The Delta Connectome: A network-based framework for studying connectivity in river deltas

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Abstract

Many deltas, including the Mississippi River Delta, have been losing land at fast rates compromising the safety and sustainability of their ecosystems. Knowledge of delta vulnerability has raised global concern and stimulated active interdisciplinary research as deltas are densely populated landscapes, rich in agriculture, fisheries, oil and gas, and important means for navigation.

There are many ways of looking at this problem which all contribute to a deeper understanding of the functioning of coastal systems. One aspect that has been overlooked thus far, yet fundamental for advancing delta science is *connectivity*, both physical (how different portions of the system interact with each other) as well as conceptual (pathways of process coupling).

In this paper, I propose a framework called *Delta Connectome* for studying connectivity in river deltas based on different representations of a delta as a network. After analyzing the classic network representation as a set of nodes (e.g., bifurcations and junctions or regions with distinct physical or statistical behavior) and links (e.g., channels), I show that from connectivity considerations the delta emerges as a leaky network that continuously exchanges fluxes of matter, energy, and information with its surroundings and evolves over time. I explore each network representation and show through several examples how quantifying connectivity can bring to light aspects of deltaic systems so far unexplored

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and yet fundamental to understanding system functioning and informing coastal management and restoration. This paper serves both as an introduction to the Delta Connectome framework as well as a review of recent applications of the concepts of network and connectivity to deltaic systems within the Connectome framework.

Keywords: deltas, distributary networks, topology, graph, connectivity, hydrodynamics, morphodynamics

1. Introduction: Why study connectivity in deltaic systems?

Deltaic systems show tremendous variability of shape and structure (Figure 1); their location, at the boundary between land and water, makes them prone to dynamic spatial and temporal disruptions due to environmental factors such as waves, wind, and tides. The relevance of deltaic systems goes well beyond aesthetics; home to wetlands and hot-spots of biological productivity, deltas are ideal environments for fish and agricultural productivity, oil and gas resources, and navigation pathways. It is natural that because of all these factors and a tendency for people to settle in fertile soils in proximity of sources of water, deltas are home to more than 500 million inhabitants (Giosan et al., 2014).

International attention has been recently focused on deltaic systems; their low elevation gradients and the natural and anthropogenic subsidence they are subject to (Syvitski et al., 2009) make them vulnerable to relative sea-level rise (actual sea level plus subsidence) (Horton et al., 2014; Jevrejeva et al., 2014), raising concern in numerous areas of the world, including the Mississippi River delta and the highly populated South Asian deltas (Ericson et al., 2006).

Experiments have shown that under the right conditions deltas are able to match forcings such as sea-level rise. For example, an increase in sea level does not necessarily cause shoreline retreat (land loss) and aggradation of the delta top is possible as long as enough sediment is supplied to the system (Helland-Hansen and Martinsen, 1996; Muto, 2001; Carvajal et al., 2009; Martin et al., 2009; Sverre et al., 2009; Paola et al., 2011).

Figure 1: Examples of delta systems. (a) Portion of the Ganges-Brahmaputra-Meghna Delta; (b) Lena Delta; (c) Yukon Delta; (d) Parana Delta; (e) Mississippi River Delta; (f) Wax Lake Delta. Images from NASA Visible Earth.

Why then are so many deltaic systems in danger? The tremendous development of dams and reservoirs in many parts of the world contributes to the sinking of many deltaic systems (Giosan et al., 2014). Flood management interventions, such as the construction of levees, and cutting of channel networks into wetlands for transport and draining further exacerbate this problem. For example in the Mississippi River delta, a lowland system where connectivity of channel and floodplains should be high (Fryirs, 2013), the construction of levees has contributed to the loss of 1/3 of the land since colonization (Craig et al., 1979; Gagliano et al., 1981; Kesel, 1989; Day et al., 2000, 2007) as sediment is routed to the Gulf of Mexico by a very efficient pipe flow (Falcini and Jerolmack, 2010; Paola et al., 2011; Falcini et al., 2012). Problems related to anthropogenic structures are not unique to the Mississippi River delta; for example, in the Ganges-Brahmaputra-Meghna delta (GBMD) increasing inundation has been recently attributed to the amplification of the tidal signal due to the construction of embankments (Pethick and Orford, 2013) and high subsidence rates have been measured at aquaculture facilities in the Yellow River delta (Higgins et al., 2013). Engineered flood protections disconnect the river from its floodplain resulting in increased vulnerability of delta systems (Temmerman and Kirwan, 2015).

There are several ways to understand delta processes and response to perturbations; efforts have been focused on numerical (e.g., Seybold et al., 2007, 2009; Geleynse et al., 2010; Rowland et al., 2010; Sassi et al., 2012; Liang et al., 2015b) and experimental modeling (e.g., Hoyal and Sheets, 2009; Kim et al., 2009; Martin et al., 2009; Reitz et al., 2010) as well as on the analysis of field observations (e.g., Shaw and Mohrig, 2014; Shaw et al., 2013) and of remotely sensed imagery (e.g., Brakenridge et al., 2013; Passalacqua et al., 2013; Geleynse et al., 2015) to gain an understanding of delta formation and evolution under a suite of initial and boundary conditions. Most of this research, though, has focused on one specific portion of the system, for example channels or islands, without quantifying their connectivity (Hiatt and Passalacqua, 2015).

Connectivity has been the subject of a significant number of recent papers in

the hydrologic literature (e.g., Pringle, 2003; Ali and Roy, 2009; Bracken et al.,
55 2013) that point at three main mechanisms; *structural connectivity* (driven by
physical adjacency of a system’s elements (Bracken et al., 2013)), *functional*
connectivity (also referred to as *process-based*; processes that control the direc-
tionality and magnitude of fluxes across a landscape (Bracken et al., 2013)), and
process connectivity (flow of information among a system’s drivers, where *infor-*
60 *mation* is a reduction in the uncertainty of a variable’s state (Ruddell and Kumar,
2009a; Larsen et al., 2012; Miller et al., 2012; Wang et al., 2012)). The analysis
of these connectivity mechanisms is recognized as a key step to inform wa-
tershed management decisions and hydrologic prediction (e.g., Western et al.,
2001; Bracken et al., 2013).

