this form, there are numerous statistical and algebraic techniques available for analyzing and interpreting the network (Newman, 2003; Phillips et al., 2015; Rubinov & Sporns, 2010). These approaches can be used to quantify the propagation of disturbances through a system, to identify vulnerabilities or critical nodes, or to test sensitivity of transport across a system to changes in network structure (Callaway et al., 2000; Tejedor et al., 2015a). Furthermore, connectivity is a relatively accessible technique, as numerous open-source software libraries and packages are already available (e.g., *Pajek*, Batagelj & Mrvar, 1998; *iGraph*, Csárdi & Nepusz, 2006; *the Brain Connectivity Toolbox*, Rubinov & Sporns, 2010, and *Cytoscape*, Franz et al., 2016).

Within geomorphology, the use of graph theory for analyzing connectivity has grown in popularity (Heckmann et al., 2015, 2018; Phillips et al., 2015), for applications including sediment delivery in catchments (Cossart et al., 2018; Heckmann & Schwanghart, 2013) and the development of sand bars in rivers (Koohafkan & Gibson, 2018). Graph theory has also been used effectively for studying channel networks in river deltas (Hiatt et al., 2020; Passalacqua, 2017; Tejedor et al., 2015a, 2015b, 2016, 2017) and sea level rise impacts on drainage networks in coastal regions (Poulter et al., 2008). Aggregated morphodynamic models like ASMITA (Lodder et al., 2019; Stive et al., 1998), the reservoir model of Kraus (2000), and BRIE (Nienhuis & Lorenzo-Trueba, 2019) represent sediment pathways at tidal inlets using a series of reservoirs and the fluxes between them but do not explicitly analyze connectivity in a graph theoretic framework.

A key strength of graph theory is the assessment of sediment cascades, the succession of different pathways from sources to sinks via a series of temporary storage landforms, in a sort of "jerky conveyor belt" (Burt & Allison, 2009; Heckmann & Schwanghart, 2013). In coastal or estuarine contexts, this cascade begins with sediment supplied from fluvial sources, reworking of marine deposits, or coastal erosion (Spencer & Reed, 2010) and can end in a wide range of sinks from estuaries to submarine canyons (Cowell et al., 2003). Graph theory provides a mathematical means of identifying and quantifying the structure of these individual connections in the context of a larger cascade or network (Newman, 2003). Furthermore, assessing connectivity in this way can reveal emergent patterns not evident in other approaches (e.g., Rossi et al., 2014), such as sediment transport vector fields produced from numerical models.

In spite of its widespread adoption for connectivity studies, graph theory has its limitations. Chiefly, delineating complex natural systems into a limited number of nodes, patches, or cells (e.g., Galpern et al., 2011) requires simplifications which can lead to a significant loss of information (Moilanen, 2011). Thus, the initial schematization of a network is a step requiring careful attention and scrutiny, in order to ensure that important signals and patterns are not oversimplified.

Schematizing open coastal systems (exposed to the open ocean and whose flows are unconfined by channels like in river catchments or deltas Li et al., 2006) into networks is a nontrivial geomorphological mapping task. Nonetheless, graph theory has been embraced for connectivity analysis by the marine ecology and physical oceanography communities, primarily for analyzing larval dispersal, planning marine reserves, or quantifying the spread of pollutants (Burgess et al., 2013; Condie et al., 2018; Cowen & Sponaugle, 2009; Hock et al., 2017; Gillanders et al., 2012; Grober-Dunsmore et al., 2009; Kool et al., 2013; Paris et al., 2013; Rogers et al., 2016; Rossi et al., 2014; Storlazzi et al., 2017; Treml et al., 2008; van Sebille et al., 2018). Since graph theory has already proven its usefulness for describing transport processes in marine environments, it is therefore also well suited to analyzing sediment connectivity there. However, feedbacks between topography or structure and transport processes are less critical in marine ecology than in coastal geomorphology, so additional considerations must be taken to successfully adapt this approach for coastal sediment transport (section 2).

1.3. Objectives and Outline

The objective of this study is to demonstrate that connectivity analysis using graph theory is a useful framework for understanding sediment transport pathways in coastal environments and solving related sediment management problems. We summarize the relevant advances in connectivity analysis made in other fields and highlight their utility for coastal applications. The remainder of this paper is presented in four sections. In the following section, we lay out a general methodology for applying connectivity (section 2). To demonstrate the use of connectivity in coastal settings, we apply the concept to a case study of Ameland Inlet in the Netherlands (section 3). We then discuss the utility and limitations of this approach and provide an outlook for future research into how connectivity might be further adapted and improved for use in coastal environments (sections 4 and 5).

2. Methodology

We consider three main questions in order to apply connectivity to a coastal system:
1. *Defining connectivity*: What is the fundamental unit of connectivity, and are we concerned with structural or functional connectivity?
2. *Developing a network*: How can available data or model output be schematized in a network?

3. *Analyzing connectivity*: How can we measure the connectivity and emergent patterns of a network at different scales?

Answering these questions provides a framework with which connectivity can be assessed for coastal systems.

2.1. Defining Connectivity

2.1.1. Fundamental Units

In order for the concept of connectivity to be applied, we must first define the entities or *fundamental units* between which connections exist. In neurological connectivity, the fundamental unit could be neurons or different parts of the brain, and in social networks it could be an individual person (Turnbull et al., 2018). Ecologists often use the concept of the *habitat patch* (Calabrese & Fagan, 2004) or ecosystem (Turnbull et al., 2018). For geomorphological applications, Poeppl and Parsons (2018) propose the concept of the geomorphic cell as the fundamental unit of connectivity, comparable to the landforms or units in a geomorphological map. Within a geomorphic cell, morphology and sediment transport processes remain relatively uniform.

Known sources and sinks of sediment (e.g., sea cliffs or submarine canyons) or criteria like depth, sediment transport patterns, or morphological characteristics can be used to define these cells (e.g., Jeuken & Wang, 2010; Lodder et al., 2019; Stive et al., 1998; Stive & Wang, 2003). Geomorphic cells can also be defined without any reference to their function or position. In extremis, the cells of a high-resolution digital terrain model (DTM) could be used. However, Poeppl and Parsons (2018) discourage the "thoughtless adoption of DTM cells at whatever resolution happens to be available," since those cells do not necessarily have a meaningful relationship to the sediment transport within them. Geomorphic cells can be derived more effectively by combining geomorphological maps and high-resolution DTM cells (Heckmann et al., 2015). If no information about sediment fluxes is known a priori, then expert judgment may be used for identifying appropriate geomorphic cells.

The spatial definition of geomorphic cells depends on the timescale under consideration. Regions delineated as geomorphic cells based on morphological characteristics or relatively constant sediment and water fluxes may cease to be representative as the landscape evolves. For example, on a long enough timescale, a shallow shoal could develop in a cell originally defined as a deep channel. Thus, the spatial scale of geomorphic cells can affect the connectivity observed in a given period (Poeppl & Parsons, 2018).

2.1.2. Structural and Functional Connectivity

Once the fundamental unit is defined, we must consider which type of connectivity is relevant: structural or functional. Structural connectivity concerns the spatial anatomy or form of the network (i.e., how the units are spatially arranged relative to one another), whereas functional connectivity concerns the dynamic fluxes passing within the network (e.g., how much material passes between cells).

Structural connectivity is often defined in terms of adjacency: Two neighboring units not separated by physical barriers are structurally connected. For example, we can consider an open tidal inlet and the adjacent sea, or a river channel and its tributary. However, just because two units are adjacent, this does not mean that they will be functionally connected with fluxes between them. This is why it is important to distinguish between structural and functional connectivity.

Two units are functionally connected if there is some flux between them, such as sediment, water, or organisms. Units need not have strong structural connections to be functionally connected: Fluxes may exist between adjacent units, but there may be teleconnections, wherein spatially remote cells can still influence one another (e.g., Phillips et al., 2015). For functional connectivity, it is also necessary to define the dimensions and units of the fluxes under consideration (e.g., mass of sediment, number of particles, discharge, number of organisms in a given time period). Furthermore, functional connectivity can be derived using either Eulerian input (i.e., measured or modeled fluxes at fixed locations) or Lagrangian input (i.e., by tracking a given particle as it moves through the system (van Sebille et al., 2018). Consensus on how to definitively measure and quantify connectivity is currently lacking (Wohl et al., 2019).

As with defining geomorphic cells, the inherent feedback between structural and functional connectivity complicates matters. Sufficient gradients in sediment fluxes will eventually modify the landscape or seascape, which will in turn modify the sediment fluxes. For example, high alongshore sediment transport

can lead to the closure of a tidal inlet, which then disconnects the associated basin from the sea (e.g., Duong et al., 2016). Morphodynamics are essentially the relationship between form and process, between structural and functional connectivity.

Transport pathways have a wide range of timescales (Tejedor, Longjas, Foufoula-georgiou, et al., 2018), so functional connectivity therefore has a temporal dimension (Defne et al., 2016). Functional connectivity should thus be determined over a sufficiently long interval that areas of interest can be connected, but not so long that the structural connectivity changes (Heckmann et al., 2018). At longer timescales, length scales of connectivity increase, and the likelihood of larger magnitude, highly connective events also increases (Heckmann et al., 2018). Spatial and temporal scales determine connectivity and vice versa. Keesstra et al. (2018) argue that structural connectivity has no temporal dimension, as it is a snapshot of the system's architecture at a given moment. This suggests that it would be better to analyze connectivity at a fixed moment in time, if the timescale of sediment fluxes is smaller than the timescale of observable morphologic change at the considered spatial scale. This interdependency between structural and functional connectivity is still regarded as an intractable problem across the literature (Turnbull et al., 2018; Wohl et al., 2019).