65 In connectivity analyses the system can be represented as a network; a set
of nodes and of links connecting them. Network theory, the mathematical field
that analyzes networks, their structure, and dynamics, has been widely applied
across disciplines (Newman et al., 2006), from computer science, to biology, to
the human brain, and it is beginning to appear in the geomorphology litera-
70 ture (see Heckmann et al. (2015) and Phillips et al. (2015) for recent reviews).
The hydrologic literature offers many examples of network analysis applied to
watersheds and river networks. From early work to recent applications, the
connection between river network topology and watershed hydrologic response
has been tackled (e.g., Gupta and Mesa, 1988; Rodriguez-Iturbe and Rinaldo,
75 1997; Biswal and Marani, 2010; Gupta et al., 2010; Zaliapin et al., 2010), as well
as its effect on ecosystem, sediment, nutrients, and riparian vegetation (e.g.,
Benda et al., 2004a,b; Kiffney et al., 2006; Lowe et al., 2006; Sklar et al., 2006;
Czuba and Foufoula-Georgiou, 2014). The development of similar knowledge
on the relationship between the network structure and the dynamics of water,
80 solids, and solutes in coastal systems is in its infancy.

Is an analysis of connectivity (and dis-connectivity) needed in deltas? There
are several issues relevant to deltaic systems that require knowledge of connec-
tivity. Deltaic channels distribute water, sediment, and nutrients; their dis-
tributary network emerges from processes such as mouth-bar deposition and

85 avulsions and the contribution of environmental factors such as tides and waves.
Yet, we do not completely understand the relationship between network form
and function. We lack an understanding of how water and sediment fluxes are
partitioned and of where hotspots of nutrient delivery and uptake are located.
The connectivity between surface water and groundwater is largely unknown, as
90 well as the connectivity of surface patterns and the stratigraphic record. Cou-
plings among delta variables are only qualitatively, rather than quantitatively
known. On the other hand, management decisions and coastal restoration re-
quire knowledge on how different portions interact with each other across scales
(Paola et al., 2011).

95 The recent availability of satellite imagery over much of the Earth (Syvitski,
2006) has greatly improved the quantitative analysis of geomorphic features.
Over smaller spatial extents, techniques such as lidar have increased the capabil-
ity of remotely capturing geomorphic processes at fine scales (Passalacqua et al.,
2015). Advanced tools for the extraction of geomorphic features from remotely
100 sensed data of coastal environments are now available (Shaw et al., 2008; Geleynse et al.,
2012; Isikdogan et al., 2015) and physical and numerical modeling of deltaic
systems have been underway for more than a decade. Techniques for field
data acquisition have also been improved and new techniques have been de-
veloped (e.g., multi-beam sonar, green lidar, ADCP sensors), providing detailed
105 bathymetry and flux data. Also, research in river network structure and wa-
tershed connectivity has been pursued for more than a decade, which provides
us with good background knowledge and tools on how to study connectivity in
the upstream counterpart of delta networks, i.e. river tributary networks (e.g.,
Bracken et al., 2013; Fryirs, 2013; Czuba and Foufoula-Georgiou, 2014). Also,
110 ideas can be taken from other fields where complex networks have been analyzed
(see Newman (2010) for a review).

Motivated by these factors, in this paper I propose the *Delta Connectome* as
a framework to study deltaic systems by exploring their connectivity in struc-
ture, dynamics, and process, which relies on the representation of the delta sys-
115 tem as a network that continuously exchanges fluxes of matter, energy, and/or

information with its surroundings and changes over time. I introduce the Delta Connectome framework with an analogy to brain networks and a discussion on scale and observations (Section 2) and then apply it through different representations of the delta system as a network, reviewing also recent network theory and connectivity work in delta systems (Section 3). I then discuss the relevance of a connectivity approach for coastal sustainability and provide ideas for future applications of the Connectome framework (Section 4). Finally, the conclusions of this work are presented (Section 5).

2. How to quantify connectivity in deltaic systems: The Delta Connectome framework

2.1. Inspiration for the Delta Connectome: Deltas as complex networks

The Human Connectome framework was introduced by Sporns et al. (2005) to advance knowledge of the structure and function of the human brain by detailed mapping of neural connections. This is not a trivial task given the number of neurons and connections that on average characterize the complex network of the human brain (10^{11} neurons and 10^{15} connections (Sporns et al., 2005)). From the microscale or scale of single neurons, to the mesoscale of neuronal groups or populations, to the macroscale of brain regions and regional pathways, the brain shows multiple levels of connectivity whose quantification requires appropriate techniques for data collection and analysis (Sporns et al., 2005). In addition to the wide range of spatial scales, the brain goes through tremendous development through time from the early stages of the embryo up to adult life and is subject to changes and perturbations. These characteristics are not unique to the human brain as many systems across disciplines can be viewed as complex networks (Newman et al., 2006).

Deltas are seldom analyzed with network theory tools; however, their complexity and multi-scale (spatial and temporal) characteristics would suggest they are in fact complex networks. A wide range of spatial scales contribute to delta functioning, from the interactions at the scale of grains and particles (the neu-

145 rons) to the network of channels that transport water, sediment, and nutrients
 (the regional pathways) and regulate the system’s response to forcings such as
 sea-level rise and subsidence. The channel network can be complex and char-
 acterized by the presence of loops and multiple paths between the apex and
 the shoreline. This characteristic makes deltas ‘networks’ as opposed to ‘trees’
 150 where a unique path exists between a source and a sink (see Newman (2010)
 and references therein for more information on networks and trees). Tributary
 river networks are an example of the latter. Deltas also continually evolve and
 change in time; mechanisms such as channel avulsions, for example, change the
 network structure, essentially rewiring the system by favoring new pathways
 155 and abandoning previous ones (Slingerland and Smith, 2004; Kleinhans et al.,
 2013). Environmental factors such as wind, tides, and waves vary patterns of
 inundation daily and contribute to the transport of sediment and solutes.

A connectivity analysis consists of identifying a set of objects (e.g., locations
 or variables) and the connections among them. Methods to quantify connec-
 160 tivity often rely on network representations of the system, as objects can be
 thought of as nodes of a network and connections or physical dependencies as
 network links. Mathematically, an adjacency matrix in its simplest form cap-
 tures whether two nodes are connected. The adjacency matrix can also include
 link directionality, in which case the matrix is not symmetric, and strength of
 165 the connection, in which case weights are associated to each link in the adja-
 cency matrix. The advantage of relying on the representation of a system as
 a network and its related mathematical analysis is that the same tools can be
 applied to different network representations and over multiple scales. Essen-
 tially, while the mathematical representation is overall the same, the definition
 170 of nodes and links dictates what aspect of the system is captured and thus what
 type of connectivity can be measured.

With the *Delta Connectome* framework I extend the term ‘network’ from
 the rigid definition given above, where a set of nodes and their links completely
 describes the system, to the one of a network where physical locations exchange
 175 fluxes of matter, energy, and information, essentially embedding the network

in a continuous field where it is also able to evolve and reconfigure itself over time. The network representations are here designed to quantify aspects of physical connectivity among different portions of the system (physical adjacency - structural connectivity) and to analyze how that adjacency affects fluxes of water, sediment, nutrients (functional connectivity) and information (process connectivity).
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Given the wide range of scales that contribute to delta functioning, at what scale can connectivity be quantified? Below, I briefly review the approaches that are commonly used to study deltas and the types of observations that are currently available to quantify connectivity.
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2.2. At what scale can connectivity be quantified? Approaches commonly used to study deltas

Commonly used approaches to study deltas include numerical and physical experiments, field and theoretical studies, as well as the analysis of remotely sensed observations, which all provide useful information to perform a connectivity analysis of delta systems.
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Numerical models commonly rely on governing equations of delta formation and evolution based on a conservation approach within and across a control volume of interest. High fidelity modeling approaches such as Delft3D (Lesser et al., 2004), for example, solve the Navier-Stokes equations. In this case, limitations to the model grid resolution and the amount of flow detail directly resolved come from the computational costs associated with the simulations. Modeling results provide a range of delta morphologies, simulated under a variety of boundary conditions, and related synthetic observations of water and sediment fluxes, which can be used to quantify physical and process connectivity. The scale of analysis is commonly the macroscale of channels and islands, while microscale interactions are usually embedded in laws, such as those governing sediment transport. Lagrangian approaches to delta modeling exist, in which commonly not all details of the system are captured (Liang et al., 2015b), that allow following movements and interactions at the particle scale
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and their contribution to delta formation and evolution.

Model results should be compared to other types of observations (e.g., from the field) with robust metrics. While metrics for the assessment of the hydrodynamic component are overall well defined (Liang et al., 2015a), robust metrics
210 for the analysis of morphodynamic results are lacking, although efforts in this direction are appearing in the literature (Edmonds et al., 2011; Marra et al., 2013; Liang et al., 2016).

Physical experiments have been extensively used to capture the formation and evolution of deltaic systems under a variety of boundary conditions, including differential subsidence and changes in sea level (Paola et al., 2001).
215 Observations from physical experiments can inform both structural and functional connectivity studies as well as process connectivity. Scaling of a real system to laboratory scale entails challenges in reproducing the richness and complexity of patterns observed in the field (and to some extent in numerical
220 models). Nevertheless, a significant portion of knowledge of delta formation and evolution comes from physical experiments, particularly in capturing long term dynamics through the analysis of the stratigraphic record and avulsion patterns (e.g., Hoyal and Sheets, 2009; Martin et al., 2009; Reitz et al., 2010; Ganti et al., 2013).

Field surveying offers the opportunity to quantify connectivity at finer scales,
225 especially functional and process connectivity. While any numerical and physical model goes through some level of simplification, field observations can potentially capture processes over their whole range of scales (given appropriate instrumentation). Most of the knowledge on ecological and biogeochemical
230 processes in deltas, for example, is derived from field observations, due to limitations in reproducing these processes in physical or numerical models. Spatial and temporal extent of field surveys depend on the available resources. Even in systems of reasonable size, for example the Wax Lake Delta (WLD) (≈ 100 km^2), the collection of observations at the network scale is challenging due to the
235 highly dynamic conditions that characterize deltaic systems. The rapid change in hydrodynamic conditions due to environmental forces such as wind and tides,

often prevents the collection of observations over the whole system under the same hydrodynamic and morphodynamic conditions unless enough instruments are available to take measurements at different locations simultaneously. Measurements of fluxes of water, solids, and solutes over the subaqueous and sub-aerial extent of delta systems are needed to improve our understanding of delta growth and evolution under various boundary conditions. The recent study of Shaw and Mohrig (2014), for example, has shown mechanisms of delta growth during low and high flows through the analysis of bathymetric data acquired in the subaqueous portion of the WLD.

Many delta studies also rely on remotely sensed observations, particularly useful for the analysis of large systems, such as the GBMD, where field work over extensive areas is not easily achievable, or to gain an understanding of the evolution of a system through time. Limitations to the scale of analysis are given by the resolution of the image. The freely available Landsat data, for example, have spatial resolution of 30 *m*, which sets the minimum scale of the objects that can be analyzed. While higher resolution data sets exist, they are seldom available over large extents. Remotely sensed imagery allows capturing patterns of inundation (e.g., Geleynse et al., 2015; Kuenzer et al., 2015) with a frequency dependent on the passes of the instrument over the area of interest. The time evolution of young deltas, as WLD, can also be captured with these data, but limitations exist for older systems as the record may not go back in time enough to truly capture their temporal changes. The information obtained from remotely sensed data can inform the analysis of structural connectivity and can also indirectly inform studies of functional connectivity (as fluxes cannot be directly measured but their effect can be visualized, e.g., patterns of inundation).

I present in the next section applications of the Delta Connectome framework based on several network representations of a delta system, both physical and conceptual, and discuss the connectivity aspects captured by each of them. Given the scale of the observations produced by the approaches briefly described above, the physical network representations are defined at the scale of channels and islands rather than the microscale of single particles. These network repre-

sentations are not meant to be the only ones possible, but rather offer examples of application of the Delta Connectome framework and inspire further work in this direction.

3. Application of the Delta Connectome framework

3.1. The delta as a network of channels

Perhaps the most classic way of representing a delta as a network is its distributary network of channels. In this representation, we can view channel bifurcations, junctions, outlets at the bay, and the apex as network nodes and the channels connecting them as network links (Figure 2). Properties of the channels, such as their width, can be used as weights to express a measure of strength of network links (Passalacqua et al., 2013). Flow directions along channels indicate link directions. A representation of the delta as a network of channels can be used to quantify the transport of water, sediment, and solutes via channelized flow to the shoreline and to island interiors (if the secondary network of channels is included), and travel times through the system.