To investigate the temporal dynamics of connectivity, multilayer or multiplex networks can be used (Kivela et al., 2014; Pilosof et al., 2017). These networks can be represented as a three-dimensional tensor A^α: a stack of adjacency matrices, with each layer representing connectivity at a different time step α (Newman, 2018). Multilayer networks can also be used to incorporate connectivity of different processes or transport of different sediment classes simultaneously (e.g., Tejedor, Longjas, Passalacqua, et al., 2018).

Also important to consider is the notion of disconnectivity: the absence or removal of a given connection. Blockages in a system may inhibit sediment fluxes and thereby change the structural and functional connectivity of a given network (Fryirs, 2013). Such disconnections may be natural (e.g., the closure of a seasonal tidal inlet) or anthropogenic (e.g., the construction of a storm surge barrier or tidal energy barrage across an estuary).

2.2. Developing a Network

Numerous qualitative and quantitative metrics have been developed to estimate connectivity (Calabrese & Fagan, 2004; Heckmann et al., 2018; Kindlmann & Burel, 2008), but the most powerful means of quantifying connectivity is via graph theory (Heckmann et al., 2015; Newman, 2003; Phillips et al., 2015; Rubinov & Sporns, 2010). To develop a network, geomorphic units can be represented as nodes and the sediment fluxes or structural connections between them as links. Coastal sediment connectivity networks can be populated using field measurements, numerical model output, or a combination of the two. The possibility to integrate and compare multiple sources of data in a unified framework is an advantage of the connectivity approach.

Sediment transport can be estimated using Eulerian measurements at a single point, based on current velocities and suspended sediment concentrations (e.g., Erikson et al., 2013; Gartner et al., 2001). However, it is expensive and impractical to measure continuously for long periods of time at a sufficient number of points to reveal connectivity. While analyzing the differences between repeated bathymetric surveys can yield insight into the rates of morphological change (e.g., Elias et al., 2012; Jaffe et al., 1997), it does not give sufficient information to attribute directional transport.

Sediment tracer studies (both artificial, Black et al., 2007; Bosnic et al., 2017; Elias et al., 2011, and natural, Hein et al., 2013; McGann et al., 2013; Reimann et al., 2015; Rosenbauer et al., 2013; Wong et al., 2013) offer a Lagrangian technique for identifying pathways but are challenging to execute and recover (Elias et al., 2011). Grain trend analysis (Duc et al., 2016; Gao & Collins, 1991; Le Roux & Rojas, 2007; McLaren, 2013; McLaren & Bowles, 1985; McLaren et al., 1998; Poizot et al., 2006, 2008; Velegrakis et al., 2007) and analysis of bedform asymmetry (Barnard, Erikson, et al., 2013; Bartholdy et al., 2002; Sha, 1989; Velegrakis et al., 2007) offer additional techniques for identifying sediment pathways. However, field measurements alone are generally too limited to quantify sediment connections on the timescales of typical interest for engineering and policy decisions.

As an alternative or complement to field measurements, numerical models provide a convenient way of inferring connectivity, since they can calculate fluxes at every point in a system (Wohl et al., 2019). The mean sediment transport vector field generated by a model can be used to visualize residual transport pathways (e.g., Elias & Hansen, 2013; Gelfenbaum et al., 2017; Herrling & Winter, 2014). Alternatively, Lagrangian
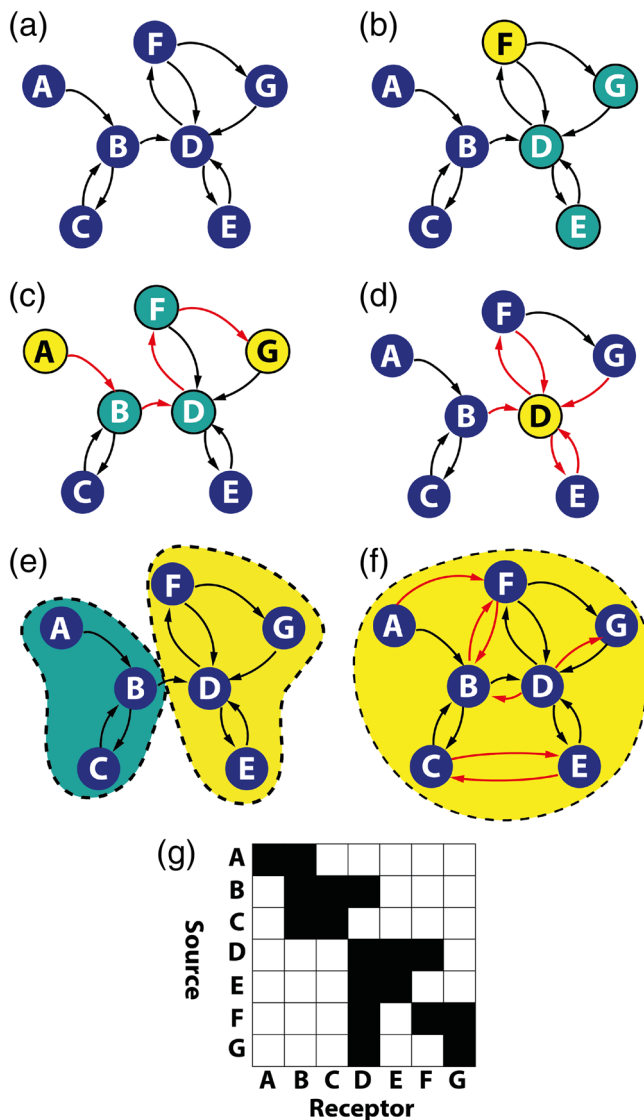
Figure 3. Examples of questions that can be answered via connectivity. (a) Simple unweighted directed network diagram from Figure 3c. (b) What are the possible receptors for sediment from Source F? Nodes that cannot be reached from F are dark blue, and possible receptors are in teal. (c) What is the shortest pathway between A and G? The shortest pathway is indicated by red arrows and teal nodes (A-B-D-F-G). (d) Which node is the most interconnected (has the highest degree) in the system? Connections with this node are indicated by red arrows. (e) Can the system be easily separated into distinct modules? (Yes: one green module of three nodes (ABC), and one yellow module of four nodes (DEFG)). (f) If additional links are added, can the system still be easily separated into modules? (No: There is now a single yellow module containing all nodes). (g) Adjacency matrix for the simple network shown in (a)–(e). Black squares indicate that a given source and receptor pair are connected.

approaches to analyzing modeled sediment transport can be used. Elias et al. (2011), Nienhuis and Ashton (2016), and Beck and Wang (2019) used an approach where sediment originating from a particular location was labeled as a unique sediment class in a morphodynamic model and then followed as it dispersed throughout the model domain.

Lagrangian particle tracking models (e.g., MacDonald & Davies, 2007; Soulsby et al., 2011; van Sebille et al., 2018) are also a useful tool for tracking sediment and defining transport pathways. One can either consider the final resting place of a given sediment particle at a given time (a depositional approach) or instead track the complete history of that particle. The disadvantage of a depositional approach to connectivity is that a pathway with zero transport gradient may be very well connected and yet leave no trace of the sediment it is transporting (Wohl et al., 2019). For example, the main channel of a tidal inlet near morphological equilibrium may convey large volumes of sediment, but this sediment does not necessarily accumulate there, which would give the erroneous impression of low connectivity. Hence, the choices made in how sediment transport or particle trajectories are tabulated from numerical model output can significantly affect the conclusions drawn from connectivity analysis.

Once the data source has been chosen and organized into cells and fluxes, the network can be compiled. The contribution from a given source cell to every other possible receptor cell in the system constitutes one row of an adjacency matrix. By carrying out this calculation for each source in the system, we arrive at a fully populated adjacency matrix representing all the sediment fluxes in our system (e.g., Figure 3g). Thus, these large and complex data sets can be reduced to a relatively simple form, all visualized as a network diagram (e.g., Figure 3a). Once the adjacency matrix has been defined, it can be analyzed using a variety of algebraic and statistical techniques.

2.3. Analyzing Connectivity

With the coastal system reduced to an adjacency matrix of sediment fluxes, we can begin to quantify and analyze connectivity. This is where connectivity has added value as a framework over existing approaches: An abundance of analytical metrics and statistics can be used once the data has been organized into a network. Here, we focus on a selection of connectivity metrics that lead to useful insights for coastal sediment management, both at a system level and for individual units.

2.3.1. System Level

System-level connectivity metrics (at the scale of the entire network) are important to consider because in a complex network, the overall structure and connectivity will influence the connections between individual nodes at smaller scales. The applicability of these indices depends on the temporal scale at which the system's structural connectivity undergoes significant change (Heckmann et al., 2018).