Several early and recent studies have focused on delta distributary channel networks to identify robust metrics able to describe them quantitatively (Smart and Moruzzi, 1971; Edmonds et al., 2011; Tejedor et al., 2015a,b), predict their development based on simple laws (Syvitski, 2006; Edmonds and Slingerland, 2007; Jerolmack and Swenson, 2007; Syvitski and Saito, 2007; Wolinsky et al., 2010), quantify the controls exerted by grain size (Caldwell and Edmonds, 2014), and analyze network response to forcings such as sea-level rise and subsidence (Jerolmack, 2009; Liang et al., 2016). Issues of connectivity are not addressed in the majority of these studies; however, knowledge derived from them, including metrics, can inform connectivity analyses and is reviewed below.

In the early work of Smart and Moruzzi (1971), the network was analyzed as a directed graph and its characteristics quantified based on a directed adjacency matrix. The directed adjacency matrix accounts for the directionality of the link between two nodes i and j : location a_{ij} is assigned a value equal to 1 only if the

Figure 2: Example of delta channel network. Network links (lines) and nodes (circles) are overlaid on Landsat data of the Wax Lake Delta. The low water level conditions at which the image was taken allow secondary channels within islands to be detected. An example of island is indicated by the shaded polygon. Image specifications: LANDSAT 5 TM+ image from 02 January 2011 at 30 m resolution obtained from the USGS Global Visualization Viewer (available online at <http://glovis.usgs.gov/>). The extracted channel network is part of the WLD Network Evolution Database developed as part of the Delta Dynamics Collaboratory at Wax Lake Delta.

flow is directed from node i to node j and a value equal to 0 if the flow is directed in the opposite direction. Only the primary network of channels was included in this study, while secondary channels draining to island interiors were neglected.

300 Metrics analyzed by the authors included the number of alternative paths from the apex to the shore and the recombination factor, defined as the ratio of the number of junctions to the number of bifurcations to capture the loopiness of the network. The comparison of five natural systems (Colville, Irrawaddy, Yukon, Niger, Parana) to random networks with the same number of nodes and links
305 showed that delta networks carry distinct network characteristics with respect to random connections and that some degree of similarity among delta systems could be captured based on the defined metrics.

The same directed graph representation of the primary channels was also adopted by Tejedor et al. (2015a,b), who proposed a set of metrics to quan-
310 tify the vulnerability of delta channel networks to change. With a definition of vulnerability as lack of or reduced delivery of fluxes to the shore (connections to island interiors were neglected), the authors used graph theory and constructed vulnerability maps for two delta networks (Wax Lake Delta and the Niger Delta). The authors then extended their analysis to seven delta networks
315 and computed several topological and dynamic metrics aiming at quantifying the network loopiness, the amount of link overlap among subnetworks, and the degree to which fluxes (here intended as a general flux of some quantity) are distributed and shared among network links before reaching the outlet nodes. In order to include link directionality and represent the delta as a directed graph,
320 both Smart and Moruzzi (1971) and Tejedor et al. (2015a,b) guessed flow directions based on the topological configuration of the network and the assumption of a general downstream direction. It is worth noting that in the case of loops this operation is not trivial as links are not necessarily oriented in an obvious downstream direction. Furthermore, directions along delta channels may not be
325 uniquely defined in those systems where channels experience periodic changes in flow direction due to tides.

Besides the above studies based on graph theory, other efforts have analyzed

distributary channel networks to develop simple predictive laws of delta network evolution. Syvitski (2006) and Syvitski and Saito (2007) analyzed a large
330 database of delta systems and derived the scaling of the number of distributary channels with river length and delta gradient and the distribution of channel width. Edmonds and Slingerland (2007) developed a predictive model of distributary network formation based on the process of mouth-bar deposition at the shoreline, ideas extended by Jerolmack and Swenson (2007) to include avul-
335 sions and the action of waves at the shoreline. The analysis by Wolinsky et al. (2010) led to the development of additional laws of delta growth and included the application of a box counting technique which showed fractality of the distributary network and the nonfractal nature of the delta shoreline.

Fractal dimension was also used as metric for comparison of five deltas (numerical, experimental, and real systems) in the study by Edmonds et al. (2011).
340 A representation of the delta as channel reaches (links) between bifurcation points (nodes) was used in the same study to estimate the sediment flux delivered by each channel at the shoreline, where the sediment flux was assumed to be proportional to the water discharge. The distribution of sediment flux
345 delivered by channels to the shoreline was used to infer the stability of the distributary network; uniform distributions indicate stable network configurations, differently from cases in which most of the sediment is delivered by one channel, which likely lead to avulsions and changes in the network configuration.

Characteristics of the delta channel network have also been used in numerical modeling studies to quantify the effect of changes in initial conditions and
350 boundary conditions. The study of Caldwell and Edmonds (2014) analyzed how grain size affects delta morphology. The results showed that increasing the grain size results in denser networks in deltas of more circular shape, while finer sediment systems are characterized by less channels and more elongated shapes.
355 Liang et al. (2016) quantified the delta channel network response to stressors such as sea-level rise and subsidence. In this case, the analysis of the network structure was used to quantify its dynamic response to a forcing. The results showed increased branching (denser network and higher connectivity) of the

channel network with increased fractality and higher mobility in response to
360 uniform subsidence and absolute sea-level rise.

Jerolmack (2009) developed a conceptual model to analyze the response of
delta channel networks to the rapid mid Holocene sea level rise and its later de-
celeration. The model predicted initial aggradation and an increase in avulsion
frequency with formation of large scale distributaries, followed by prograd-
365 tion, a decrease in the number of large distributaries, and an increase in small
branching channels at the shoreline.

3.2. The delta as a leaky network of channels and inter-channel islands

The work described above analyzes delta systems by relying on their some-
what rigid representation as a network of channels. While this representation
370 is commonly used, is it enough to capture the delta structure and dynamics?
Many studies of river systems focus on the role of floodplains and their chan-
nel networks (e.g., Day et al., 2008; Rowland et al., 2009; Trigg et al., 2012)
and the connectivity between channels and floodplains (e.g., Croke et al., 2013).
Floodplains in river deltas are inter-channel islands; portions of land which are
375 bounded by channels (or by channels and the shoreline; e.g., the shaded polygon
in Figure 2). Do islands participate in transport processes or are transport pro-
cesses only active along the channel network? The delivery of sediment to the
island interiors is a fundamental process to maintain and grow land and con-
trast the effect of subsidence and sea-level rise; thus, the analysis of the primary
380 channel network may not be sufficient to characterize the transport of water,
sediment, and nutrients through the system.

Recent literature has relied on islands as descriptors of the delta network
structure. These efforts are briefly reviewed below before summarizing recent
research that points at the importance of quantifying the connectivity between
385 channels and islands and extends the notion of delta network to a leaky network
of channels and islands.

3.2.1. *The role of islands in delta networks*

The analysis of island characteristics may be as informative as the analysis of the distributary channel network, and perhaps even more as characteristics of the islands carry the signature of interactions among nearby channels. The metric
390 nearest-edge distance (Edmonds et al., 2011), for example, is defined as the shortest distance to the nearest source of water (channelized or unchannelized) from any land pixel in the delta. This metric is essentially the inverse of drainage density as in very dense networks, where drainage density is high, nearest edge
395 distance would be small and vice versa.

When applied to heterogeneous deltas, the analysis of island characteristics can highlight regions of the system characterized by distinct physical and statistical behavior (assuming that the delta has a large enough number of islands to yield robust statistics). In the GBMD, Passalacqua et al. (2013) found
400 that island properties (roughness, nearest-edge distance, and area) showed power-law behavior, suggesting the lack of a characteristic island scale in deltaic systems. The statistical behavior of the analyzed properties distinguished the active portions of the delta from the inactive one, closely reproducing a physiographic zonation previously identified based on geological maps (Alam et al.,
405 1990; Persits et al., 2001). Connectivity varied among different portions of the system, with the tidal zone (particularly within the mangrove zone) being the most connected, reflected in small island size and short nearest-edge distance (Figure 3 (a)).

Island characteristics can also be used to capture the delta response to forcings and disturbance; the study of Liang et al. (2016) showed decreasing island
410 size and nearest-edge distance with increasing relative sea-level, in agreement with the increased branching of the channel network.

3.2.2. *The connectivity of channels and islands and the concept of a leaky network*

415 So far, we have covered two fundamental components of delta systems: channels and islands. While a classic view of the delta network comprises only its

Figure 3: Connectivity analysis of the Ganges-Brahmaputra-Meghna Delta. (a) Map of channels and network links (channel centerlines) extracted from Landsat data (GeoCover TM1990 EditionMosaics, tiles N4520 and N4620). (b) The elimination of network links with width ≤ 60 m results in reduced network connectivity, particularly in the inactive zone (marked as *I*). Channels connecting the upstream portion of the delta to the shoreline are predominantly narrow. The regional boundaries are marked as *T* (tidal), *A* (active), and *I* (inactive) and they are from Alam et al. (1990) and Persits et al. (2001). Figure produced with data from Passalacqua et al. (2013).

channels, the work reviewed above shows that islands, the ‘negative’ of channels, are useful descriptors of the structure of the system. Do islands play a role also in transport dynamics? Hiatt and Passalacqua (2015) measured the hydrological connectivity between channels and islands and found significant exchange between the two. Field observations collected at WLD showed that up to $\approx 50\%$ of the water discharge of distributary channels can be transferred to islands (wetlands). Structural connectivity relies on a combination of secondary channels connecting the main distributary channel to the island interior and unconfined flow in the portion of the channel near the bay, favored by a transition in levee morphology from subareal and vegetated in the upstream portion of the island to subaqueous closer to the shore. Process-based connectivity is reflected in the impact of tides and wind on the magnitude and direction of these fluxes, as wind can significantly affect water levels and inundation (also shown by Geleynse et al. (2015)) and channels can show flow inversion due to tides.

Additional data collected at WLD during a series of tracer studies within an island showed convergence of fluxes towards the island interior and significant discharge from the island to the bay. Flow in islands is affected by tides to a higher degree than channels, resulting in higher estimates of hydraulic residence time within islands than in channels. Based on these findings, Hiatt and Passalacqua (2015) proposed a conceptual model of channel-island connectivity in delta systems (Figure 4) where both channels and islands are considered portions of the same hydrological network. An interesting aspect of this work, that merits further analysis in the future, is the combination of distributary (channels) and tributary (islands) character of the delta network, which suggests that fluxes are spread from the delta apex to the shoreline along channels, but converge towards island interiors (also noted by Shaw et al. (2016)) as in a tributary network (visible in the island secondary channels in Figure 2 in correspondence of the shaded polygon).

The conceptual model of network proposed by Hiatt and Passalacqua (2015) (Figure 4) does not fit the rigid definition of network as a set of nodes and of

links. Although some nodes and links of interest can be identified, the main characteristic of the channel-island network is its leakiness and the importance
 450 that off-channel dynamics play in delta functioning. This finding motivates the extension of the concept of ‘network’ to the one of a leaky network where matter, energy, and information are exchanged beyond the distributary channel network.

As noted by Liang et al. (2016), metrics to capture connectivity in delta sys-
 455 tems are lacking. The authors proposed a framework to categorize delta metrics based on the type of characteristic they measure; whether it is a bulk property (e.g., delta area), a spatial distribution (e.g., the distribution of island size or channel width), or a temporal distribution (e.g., the timescale of avulsions). The metrics were also organized based on the object each metric is commonly
 460 applied to or was designed for, i.e. channels, islands, shoreline, delta surface, and subsurface. Not surprisingly, most of the metrics in all three categories have been developed for or applied to channels. The other result that emerged from this metric analysis is that almost no metric exists to quantify the connectivity among different portions of the delta. As mentioned above, deltas are usually
 465 analyzed as compartments rather than connected systems.

One exception is represented by the nourishment area, metric originally proposed by Edmonds et al. (2011). Analogously to the role played by drainage area in tributary systems (the portion of the watershed that drains to a given location), the nourishment area represents the amount of land fed by the sedi-
 470 ment flux transported at a given location. In the application of Edmonds et al. (2011) the metric was calculated at a set of points along the channels by assuming symmetric spreading of fluxes downstream of any location, which resulted in a relationship between distance from the shore L and nourishment area A as $A \sim L^2$.