Link Density. To gain insight into the overall connectivity of a given system, we can consider the link density (D), which is the number of connected links relative to the total number of possible links. If self-self connections are neglected, the maximum possible connections m_{max} is $(n^2 - n)$ for directed networks and $(n^2 - n)/2$ for undirected networks, where n is the number of nodes in the network (Phillips et al., 2015). A fully connected network is one in which each node is connected to every other node ($D = m/m_{max} = 1$). A system without any transport between nodes corresponds to a fully disconnected network ($D =, m, /m_{max}, = 0$) (Cowen & Sponaugle, 2009). In reality, most networks will lie somewhere in between

(e.g., Figure 3a, with $D = 0.33$). Link density is a function of the observation or simulation time, since longer periods may allow sediment to travel greater distances and hence connect with additional receptors. This may be useful for comparing the general behavior of a system at different time scales or in different scenarios.

Asymmetry. By definition, undirected networks have symmetric adjacency matrices. For directed networks like in Figure 3, asymmetry implies a net flux: More material is going to a given node than coming from it, or vice versa. In coastal systems, the sediment transport is often characterized by large opposing gross fluxes due to reversing ebb and flood tides (Gatto et al., 2017) or variable wave climates (Harley et al., 2011). Net fluxes are a consequence of small asymmetries between these ebb and flood fluxes or gross alongshore transports. These net fluxes are coupled with the morphological behavior of a coastal system or feature. The asymmetry of connectivity is thus a direct measure of these fluxes and their interactions with the coastal system. Asymmetry can be revealed by decomposing an adjacency matrix A into its symmetric A_{sym} and skew-symmetric A_{sk} components (Kundu & Cohen, 2008):

$$A = A_{sym} + A_{sk} = \frac{1}{2}\left(A + A^T\right) + \frac{1}{2}\left(A - A^T\right) \tag{1}$$

where A^T is the transpose of the adjacency matrix. The skew-symmetric matrix A_{sk} should directly correspond to the net sediment transport of a system, and the symmetric matrix A_{sym} to the gross transports that cancel each other out. Decomposing a matrix in this way can be useful for understanding the transport pathways that drive morphological changes. The degree of symmetry s in the network can be summarized using the approach of Esposito et al. (2014):

$$\begin{aligned} s &= 1 - \frac{2}{n(n-1)-2u}\sum_{i=1}^{n}\sum_{j=i+1}^{n}\frac{|a_{ij} - a_{ji}|}{a_{ij} + a_{ji}} \\ &= 1 - \frac{2}{n(n-1)-2u}\sum_{i=1}^{n}\sum_{j=i+1}^{n}\frac{|(a_{sk})_{ij}|}{(a_{sym})_{ij}} \end{aligned} \tag{2}$$

where s is the symmetry index, u is the number of completely unconnected node pairs ($a_{ij} = a_{ji} = 0$). When $s = 1$, the network is fully symmetric, and when $s = 0$, there are no reciprocated connections in the network (fully asymmetric). High symmetry indicates relatively small net transports (and hence relatively small morphological changes), even if gross transports and connectivity are large. Conversely, low symmetry indicates relatively large net transports (and hence relatively large morphological changes), even if gross transports and overall connectivity are small.

Modularity. Modules or communities are densely interconnected clusters of nodes with limited external connection. The degree to which a network can be be divided into such clusters is known as modularity, Q (Leicht & Newman, 2008):

$$Q = f_{mod} - f_{rnd} \tag{3}$$

where f_{mod} denotes the fraction of links within a module and f_{rnd} denotes the expected fraction of such links based on random chance. These modules can be determined using a variety of cluster optimization techniques such as the Infomap (Rossi et al., 2014) or Louvain (Rubinov & Sporns, 2010) algorithms. Networks that can be clearly delineated into nonoverlapping clusters have high modularity $Q > 0$ (Figure 3e), whereas networks with few coherent groups have low modularity $Q < 0$ (Figure 3f). For instance, Rossi et al. (2014) uses modularity to identify "hydrodynamic provinces," regions that are internally well connected but are poorly linked to each other. This procedure could be used to delineate geomorphic cells (as per Poeppl and Parsons (2018)) or to examine emergent behavior. Such grouping may be the result of similarities in morphology, initial sediment distribution, or hydrodynamic forcing.

2.3.2. Individual Nodes and Links

Graph theory also offers numerous metrics with which to gauge the influence of individual nodes and links in a network. These statistics may provide practical insights into the role of a given node or link in transmitting sediment, and identify key vulnerabilities in the system.

Connectivity Between Specific Nodes. Most simply, a network can be directly queried to examine the connectivity between specific nodes or groups of nodes. For example, we see in Figure 3b that Node F is

directly or indirectly a source for Nodes D, E, and G. However, there are no possible pathways leading from Node F to Node C. Hence, if this were a coastal sediment system where the goal was to eventually nourish Node C with sand, Node F would not be an optimal location. In another example, we can consider the shortest path between two nodes (e.g., Figure 3c), where path length is calculated in topological space (rather than geographical space) as the inverse of the sediment flux between those nodes ($d_{ij} = 1/a_{ij}$) (Rubinov & Sporns, 2010). The total path length is defined by the sum of the lengths between any intermediate nodes, and the shortest path is then defined as the path with the minimum total length. That is, nodes connected by large fluxes are considered closer together in the topology of the network, and nodes with weak connections are more distant, irrespective of actual geographic distances. This metric may thus be useful for identifying the dominant transport pathways and quantifying processes like inlet bypassing. Asymmetry of connections between individual nodes or specific groups of nodes may also provide useful insight into net transport patterns.

Degree. Degree quantifies the number of links connected to a given node. For directed networks, this can further be decomposed into an in-degree k_{in} and an out-degree k_{out} (Figure 3b). For example, Node D in Figure 3d has an in-degree of 4 and an out-degree of 2. Degree provides insight into the diversity of different sources or sinks that a given node has. A network's degree distribution ($P(k) = n_k/n$, where n_k is the number of nodes of degree k and n is the total number of nodes in the network) can provide an indication of the overall network structure or topology (Phillips et al., 2015). If each node has a similar degree, the network will have a relatively uniform, distributed structure. However if the degree distribution is exponential, the network will be more centralized with a few dominant hubs or clusters. This relationship highlights how connectivity at the level of individual nodes can cascade upwards to shape connectivity at the overall system level.

Strength. Strength is the sum of all fluxes in and out of a given node for weighted networks, and can be computed directly from the adjacency matrix. For weighted, directed networks, this can be further decomposed into in-strength and out-strength. Nodes with a relatively higher in-strength than out-strength are sinks, which is useful for identifying zones of sediment accumulation or convergence. Nodes with a higher out-strength than in-strength are sources, so material will tend to disperse there. Ultimately, it is the balance between in- and out-strength that determines morphological change. Knowledge of these key nodes can inform dredging/nourishment strategies.This may be more insightful than degree, since high degree does not necessarily equal high strength, especially where fluxes are unevenly distributed throughout the system. For example, even though Node D in Figure 3d has a higher in-degree than out-degree, if the out-strength is higher than in-strength, it will be a net source rather than net sink.

Centrality. Centrality quantifies how important or "central" a given node or link is within the context of the system as a whole. There are numerous ways of quantifying centrality (Newman, 2018), including degree, closeness, eigenvector, and betweenness, which we focus on here. Betweenness centrality B refers to the proportion of all shortest paths in a network that pass through a given node or link (Phillips et al., 2015), where the "distance" along paths is calculated in terms of inverse sediment flux between nodes ($d_{ij} = 1/a_{ij}$). Hence, nodes with high betweenness centrality represent crucial nodes that may more efficiently transmit sediment through the rest of the system. This could translate to a greater vulnerability to disruptions, or could be used identify strategic locations for more dispersive nourishments. Thus, betweenness centrality gives more insight into the relationship between network structure as a whole and individual nodes than just degree or strength.The comparison metrics in this section examine connectivity at the system or network-wide level, as well as at the scale of individual nodes or links. To illustrate their ease of application and usefulness in answering practical questions about coastal sediment systems, these metrics are applied to a case study of a Dutch tidal inlet in the following section.