475 Liang et al. (2016) revisited the concept of nourishment area to quantify the channel-island connectivity identified by Hiatt and Passalacqua (2015). The authors relied on the lagrangian model DeltaRCM (Liang et al., 2015b) to track particle spreading from any location along the channel network. Based on their

Figure 4: Channel-island connectivity in deltas. The conceptual model developed by Hiatt and Passalacqua (2015) showing the connectivity between channels and island in a delta system as it varies from mainly driven by secondary channels (in correspondence to subaerial and vegetated levees (b) and (c)) to unconfined flow (in correspondence to subaqueous levees (d)). Also indicated are flow directions along channels (a) and islands, including areas where bi-directional flow is expected due to the influence of tides (e.g., (b)). Figure reproduced from Hiatt and Passalacqua (2015).

results, Liang et al. (2016) proposed a conceptual model to quantify channel-
480 island connectivity based on the variation of the degree of channel confinement
from upstream to downstream. In this case, the relationship between the dis-
tance from the shore L and the nourishment area A is given by $A \sim L^\theta$ where
the exponent θ takes a value < 2 for decreasing confinement towards the shore
(increasing channel-island connectivity), a value > 2 for increasing confinement
485 towards the shore (decreasing connectivity; an unlikely behavior for delta sys-
tems), and a value of 2 in the case of constant degree of confinement. With
this definition, the variation of channel-island connectivity can be quantified as
a function of distance from the shore under a variety of boundary conditions.

The other existing metric that could be adapted to quantify connectivity is
490 the synthetic sediment flux distribution at the shoreline, which was reviewed in
Section 3.1. Although originally developed as a delta channel network metric
(the delivery of sediment to the shore from channels (Edmonds et al., 2011)),
the metric could be easily applied to the channel-island network and to the
transport of nutrients. Liang et al. (2015a), for example, applied this metric to
495 quantify the water fluxes at the shoreline and analyze the partitioning of water
discharge delivered at the shoreline between channels and islands.

3.3. The delta as a network of regions of different physical or statistical char- acteristics

Another factor that contributes to the complexity of delta systems is the role
500 played by environmental forcings such as discharge, wind, tides, and waves on
the delta formation and evolution. Interest in identifying dominant forcings
on delta morphology stimulated research early on. Wright and Coleman (1972)
identified river discharge and wave strength among the fundamental drivers of
delta morphology, initiating the well known ternary classification according to
505 rivers, waves, and tides (Wright and Coleman, 1973; Galloway, 1975). Even if
more complex classifications have been proposed since then (Elliot, 1986; Hart,
1995; Syvitski, 2006), they are still challenged by the fact that forcing factors
can vary in space and time.

Do different forcings result in distinct spatial morphological patterns across the delta? How are these regions connected? As mentioned above, the statistical analysis of a set of island metrics in the GBMD highlighted regions of the delta with distinct statistical and morphological characteristics (Passalacqua et al., 2013). In systems as heterogeneous as the GBMD it is thus possible to identify distinct delta ‘regions’. A connectivity analysis can be performed at this scale to analyze how different regions are connected to each other and how this connectivity (or lack of) may affect transport processes. Passalacqua et al. (2013) built the adjacency matrix of the GBMD network where link connections were weighted by channel width; in this network representation, wider channels are stronger network links than narrower channels. The authors added disturbance in the system by removing the links with width less than $\approx 60\text{ m}$ (two pixels), reproducing, for example, a scenario of reduced rainfall or increased siltation (Alam, 1996; Rahman et al., 2013; Wilson et al., 2015) that could cause the elimination of the weakest network links. This operation caused the reduction of links across the delta and in particular in the ‘inactive’ region that after disturbance resulted mostly disjointed from the active regions of the delta (Figure 3 (b)). The weak structural connectivity (via narrow channels) of the inactive portion of the GBMD was hypothesized by the authors to contribute to the reduced sediment transport and sediment starvation that characterize the inactive region.

A similar analysis may not be applicable to smaller systems as the lack of a significant number of channels and islands would prevent a robust characterization of the statistical distribution of their properties. On the other hand, the findings here reviewed suggest that, when applicable, this analysis can help tease apart the controls of different environmental factors on network topology and geometry.

3.4. The delta as a network through time

There are a couple of ways in which deltas can be represented as networks through time; the first is the application of the analyses above as a function

of time to determine how connectivity patterns change as a function of auto-
540 genic or allogenic processes and disturbances. In this case multiple networks
can be analyzed to quantify how the configuration of channels and islands re-
organizes itself over time. For example, the results of numerical or physical
experiments can be analyzed to capture channel mobility and reworking of the
delta surface with metrics such as channel instantaneous planform change, chan-
545 nel planform overlap, and fluvial reworking timescale (Cazanacli et al., 2002;
Kim et al., 2010; Wickert et al., 2013; Liang et al., 2016). In addition, any of
the channel and island metrics discussed in the previous sections can be ana-
lyzed over time. This type of analysis can be also performed in real systems
when the available data cover a large enough time span. Several studies on the
550 Niger Delta, for example, have quantified changes in land use and coastline dy-
namics (Onojeghuo and Blackburn, 2011; Kuenzer et al., 2014) in response to
anthropogenic disturbance.

Another way of thinking about the delta as a network through time is via the
imprint of its past dynamics in the stratigraphic record; time is thus captured
555 along the vertical axis. Although boundary conditions can change over time,
and thus surface patterns will not always be good indicators of the subsurface
structure, spatial correlations between the surface morphology and the subsur-
face structure have been qualitatively assessed in systems such as the GBMD
(Goodbred et al., 2003; Pickering et al., 2014; Wilson and Goodbred, 2015).

560 Whether or not surface patterns are good indicators of the subsurface struc-
ture, there is much to be gained by developing approaches to quantitatively
assess the connectivity (or lack of) of surface and subsurface patterns. As noted
above in the case of channel-island connectivity, metrics to quantify surface-
subsurface connectivity are lacking (Liang et al., 2016). A first step in this
565 direction is the sedimentograph, proposed by Liang et al. (2016), based on the
metric net:gross used in the hydrocarbon industry. This metric measures the
deposited coarse sediment fraction and it can be computed spatially (over the
whole network or along transects, e.g., distance from the shoreline) and over
time (at one fixed location).

570 The behavior of the sedimentograph changes as a function of grain size in
 agreement with changes in the surface patterns; in finer sediment deltas, where
 channels are likely to create new pathways on the floodplain, the sand fraction
 increases over time, while it decreases in coarser sediment deltas where channels
 tend to reoccupy existing pathways allowing mud deposition in the floodplain
 575 between active channels. This knowledge can also be used to interpret deposits
 from cores collected in the field. Liang et al. (2016), for example, compared their
 modeling results to cores collected at WLD to quantify spatial and temporal
 deposition patterns. Given the availability of data from physical experiments,
 such as the ones performed in the Jurassic Tank (Paola et al., 2001) and other
 580 experimental facilities, the sedimentograph can be used to further quantify the
 connection between surface patterns and the stratigraphic record.

Another notable example of surface-subsurface investigation is the study of
 van Dijk et al. (2016) in the Sutlej-Yamuna plain of northwest India. By re-
 lying on remotely sensed and wells data, the authors quantified the linkages
 585 among surface morphology and characteristics of aquifer bodies such as thick-
 ness, geometry, and stacking pattern. Given the significant issues associated
 with pollutant transport in aquifers and its impact on water quality in densely
 populated deltas (Michael and Voss, 2008; Burgess et al., 2010), quantitative
 analyses of surface and subsurface patterns are of fundamental importance.

590 3.5. *The delta as a network of variables and process couplings*

Delta processes cover a wide range of spatial and temporal scales, resulting in
 couplings and feedbacks often referred to as complex and nonlinear. Despite
 their relevance to a quantitative understanding of delta functioning, delta cou-
 plings have not been quantified. The analysis of process couplings pertains to
 595 process connectivity and can be based on a network representation as for the
 cases above. The delta can be represented conceptually as a network of vari-
 ables (e.g., discharge, wind, sediment flux) that act as nodes, and of couplings
 as network links. The adjacency matrix in this case will include directionality
 (the direction of the flow of information between two variables) and weights (the

600 strength of the flow of information).

Ruddell and Kumar (2009a,b) quantified couplings and feedbacks among eco-hydrologic variables measured at a FLUXNET tower using statistical metrics developed in the field of communication theory, in particular mutual information and transfer entropy (Schreiber, 2000). This statistical method measures the reduction in the uncertainty of the current state of a variable due to
605 knowledge of the history of another variable that is not already contained in the history of the variable itself (Ruddell and Kumar, 2009a). In their analysis, the authors were able to characterize couplings of ecohydrological variables in strength, directionality, scale, and statistical significance.

610 Recent work on the WLD has suggested that delta dynamics (for example shoreline hydrodynamics and thus island flooding) are controlled by discharge, wind, and tides (Geleynse et al., 2015). These environmental factors exert controls on the water surface elevation of the same order of magnitude despite the fact that the system is commonly considered river dominated. Thus, wind and
615 tides contribute to the transport of sediment and nutrients with implications for land building and potential denitrification in delta islands (Hiatt and Passalacqua, 2015). Discharge will likely control inundation on longer time scales, on the order of weeks, while a forcing such as wind will affect water levels on much shorter (daily) scales.

620 An information theory approach, similar to the one used in the analysis of Ruddell and Kumar (2009a,b) could be used to quantify couplings in delta systems. A first step in this direction has been taken by Sendrowski et al. (2014) and Sendrowski (2015) who applied transfer entropy to the problem of island inundation at the WLD via the analysis of water surface elevation time
625 series collected over several months. In their work, the behavior of channels and islands was contrasted to quantify the larger effect that wind and tides have on island water levels with respect to channels. This analysis was also performed at several spatial locations to quantify how the spatial location of the island within the network affects couplings. The importance of spatial location within
630 the delta prompts again the extension of the classic definition of a network as

a set of nodes and links (whose spatial location does not matter) to the one of a geographic network where spatial location plays a role in the transport of matter, energy, and information.

3.6. Summary of connectivity in river deltas

635 To summarize the ideas here presented, a schematic depicting structural, functional, and process connectivity is in Fig. 5. Primary and secondary channels (solid lines marked on the left channel, Fig. 5(a)) and the transition from sub-aerial to subaqueous levees (unconfined flow near the bay represented by solid arrows on the right channel, Fig. 5(a)) are elements of structural connectivity. 640 Examples of functional connectivity are the changes in flow direction due to tides in channels and islands (dashed arrows) and the magnitude and extent of the overbank flow. Process connectivity captures the shared and transferred information (solid lines, Fig. 5(b)) among delta variables and can be quantified by computing information theory metrics (mutual information and transfer en- 645 tropy) among relevant delta variables (e.g., water level, wind speed, discharge, turbidity, temperature). The variables can be measured at several channel (triangles) and island (circles) locations and/or multiple locations within one island to quantify spatial differences in process connectivity.

4. Discussion

650 In recent years significant interdisciplinary research has been focused on delta systems in response to the evidence of risk and increased vulnerability that characterize many coastal systems. These efforts have included numerical modeling, physical experiments, theoretical studies, field surveying, and remotely sensed imagery analysis with the goal of capturing the formation and evolution 655 of delta systems under a variety of boundary conditions. Several of these studies have also developed metrics to quantify deltaic patterns and facilitate robust comparison of systems across environments and assessment of modeling results.

Connectivity in deltaic systems has not been quantified thus far; however, knowledge of how different portions interact with each other and of couplings

Figure 5: Connectivity in river deltas. (a) Elements of structural connectivity are primary and secondary channels (solid lines on the left channel) and unconfined flow close to the bay as levees transition from subaerial to subaqueous (solid arrows on the right channel). Functional connectivity manifests itself as changes in flow direction due to tides in islands and channels (dashed arrows) and in the magnitude and extent of the overbank flow. (b) A group of measurement stations located in channels (triangles) and islands (circles). Information shared or transferred (solid lines) among the measured variables can be quantified by computing mutual information and transfer entropy. Spatial variations among couplings can be quantified by measuring relevant delta variables at several locations within the delta (or within one island).

660 and feedbacks among variables is needed to understand delta functioning and
inform coastal restoration design. The restoration plan in act for the coast
of Louisiana (LACPRA, 2012), for example, includes the design of engineered
river diversions to reestablish the connectivity between channels and floodplains
at strategic locations and promote land building. A connectivity analysis is
665 important not only for quantifying the advantages of increased system's con-
nectivity but also its disadvantages. Increased hydrological connectivity and
residence times in wetlands represent favorable conditions to the spread of
harmful algae blooms corresponding to deteriorated water quality conditions
(Rivera-Monroy et al., 2010).