3. Case Study: Ameland Inlet

To illustrate the principles and analysis techniques discussed in previous sections, we apply the sediment connectivity approach to Ameland Inlet, a tidal inlet located in the Wadden Sea to the north of the Netherlands (Figure 1). The safety of the Dutch coast against coastal flooding is directly linked to the volume of sand contained in its dunes and beaches, so there is a strong need for sediment management there (Hanson et al., 2002; Stive et al., 2013). The beaches and shoreface are regularly nourished with sand, so connectivity provides an approach that can be used for optimizing those nourishments and improving our understanding of the underlying natural system. Since ebb-tidal deltas represent a key component in the
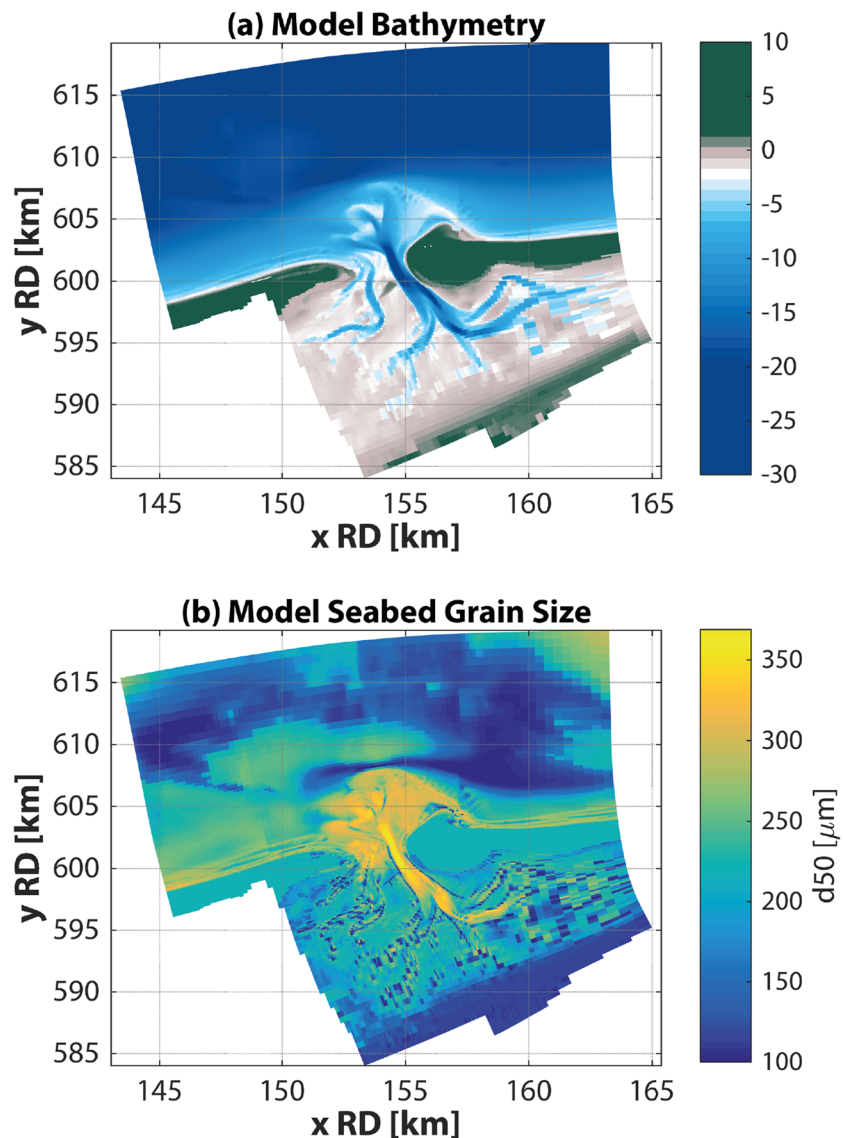
Figure 4. (a) Initial bathymetry of Delft3D numerical model used to calculate connectivity, based on Rijkswaterstaat (2016). The maximum resolution of the grid is approximately 80 m at the inlet. (b) Initial sediment distribution in Delft3D model. Median grain size (d_{50} [μm]). The coarsest sediment can be found in the deepest parts of the channel where tidal currents are strongest, whereas the finest sediment is located offshore, on intertidal flats inside the basin, and seaward of the ebb-tidal shoals. Coordinates are given in Amersfoort/RD New system.

sediment budget of the Wadden Sea and its adjacent coasts, quantifying sediment pathways across them is of critical importance (Elias et al., 2019). This knowledge gap prompts the research questions outlined in Figure 1, which we will answer using the concept of connectivity.

Based on our general understanding of tidal inlets and our prior knowledge of Ameland, we can make a hypothesis about the system's connectivity. Connectivity of a given grain size class should depend on its mobility threshold, the energy available to transport it, and its initial spatial distribution. We thus expect higher connectivity for finer sand and lower connectivity for coarser sand, because the lower critical shear stress threshold for fine sand means that it will be more easily mobilized and transported longer distances. Conversely, the higher threshold for mobilization of coarse sediment means that only the most energetic conditions can transport it. In addition, fine sand has a wider initial spatial distribution in this model, whereas coarser sand is only found in the deepest channels (Figure 4).

We also expect higher connectivity in regions with greater hydrodynamic energy to mobilize sediment, like the main channels and ebb-tidal delta. Conversely, deeper areas offshore and calmer areas at the periphery of the inner basin are expected to have low connectivity. We also expect the main channels to function as transport bottlenecks, since they represent the only routes from the ocean to the inner basin (i.e., no transport over the islands in this model), whereas there are many possible pathways between different points on the ebb-tidal delta (e.g., Herrling & Winter, 2018).

To illustrate the coastal sediment connectivity framework, we used the Delft3D process-based numerical sediment transport model to assess the fate of sediment as it moved between specific morphological units defined in the model domain. For a detailed description of the Delft3D model formulations see (Lesser et al., 2004). Delft3D has been widely used for simulating coastal sediment transport (Elias et al., 2006; Herrling & Winter, 2014; Huisman et al., 2018; Nienhuis & Ashton, 2016). We used an existing Delft3D model (Bak, 2017; de Fockert, 2008; Elias et al., 2015; Wang et al., 2016) as a basis for this example. The model is 2D and represents a 40×30 km domain, with a maximum resolution of ≈ 80 m (Figure 4). Data from the 2016 Vaklodingen survey (Rijkswaterstaat, 2016) was used to create the bathymetry.

The existing model was simplified to demonstrate the concepts of connectivity, featuring a schematized morphological tide (e.g., Latteux, 1995) that propagates eastward along the offshore and seaward lateral boundaries. The morphological tide represents the equivalent net transports observed in the main channel during a full spring-neap tidal cycle as two semidiurnal tides using the M2, M4, M6, and artificial C1 diurnal components, as per (Lesser, 2009). The lateral boundaries within the Wadden Sea are considered closed in these simulations. Ameland Inlet has a tidal range of between 1.5–3 m, and tidal prism of 400–500 Mm^3 (Elias et al., 2019). The tide drives currents of approximately 1 m/s in the main channel of the inlet at ebb and flood. Waves and interbasin wind-driven flows are known to be important processes for Ameland Inlet (Brakenhoff et al., 2019; De Wit et al., 2019; Duran-Matute et al., 2014; Elias et al., 2019; Lenstra et al., 2019; Van Weerdenburg, 2019) but are neglected here for simplicity.

Seabed sediment at Ameland Inlet is typically fine to medium sand, so four sediment grain size classes were chosen to simulate the influence of grain size variation (100, 200, 300, and 400 μm). The sediment was initially distributed according to measured samples (Rijkswaterstaat, 1999), after which a bed composition generation run was carried out to redistribute the sediment in equilibrium with the model bathymetry, as per Van Der Wegen et al. (2011). The model has a 12 hr spinup period to limit the effect of initial instabilities. An equilibrium concentration condition is specified at the boundaries, which sets the sediment load there equal to the sediment load in the interior of the model and ensures that there is little erosion or accretion at the boundaries. A transport or surface bed layer thickness of 0.5 m and maximum underlayer thickness of 1 m (for bookkeeping of subsurface sediment layers) are used to describe vertical variations in bed composition.

We adopted a morphostatic (fixed bed) modeling approach, but permitted sediment exchange between the bed and water column. We ran the model for 6 months (360 tidal cycles), which ensures that the modeled timescale is smaller than the timescale of observable morphologic change at the chosen spatial scale, based on annual bathymetric surveys (Elias et al., 2019). This is also long enough to ensure that the network is well connected with few separate subsystems or *components*.

This model output (a spatial map of sediment mass in the bed and water column at every model grid cell, for each time step) was used to populate a network (sections 3.1 and 3.2). We then used graph theory to analyze connectivity at different space and time scales (section 3.3).