670 In this paper, I introduced the Delta Connectome as a framework for study-
ing connectivity in deltaic systems through the representation of the delta as a
network that defines the type of connectivity that can be captured. A network
of channels is perhaps the most classic representation of a delta network, but
only captures the main distributary network of channels. The analysis of field
675 observations and remotely sensed data has pointed at islands, or the delta flood-
plain, as important portions of the network, whose connectivity with channels
is of first-order importance for delta eco-morphodynamics. This finding has
prompted the representation of the delta as a leaky network of channels and
islands of mixed distributary/tributary character.

680 Metrics to quantify channel-island connectivity are scarce. A first step in
this direction are the nourishment area and the distribution of fluxes at the
shore. Further studies are also needed to formalize the conceptual diagram of
channel-island connectivity (Figure 4) via modeling and analysis of other deltaic
systems.

685 Several environmental factors are active on deltas, often resulting in regions
of distinct physical or statistical behavior. The representation of a delta as a
network of regions and the quantification of their connectivity may inform about
the large scale morphodynamics of a delta system by identifying, for example,
strongly or weakly connected regions within the system. Further analysis in
690 this direction is needed. Fundamental to describe this regional connectivity is

the quantification of delta structure via spatial distribution metrics, rather than bulk metrics only. Characterizing the full probability density function of metrics rather than relying, for example, on a single descriptor such as a mean value, will allow the quantification of spatial heterogeneity.

695 The representation of a delta as a network through time can be used to analyze how the connectivity patterns of channels or channels and islands vary as a function of autogenic and allogenic processes. This analysis can also quantify changes in the system due to disturbances, given the availability of data over a large enough time span. An analysis of delta networks through time can also be
700 performed by using the information in the stratigraphic record. Even if surface patterns are not always representative of the subsurface, better quantification of the connectivity between the surface and the subsurface is needed. Robust metrics are needed to quantify this type of connectivity.

The extension of the information theory approach of Sendrowski (2015) to
705 include more delta variables, for example nutrient and sediment fluxes, offers the opportunity to create the *process network* of a delta, in analogy with the process network developed by Ruddell and Kumar (2009a,b) for eco-hydrology variables. Quantitative knowledge of delta couplings would allow the quantification of delta response to disturbance and change by comparing the process
710 network of a healthy system to the one of a system under change. A similar analysis performed by Ruddell and Kumar (2009a) captured the effect of a drought by measuring reduced couplings in the process network. In order to build the process network of a delta system, field observations of water, sediment, and nutrient fluxes as well as water temperature and meteorological data are needed
715 at fine temporal resolution and over a spatial extent that covers the domain of interest. Field observatories as the one established at the WLD can provide this type of information.

Most of the studies cited in this paper have relied on the analysis of one or a handful of delta systems due to practical difficulties in extracting many
720 networks. The inherent complexity of distinguishing land and water in areas subject to frequent inundation and the lack of steep gradients to guide the

extraction based on classic steepest descent approaches make the extraction of delta networks challenging. Recent developments in image processing offer robust solutions to this problem; the multi-scale singularity approach of Isikdogan et al. (2015) has been successful in extracting channel networks in coastal systems. While more work is needed in ensuring the connectivity of the extracted network, the procedure is robust and has already been applied to other systems including numerical modeling results (Liang et al., 2016).

There are remaining portions of deltaic systems so far not fully explored, for example the connectivity of surface water and groundwater. A first step in this direction is the analysis of field observations collected at WLD (O'Connor and Moffett, 2015) to understand surface water-groundwater connectivity in a young evolving delta, as well as work in older systems such as the finding of paleochannels as conduits for groundwater in the Mississippi River Delta (Kolker et al., 2013). The study of Sawyer et al. (2015) analyzed surface water-groundwater connectivity numerically. Further work is needed to fully quantify surface water-groundwater connectivity at the network scale and its implications on water and solutes transport in coastal systems.

Another area to be explored is the role of vegetation in the formation and evolution of deltaic systems and how it relates to hydrological connectivity. Knowledge on the role of vegetation in deltaic processes has come thus far from field observations, although recent numerical modeling studies have included vegetation and analyzed its effect on delta sedimentation (Nardin and Edmonds, 2014).

Overall, this study points at several characteristics of delta systems that make them distinct with respect to classic complex network representations. Delta networks may be leaky and characterized by the exchange of matter, energy, and information between channels and their surroundings. These networks are geographic, rather than purely topologic, meaning that physical location within the system matters rather than topological connectivity only. Lastly, delta networks evolve over time by reconfiguring themselves in response to avulsions or similar processes or changing transport directions in response to periodic

tidal forcings. These characteristics suggest that the model of nodes and links mathematically quantified by an adjacency matrix will not be applicable in all cases, opening the door to the development of new mathematical approaches of network analysis.

5. Conclusions

Coastal restoration efforts require quantitative knowledge of connectivity in delta systems. Connectivity can be thought of as physical linkages among different portions of the delta, for example channels and wetlands or surface and subsurface, and process connectivity (couplings among delta variables).

In this paper I proposed a framework, called Delta Connectome, for studying connectivity in delta systems by analyzing representations of a delta system as a network (physical or conceptual). Research efforts, mostly recent, were reviewed and cast within this framework. Besides the classic representation of the delta as a network of channels, recent research points at the need of including islands (wetlands) within the hydrological network of a delta as significant fluxes are transferred from channels to islands. This finding has important implications both for the delivery of sediment to island interiors as well as the potential for nutrient reduction in delta islands given the longer travel times associated with flow paths through islands. Another relevant type of connectivity is the one between the surface and the subsurface, to connect surface patterns to the past dynamics imprinted in the stratigraphic record. More work is needed to formalize recent findings and also quantify other types of connectivity in the system such as the one of surface water-groundwater.

An approach based on information theory can be used to quantify delta couplings; methods such as transfer entropy are able to measure directionality, strength, statistical significance, and scale of process couplings. The approach could also lead to the quantification of delta response to change and disturbances.

Metrics to quantify connectivity appear to be lacking; recent efforts in this

direction include the nourishment area, the distribution of fluxes at the shore, the sedimentograph, and transfer entropy. More work is needed in this direction to quantitatively compare deltas from different environments and robustly assess modeling results.

The connectivity analysis here performed points at important characteristics of delta networks (leaky, geographic, evolving in time) that do not fit the classic concept of network as a set of nodes and links, motivating the development of new mathematical approaches for studying delta networks.

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