3.1. Defining Connectivity

For this example, we examine the functional connectivity of Ameland Inlet by looking at sediment fluxes between different parts of the system. To determine this functional connectivity, we started by defining 25 geomorphic cells, (Figure 5a). These cells were delineated subjectively on the basis of depth contours but also of their functionality. For instance, shallow parts of the ebb-tidal delta may occur at similar depths to the inner basin, but are morphologically distinct, with different hydrodynamic forcing and sediment composition. As such, the model domain was broken into offshore regions, ebb-tidal shoals, channels, beaches, and intertidal flats.
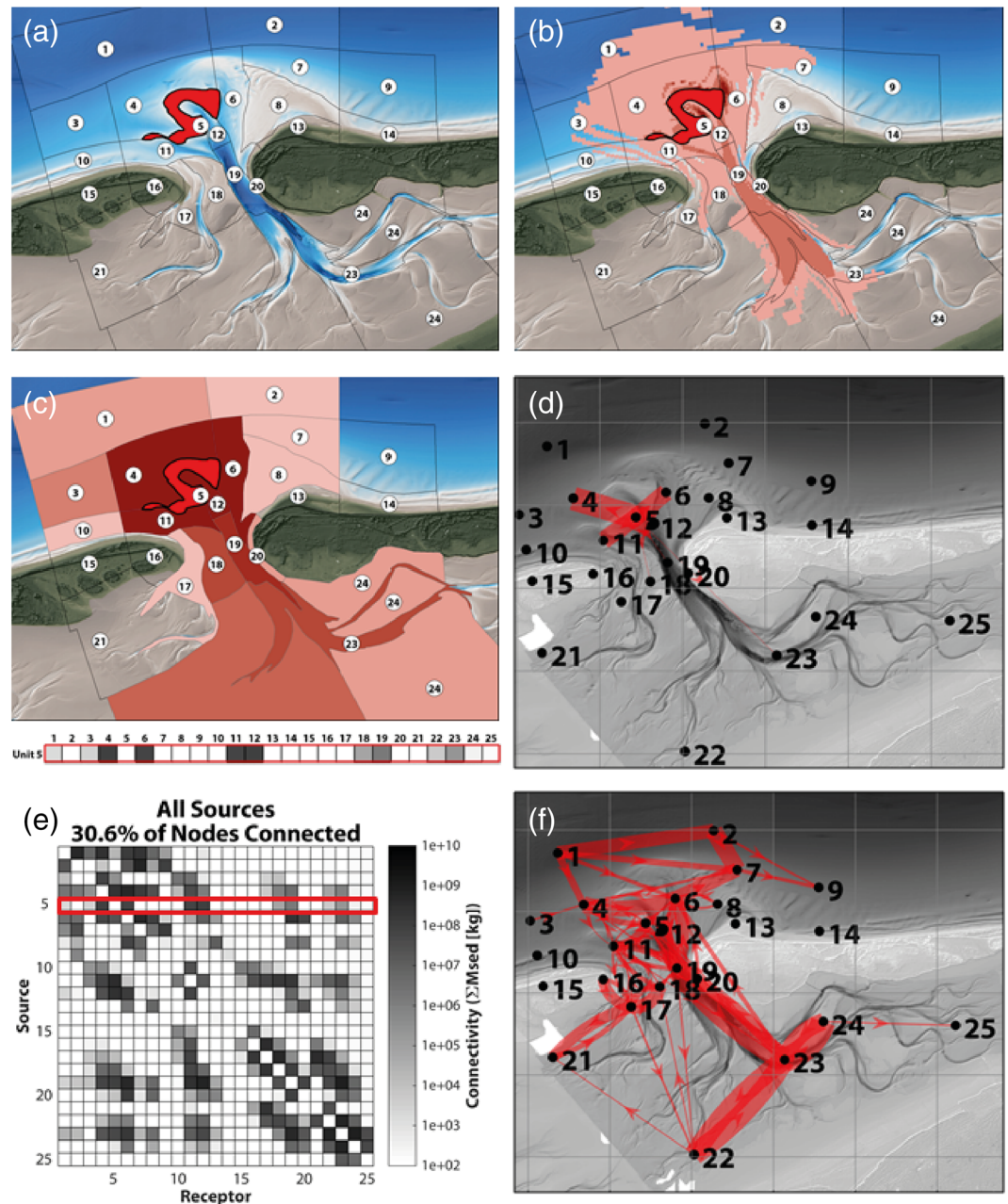
Figure 5. Deriving connectivity using a process-based numerical model. Example using sediment from Node 5. (a) Step 1: Definition of source/receptor nodes (numbered geomorphic cells) and labeling of tracer sediment classes. (b) Step 2: Running the model and tracking sediment, where darker shades of red indicate greater masses of tracer sediment in the seabed (all tracer sediment size classes aggregated). (c) Step 3: Tabulating the mass of tracer sediment from Node 5 to each other node (where darker shades of red indicate greater masses of tracer sediment in a given geomorphic cell) and compiling the data into one row of an adjacency matrix (where darker shades correspond to greater masses of tracer sediment from Node 5 in a given receptor cell and hence greater connectivity). (d) Example of a network based on sediment from Node 5 alone, with thicker lines and arrows indicating larger transports between two given cells. (e) Adjacency matrix for full weighted, directed network with contribution from Unit 5 highlighted in red. (f) Network diagram for full network, where thicker links correspond to greater sediment transport. Only the top 10% of connections are shown here, in order to clarify the dominant patterns.

25 model simulations were prepared, one for each geomorphic cell (Figure 5b). In each simulation, a different cell served as the source node, and the remaining 24 cells were receptors. Similarly to Elias et al. (2011) and Nienhuis and Ashton (2016), we track the motion of sediment (and hence functional connectivity) from

source to receptor by using a series of unique sediment classes. A total of eight sediment classes were included in the model: four "tracer" classes and four "background" classes. In each simulation, sediment within the source node was labeled as a tracer, while the sediment elsewhere in the model domain was labeled as "background" sediment. All the sources are activated simultaneously, although the analysis only focuses on tracking a single source in each run. In this way, it is possible to follow the movement of the tracer sediment and distinguish its fate from that of the surrounding sediment. Alternatively, a single model simulation with 100 sediment classes (4 grain size classes × 25 nodes) could have been used to achieve the same end result, although this was deemed computationally impractical.

3.2. Developing a Network

Net fluxes of sediment determine the long-term morphological evolution, rather than the gross fluxes of sediment passing through a given cell on each tidal cycle. However, these gross fluxes are often much larger than the net fluxes. To measure the residual rather than gross fluxes (and avoid erroneously large or misleading trends), we record the mass of sediment in the bed and water column of a given cell at the end of an integer multiple of tidal cycles—twice daily (Figure 5b). For example, consider a case with sand transport from Node 1 to Node 9 via Node 7. If there is some deposition in Node 7, we will see connections from 1 to 7 and 1 to 9, but not necessarily 7 to 9; however, if there is no deposition or mixing with the bed, only the link from 1 to 9 will be recorded. This is unlikely in the present model because the geomorphic cells considered here are comparable in size to the tidal excursion (O(1–10 km)), and because the active layer bed schematization in Delft3D means that even minute traces of sediment will likely remain mixed in the bed if it passes through a given cell. To circumvent this, alternative approaches could be to collapse all intersecting pathways and convert this network into a planar network (Galpern et al., 2011), or to use a Lagrangian transport model as input. To limit the influence of numerical errors (e.g., from rounding or truncation) and focus on pathways showing a clear signal, we apply a minimum threshold of 1,000 kg per 6 months to all connections (up to 7 orders of magnitude smaller than the strongest fluxes). This represents an Eulerian definition of connectivity, in comparison to Lagrangian methods which would consider the full lifetime path of a given tracer particle.

The total mass of sediment from a given source in each receptor produces a single row of an adjacency matrix (see example in Figure 5c where Node 5 acts as a source to all other receptor nodes). The network diagram corresponding to this single row is shown in Figure 5d. Sediment from Node 5 travels to 30.6% of all nodes, principally to nearby nodes on the ebb-tidal delta and in the main channels. When this procedure is repeated for each of the source nodes, we obtain a complete weighted, directed adjacency matrix (Figure 5e). For context, Node 5 is highlighted in a red box. The central diagonal is empty because with the current model set up, it is not possible to differentiate between sediment from a given source that remains in the bed and sediment from that source which is mobilized but recirculates or returns. The complete adjacency matrix can also be represented as a network diagram (e.g., Figure 5f). Network diagrams provide a useful and intuitive means of visualizing connectivity with thicker lines and arrows representing larger transports between a given pair of nodes.

3.3. Analyzing Connectivity
3.3.1. Network Analysis

As hypothesized, the network's strongest connections are in the tidal channels and ebb-tidal delta, where hydrodynamic energy is greater. It is important to note again here that waves are not included in this model, only tidal forcing. The strongest connections and hence dominant sediment transport pathways lie along the main inlet channel and across the ebb-tidal delta. This is because the main inlet channel serves as the central drainage point for the basin and is a convergence zone for flows in and out of the basin. Furthermore, the ebb-tidal delta features strong, convoluted currents and abrupt changes in bathymetry, so the sediment fluxes there are large. Conversely, the connections at the rear of the basin (e.g., Cell 25, which consists primarily of tidal flats with few major channels) are relatively weaker because of the decreased tidal energy to mobilize sediment there. There are also relatively few direct connections between the rear of the basin and the regions offshore/along the coast, since sediment must have both the time and energy to make the longer journey.

Density. The entire network (including all sediment size fractions) has a link density D of 30.6% (Figure 5). When we consider only 100 μm sand, the network density D is 30.2% (Figure 6a), whereas the network density for 400 μm sand is only 12.2% (Figure 6b and Table 1). The dominant pathways for 400 μm sand are confined to the main channel (Figure 6d), whereas 100 μm sand also has strong connections within the inner
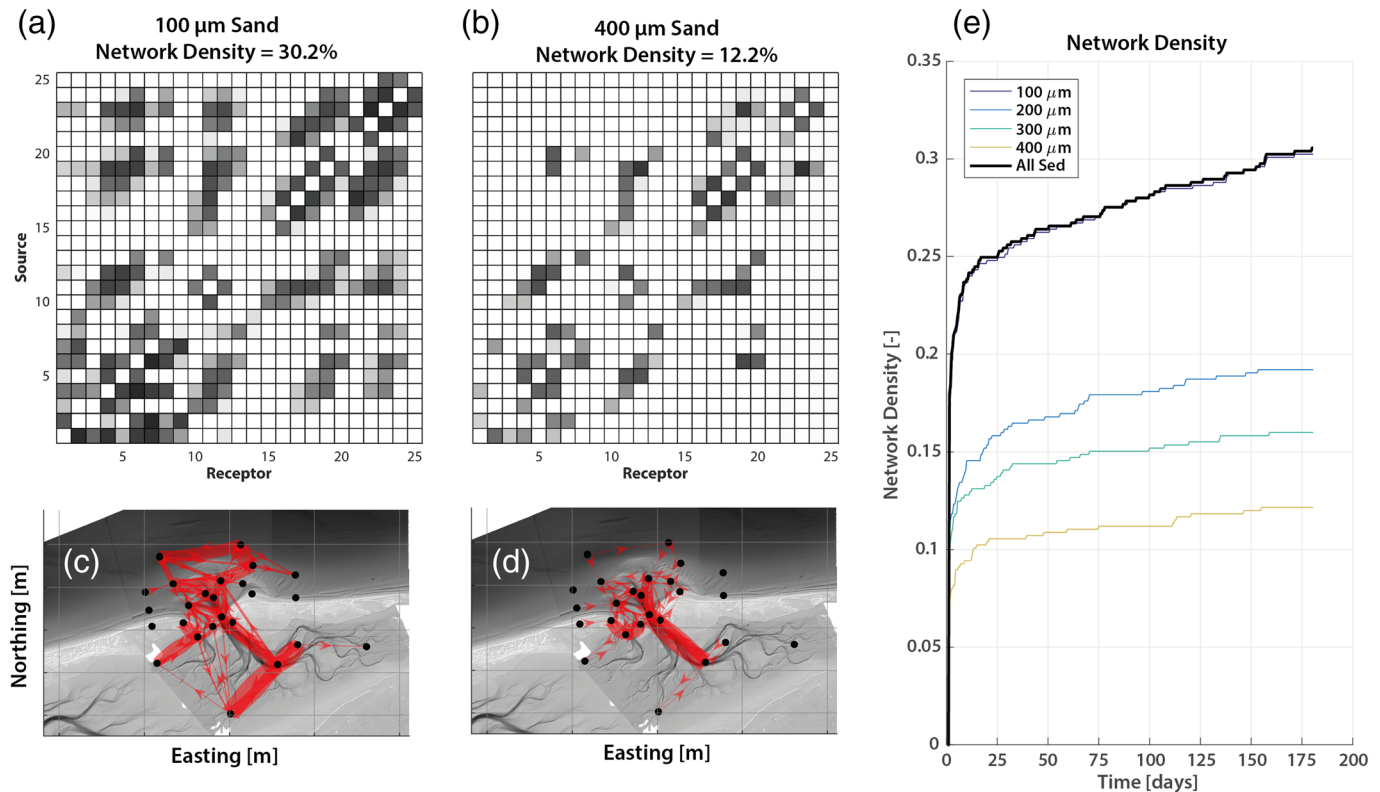
Figure 6. Connectivity matrices and network for 100 μm (a, c) and 400 μm sand (b, d). The shading of a given cell in the adjacency matrices or the thickness of the red lines in the network diagram indicate the connectivity between a given source and receptor. To illustrate the dominant patterns, only the top 10% strongest connections are displayed in (c) and (d). (e) Time series of network density D, the fraction of actual connections over potential connections.

basin and outer delta (Figure 6c). These findings confirm our earlier hypotheses about expected differences in connectivity as a function of grain size.However, the differences in connectivity for each grain size class cannot be explained solely by hydrodynamic forcing: Connectivity can be supply limited. For instance, lack of connection for 400 μm sand from the rear of the basin (e.g., Node 25) to the outer coast (e.g., Node 14) can be attributed to the relative absence of that sediment class there (Figure 4b).When link density is considered as a function of time, we see that connectivity increases rapidly during the initial time steps of the simulation, apparently due to the connection of sediment from sources to their immediate neighbors (Figure 6e). In subsequent time steps, the rate of increase in link density slows considerably, suggestive of a more gradual diffusion after the main connections in the network have been made: Sediment must travel greater distances to make new connections. Density is higher for all sediment fractions combined than for any one sediment class because of the spatial differences in sediment supply. For instance, between some locations there may be a connection for 400 μm sand but not for 100 μm sand, if there is no 100 μm sand initially present in the bed there.

Asymmetry. All of the networks are asymmetric ($s < 1$), which suggests that the system is characterized by nonzero net transports, and hence morphodynamic change (Table 1). However, the networks are not completely asymmetric ($s \approx 0$), likely due in part to the bidirectional nature of tidal transport. There is also no observable trend in asymmetry with respect to grain size.Asymmetry in a connectivity matrix implies that sediment exchange between two nodes is unequal: a net transport in one direction. In Figures 7a and 7b, this can be examined by comparing the 634×10^3 m^3 of sediment leaving the tidal basin (export) with 902×10^3

Table 1
Comparison of Different Connectivity Metrics

Scenario	D (–)	s (–)	Q (–)
All sediment	0.306	0.292	0.455
$d_{50} = 100\,\mu m$	0.302	0.276	0.465
$d_{50} = 200\,\mu m$	0.192	0.349	0.432
$d_{50} = 300\,\mu m$	0.160	0.401	0.406
$d_{50} = 400\,\mu m$	0.122	0.337	0.408

Note. Network link density, D, represents the fraction of actual connections out of all potential connections in the network. Symmetry (s) indicates the proportion of reciprocal connections between nodes, where 1 indicates perfect symmetry and 0 indicates complete asymmetry. Modularity (Q) lies between −1 and 1, where positive numbers indicate a nonrandom tendency to form nonoverlapping groups (Rubinov & Sporns, 2010).
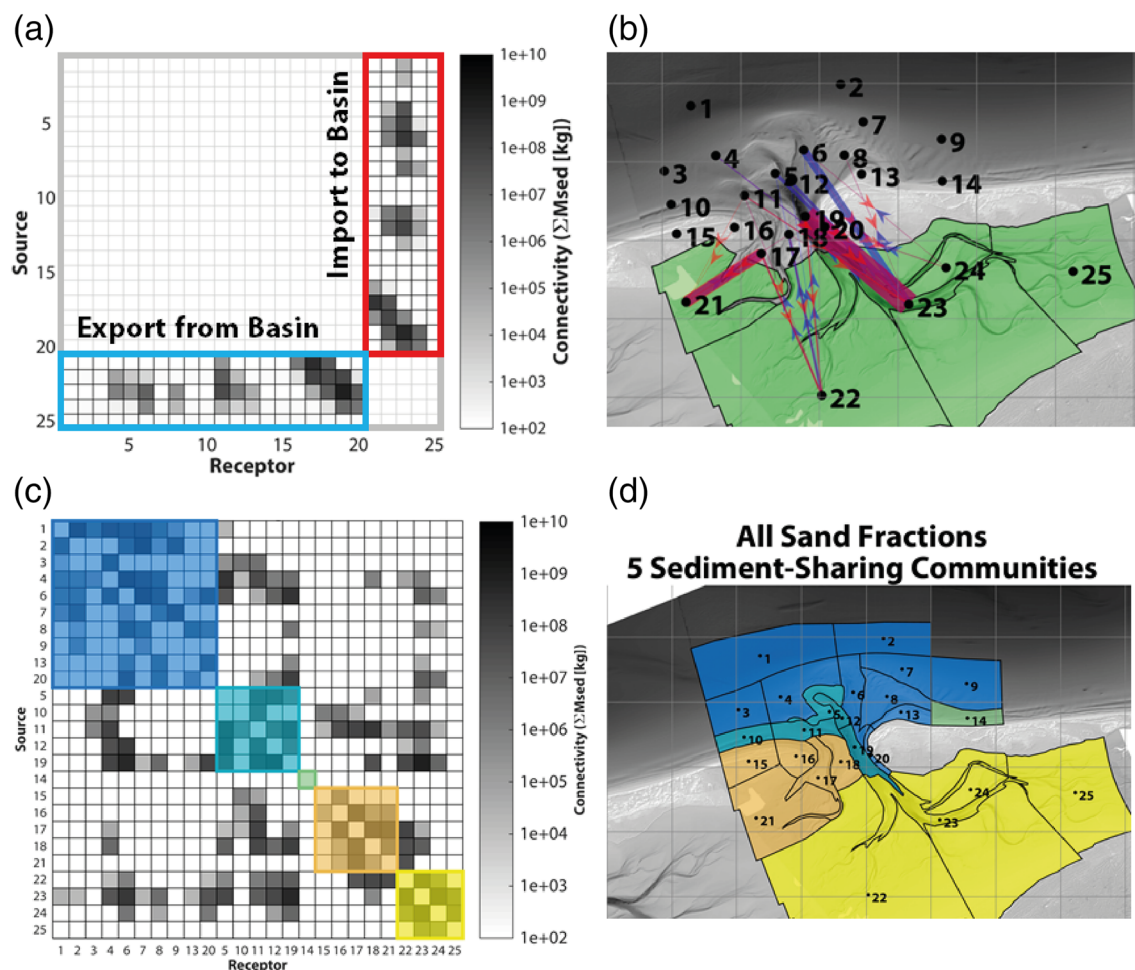
Figure 7. Example of different asymmetric connectivity between groups of nodes and modularity. (a) Adjacency matrix filtered to show only connections to (red, "import") or from (blue, "export") the inner basin (all grain size classes). Comparing the relative import and export reveals a net import of sediment, in line with historical trends for the site (Elias et al., 2012). (b) Network diagram illustrating the filtered adjacency matrix from (a). Cells in the basin are indicated in green. (c) Adjacency matrix sorted into functional sediment-sharing groups using the Louvain modularity algorithm, which maximizes within-group connections and minimizes intergroup connections (Rubinov & Sporns, 2010). Each colored patch in (c) and (d) indicates one of the five sediment-sharing modules identified for the network (all grain size classes).

m^3 of sediment arriving in the basin from elsewhere (import). In this case, we see a net import of 268×10^3 m^3 of sediment in 6 months, which is qualitatively consistent with historical trends for Ameland Basin (Elias et al., 2012). An exact quantitative comparison with measured sediment import volumes is not meaningful here since the present model neglects waves and wind-driven currents, which are important processes at the study site.

Modularity. Modularity is positive, which indicates the emergence of functional sediment-sharing groups at nonrandom levels (Table 1). There is relatively little variation in modularity for different size fractions, which suggests that the modularity in this case is more strongly controlled by the physical structure of the network and hydrodynamic distribution of energy than it is by grain size.Five distinct modules or sediment-sharing groups are identified using the Louvain algorithm (Rubinov & Sporns, 2010): the basin (yellow), offshore/downdrift coast (teal), ebb-tidal delta and main channels (blue), updrift barrier island (light brown), and far downdrift coast (green) (Figures 7c and 7d). Although transport does occur between each of these communities, the majority occurs inside of them. For example, Cell 23 is well connected with many locations in the model domain, but modularity quantitatively shows that it is most closely linked with the basin. This grouping could also be useful for defining geomorphic cells as input for larger-scale connectivity studies (as per Rossi et al., 2014), or in the development of aggregated models (e.g., *ASMITA* Stive et al., 1998).
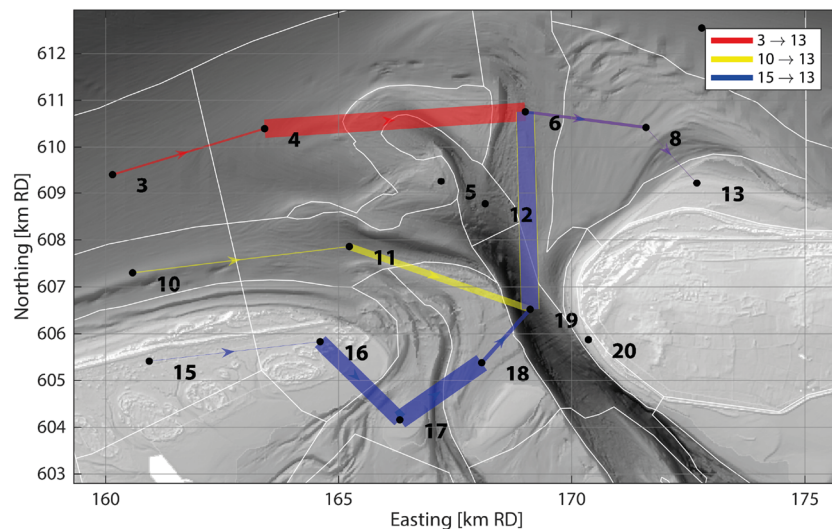
Figure 8. Shortest inlet bypassing pathway for different initial locations (Nodes 3, 10, and 15) on the updrift side of the inlet. Path "distance" is inversely proportional to sediment flux, such that stronger fluxes (indicated here by thicker lines) are effectively "shorter" topological distances. Sources closer to the updrift coastline (10, 15) are connected to the downdrift coast via the inlet, whereas the offshore source (3) is connected via the outer delta. Note that the underlying model presented here does not account for wave-driven bypassing.

3.3.2. Analysis of Individual Nodes and Links

In addition to statistics which characterize the entire network, it is also possible to assess the role of individual nodes.

Connectivity Between Specific Nodes. Individual nodes can also be queried to answer specific questions. For instance, net sediment import into or export from a tidal basin is a vital quantity for estimating coastal sediment budgets, and can be determined by examining asymmetric connections between nodes lying inside and outside the basin. For this particular simplified model, there is a net import of sediment into the basin (Figures 7a and 7b), indicated by a larger total connectivity from Cells 1–20 to Cells 21–25 than from Cells 21–25 to Cells 1–20. When we examine connections between the updrift and downdrift islands, we find that the shortest pathway (calculated in terms of fluxes on the network, not geometric distance or Lagrangian tracking of tracer sediment in the Delft3D model) depends on the offshore distance of the source (Figure 8). Sediment beginning its journey in the nearshore or outer bar region will travel via the inlet (blue and yellow lines), whereas sediment originating further offshore will travel via the outer delta. This suggests that the bypassing routes of interest in Figure 1 depend largely on cross-shore position. Bear in mind that this model uses a schematized tidal signal and neglects key processes known to be important for bypassing, such as waves and wind-induced currents. As such, these pathways should be reevaluated using a more comprehensive model.

Degree, Strength, and Betweenness Centrality. When nodes in our network are considered individually, we see that the nodes with highest degree and strength are generally those in the main channels and on the ebb-tidal delta (Figures 9a and 9b), which follows from the earlier observations on network density (Figure 6). Nodes in the main channel also have the highest betweenness centrality, which confirms and quantifies our hypothesis about the role of the channel as a transport bottleneck (Figure 9c).

3.4. Summary

This case study for Ameland Inlet was intended to show a proof of concept for how sediment connectivity could be applied to a real coastal example. The most challenging part of the approach was to configure and run the model in such a way that sediment pathways could be defined. However, once the data were compiled into a network, sediment transport patterns could be easily quantified using metrics like asymmetry, modularity, and betweenness. The availability of free, open-source analysis tools makes connectivity
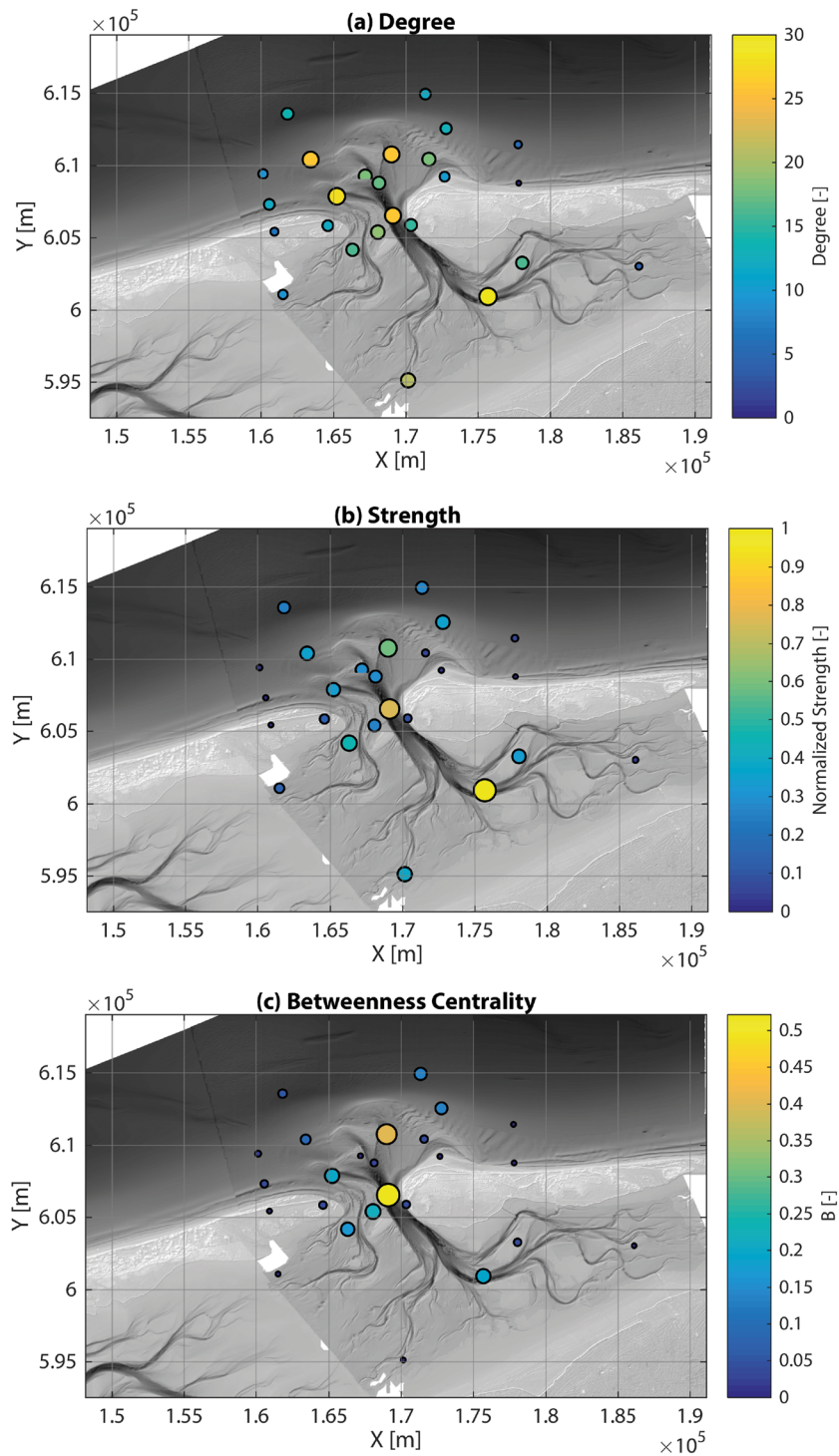
Figure 9. Connectivity metrics for individual nodes. (a) Total degree D (in-degree plus out-degree), which indicates the number of other nodes each node is connected to. Larger yellow dots indicate highly connected nodes, and smaller blue dots indicate minimally connected nodes. (b) Total strength S (in-strength plus out-strength) normalized by the node of maximum strength, which indicates the total sediment transported in and out of a given node. (c) Betweenness centrality, B, normalized by the total number of shortest pathways between nodes ($n = 625$). B indicates the number of shortest pathways passing through a given node.

analysis a highly accessible approach, which yields useful insights into sediment transport at both local and system levels.

4. Discussion

The sediment connectivity framework is a promising approach for analyzing coastal sediment transport pathways. Connectivity provides tools to quantify the dominant transport pathways for sediment originating from or leading to a particular location. Already well established in other disciplines, these techniques allow us to identify salient features of transport pathways that may be relevant for both fundamental understanding of a given coastal system, and for answering applied engineering questions. This methodology is generally applicable to coastal systems from beaches to estuaries to deltas, as long as detectable sediment exchange between different (sub)areas takes place. However, it would likely work best for systems where the sources and sinks are well posed. We demonstrated this by applying the approach to Ameland Inlet and addressing the example research questions posed in Figure 1. The analysis presented here is intended to demonstrate the novelty and usefulness of graph theory-based sediment connectivity for coastal applications, and to shine a light on the challenges which must still be addressed in order to apply the concept to its fullest potential.

Connectivity brings value to existing numerical coastal models by adding techniques in graph theory and network analysis to the "toolkit" available for interpreting sediment pathways from those models. Once sediment transport is represented in an adjacency matrix, then computing statistical metrics of connectivity using existing tools (e.g., Csárdi & Nepusz, 2006; Franz et al., 2016; Rubinov & Sporns, 2010) is straightforward. These techniques can quantify spatial and temporal variations in sediment transport beyond just existing metrics like cumulative erosion and sedimentation patterns or mean transport fields. With connectivity, we have mathematical techniques for describing not just where sediment is going, but *which* sediment is going where. However it is more useful than Lagrangian modeling alone, because it tells us not only the history of sediment from a particular source, it tells us something about the interconnected coastal system as a whole.

There are many possible metrics for evaluating connectivity, although we believe that the ones presented in this study are the most useful for studying sediment pathways in coastal systems. In Figure 1, we raised six questions about sediment bypassing at tidal inlets which we can now answer using the connectivity analysis presented here.

1. Shortest-path analysis reveals that sediment bypassing routes on Ameland ebb-tidal delta vary depending on initial source, with offshore sources mainly bypassing around the outer delta, and nearshore sediment bypassing mainly via the inlet (Figure 8). This type of analysis could also be used to identify potential pathways for spreading of nourished or contaminated sediment.
2. Asymmetry in sediment connectivity between cells in the basin and on the adjacent coast reveals a net import of sediment (Figure 7). This type of information could be useful for coastal managers who wish to understand not just total sediment budgets, but also a more detailed breakdown of source and sink locations.
3. The network shows asymmetry for all sediment classes, suggesting that the system is characterized by nonzero net transports, and hence morphological change (Table 1). Examining the asymmetry like this can shed light on system-wide trends in net transport or recirculation.
4. The optimal location for a sand nourishment depends on its goal. To maximize spreading, sites like those in major channels with high degree and strength should be chosen (Figure 9). However, if slower dispersal is preferred, then a site with lower degree and strength should be chosen. The combination of this information with shortest-path analysis could be used to design nourishments which target a particular receptor.
5. Connectivity networks developed for finer sand (100 μm) show greater connectivity throughout the model domain, whereas coarser sand (400 μm) shows less connectivity, and primarily only in the main channels (Figure 6). These differences can be explained by spatial variations in hydrodynamic energy and local particle size distribution.
6. The Louvain modularity algorithm aggregates 25 geomorphic cells into five sediment-sharing communities (Figure 7). This approach could be also be used to objectively classify geomorphic cells from high-resolution input.

Future research on this topic should go beyond the application of generic connectivity metrics, and focus on the development of connectivity metrics specific to quantifying and analyzing coastal sediment transport.

It is widely acknowledged that identifying appropriate scales for analysis (both temporal and spatial) is still a huge challenge in quantifying connectivity (Bracken et al., 2015; Heckmann et al., 2018; Keesstra et al., 2018; Wohl et al., 2019). Here, we analyze connectivity using residual fluxes, since these fluxes correspond to long-term morphological evolution. However, future research on connectivity in tidal systems should investigate the influence of this choice in analysis timescale. Connectivity changes at different temporal and spatial scales, such that the choice of time or spatial scale considered will influence the connectivity observed. Keesstra et al. (2018) maintain that there is still "no satisfactory solution to the problem of scaling in water and sediment connectivity."

The sensitivity of connectivity to different choices of spatial units depends on the resolution of the schematization, (i.e., the size of the cells). With sufficiently fine resolution (small enough cells) the results will not be dependent on the exact manner of schematization. Two different schematizations would give different adjacency matrices, but they should give the same interpretation. However, for relatively coarse geomorphic cells, the schematization should influence the results more. Aggregation to large cells only makes sense if it is done with morphological knowledge (whether objectively via modularity and clustering algorithms [section 2.3] or numerical model output, or subjectively based on expert judgment of geomorphologically meaningful units [section 3.1]).

Furthermore, the issue of separating structural and functional connectivity is still unresolved in most disciplines using connectivity (Turnbull et al., 2018). This problem is related to the time scaling issues described above, since eventually sediment fluxes modify morphology, and hence, structure. Although many geomorphological studies have examined structural connectivity and developed quantitative metrics for it, functional connectivity still needs to be better explored and quantified (Najafi et al., 2021). Heckmann et al. (2018) advocate using models under varied forcing to examine the relationship between structural and functional connectivity and identify the critical timescales at which network structure is modified.

Tied to the separation of form and function is the definition of the fundamental unit of connectivity. Geomorphic cells defined based on structural criteria like bathymetry will shift from their original boundaries after sufficient fluxes of sediment modify the seabed, so how should they be defined over longer timescales? Multilayer networks can be used to describe variations in network structure and functional connections through time, making them an ideal means for investigating these phenomena (Pilosof et al., 2017; Tejedor, Longjas, Passalacqua, et al., 2018; Thibaud et al., 2013). Although these open questions present challenges to coastal researchers looking to apply connectivity, they also present opportunities: Connectivity could be a useful approach for exploring sediment transport pathways at varying spatial and temporal scales. For instance, connectivity could be used to identify the timescales required for a coastal system to adapt to perturbations (e.g., a nourishment or coastal structure).

Recent advances in remote sensing, in situ measurements, and numerical modeling have created a wealth of data for coastal researchers (Donchyts et al., 2016; Ford & Dickson, 2018; Luijendijk et al., 2018; Vos et al., 2019). In this era of "big data," we need a standardized framework to integrate and compare the coastal sediment pathways derived from models and field data. Since it may be difficult to validate connectivity computed from a single model, this approach would allow multiple lines of evidence or modeled ensemble predictions to be integrated in a common framework (similarly to Barnard, Foxgrover, et al., 2013), increasing confidence in the predictions made. Future research should also assess the applicability of alternative modeling techniques (e.g., Lagrangian particle tracking (MacDonald & Davies, 2007; Soulsby et al., 2011) or directly computing connectivity from Eulerian transport fields) for connectivity analysis.

Connectivity is a useful approach for quantifying the transport of marine pollutants (Paris et al., 2013), including plastic particles (van Sebille et al., 2019). By extension, the sediment connectivity approach presented here could be useful in applications of marine (plastic) pollution that interacts with the seabed (e.g., Corcoran, 2015; Van Cauwenberghe et al., 2015).

Connectivity also distills complex systems into their basic essence in a visually effective manner (e.g., subway maps Derrible & Kennedy, 2009). Furthermore, online visualization tools (e.g., Cytoscape Franz et al., 2016) make it possible to develop interactive ways of visualizing connectivity, bringing tangible form to the often

abstract concepts of sediment transport. This also makes connectivity an attractive platform for communicating with stakeholders and the public (Smetanová et al., 2018).

Phillips et al. (2015) note that connectivity analysis using graph theory "should certainly be included on the standard menu of relevant methods" for geoscientists. There are still major challenges associated with quantifying connectivity at varying spatiotemporal scales and making appropriate choices in schematizing and populating networks. However, further attention to these issues and the development of metrics and techniques specific to coastal systems could improve the method's usefulness and lead to new insights in coastal geoscience.

5. Conclusions

Sediment connectivity quantifies how different locations are connected by sediment transport pathways. The concept of connectivity is well established in other disciplines, and here we use the example of Ameland Inlet to demonstrate its utility in coastal sediment transport settings. Graph theory-based sediment connectivity provides a powerful framework for identifying, analyzing, and interpreting sediment pathways in complex coastal systems.

By dividing a system into geomorphic cells and quantifying the transports between them, we can populate an adjacency matrix and network graph. In that form, existing techniques in graph theory and network analysis offer novel ways of quantifying coastal sediment transport, revealing patterns that may not be obvious with existing techniques. In the case of Ameland Inlet, density, asymmetry, and modularity are used to quantify sediment transport patterns at a system level. Other metrics like degree, strength, centrality, and shortest-path analysis are used to identify critical paths or locations within the system. These parameters give insight into natural coastal dynamics and are also useful for optimizing engineering interventions (e.g., sand nourishments).

The case study of Ameland Inlet shows the potential for connectivity to quantify sediment transport pathways in coastal systems. Quantifying connectivity across different spatial and temporal scales presents researchers with many challenges, but also many opportunities. We believe that this approach complements existing analysis techniques and that it could be valuable for addressing some of the urgent problems facing our coasts in the 21st century.

Data Availability Statement

Example model input files used in this study have been included as supporting information (at https://doi.org/10.4121/13072820.v1). The connectivity analysis in this study was carried out using the open-source Brain Connectivity Toolbox (https://sites.google.com/site/bctnet/).

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