Stable ≠ Sustainable: Delta Dynamics Versus the Human Need for Stability

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Abstract Arising from the non-uniform dispersal of sediment and water that build deltaic landscapes, morphological change is a fundamental characteristic of river delta behavior. Thus, sustainable deltas require mobility of their channel networks and attendant shifts in landforms. Both behaviors can be misrepresented as degradation, particularly in context of the “stability” that is generally necessitated by human infrastructure and economies. Taking the Ganges-Brahmaputra-Meghna Delta as an example, contrary to public perception, this delta system appears to be sustainable at a system scale with high sediment delivery and long-term net gain in land area. However, many areas of the delta exhibit local dynamics and instability at the scale at which households and communities experience environmental change. Such local landscape “instability” is often cited as evidence that the delta is in decline, whereas much of this change simply reflects the morphodynamics typical of an energetic fluvial-delta system and do not provide an accurate reflection of overall system health. Here we argue that this disparity between unit-scale sustainability and local morphodynamic change may be typical of deltaic systems with well-developed distributary networks and strong spatial gradients in sediment supply and transport energy. Such non-uniformity and the important connections between network sub-units (i.e., fluvial, tidal, shelf) suggest that delta risk assessments must integrate local dynamics and sub-unit connections with unit-scale behaviors. Structure and dynamics of an integrated deltaic network control the dispersal of water, solids, and solutes to the delta sub-environment and thus the local to unit-scale sustainability of the system over time.

Plain Language Summary River deltas are fascinating complex systems that are densely populated and host valuable resources. Prone to rapid change in response to various forcing agents and human modifications, low-lying deltas are facing environmental deterioration. Particularly in the last decade, while sea level rise accelerated, research on delta systems has increased considerably through observational studies, remote sensing, and numerical modeling. Many such studies attempt to address the question: “Will deltas be sustainable in the near future?” The narrow range of answers to this question are negatively skewed, but we argue here for a more precise perspective that acknowledges the scale dependency of the analysis and the location within the distributary network of a delta and recognizes that local instabilities caused by natural delta dynamics are not a sign of “deterioration” as they are often mischaracterized, but rather a requirement for sustaining a large delta needing sediment dispersed to a broad area. So, while delta dynamics present a challenge for humans and delta management, they are also a key piece to delta sustainability.

1. Introduction

Settled by humans since prehistory, deltas are economic hot spots and home to more than 300 million people (Edmonds et al., 2020). Delta plains are the result of the balance between fluvial sediment supply and marine dispersal, land subsidence, and sea level rise. Fluxes of water, solids, and solutes are distributed through the delta plain by a network of channels, connections to island interiors, and at the shore via tidal currents and waves. Maintaining such a balance requires constant change in the delta surface network, with scales of change ranging from local, short-term responses (≤10^3 km, ≤10^1 yr) to broader regional change (≥10^4 km, ≥10^1 yr). During the twentieth century, these adaptive responses have been impacted by river
damming, flood protection, intensified agriculture, extractive industries, urbanization and infrastructure, and increasingly by climate change, resulting in a radical transformation of these rich and diverse ecosystems (Hoitink et al., 2020). As a result, vast flat delta plains are now among the most expansive and expensive coastal lands threatened by sea level rise. Restoring the drowning Mississippi River Delta for example, which lost 5,000 km$^2$ of land over the last century, is conservatively estimated to cost 50 billion dollars over the next 50 years (Coastal Protection and Restoration Authority, 2017). Such restoration efforts aiming toward a sustainable delta environment must account for the clash between the ever-changing nature of delta systems and the human need for stability (see Table 1 for definitions). The scale of Mississippi Delta management is similar for other large delta systems, but the costs relative to GDP can be much higher for small deltaic nations such as Bangladesh, the Netherlands, and Egypt.

Sustainability, the persistence of structure and function through time, is foremost a geomorphic attribute for deltas and the foundation for their ecologic and economic well-being (Day et al., 2016). Maintained by annual river flood pulses and sediment dispersal, deltas expanded over millennia of generally stable eustatic sea level. Distributary channel networks and marine shoaling aggregated into cycles of localized delta lobe expansion and abandonment over centuries. This dynamic balance achieved across spatial and temporal scales is now short-circuited by humans. Sediment budget deficits at the system-scale are typical for many deltas even if local net land gains often occur in young delta lobes, or along channels or at the coast. By defining sustainability at more realistic local scales, maintenance and restoration will benefit from increased knowledge on deltaic channel networks that optimize the distribution of fluvial fluxes across deltas.

Here we review research on deltaic channel networks and focus on the Ganges-Brahmaputra-Meghna Delta (GBMD). With increasing recognition of rapid global sea level rise, in the 1990s and 2000s the GBMD was often depicted as a passive coastal landmass at peril of drowning, but that perception neglected large sediment fluxes originating from its Himalayan hinterland. Now, it is often cited for its widespread local instabilities (i.e., dynamics) (Auerbach et al., 2015; Bain et al., 2019; Jarriel et al., 2020; Rogers & Overeem, 2017) while simultaneously being recognized for system-scale sustainability with its large sediment supply and persistent net land growth (Allison, 1998; Wilson & Goodbred, 2015; Wilson et al., 2017). Typical for complex systems, instability reflects network dynamics and feedbacks among discrete but connected parts of the delta system, such as the upper and lower delta plain as well as the inner shelf. We argue that other deltas behave similarly and call for (a) the development of remote sensing and modeling tools to capture fluvial flux distribution and network dynamics along deltaic channels and coastal transport pathways, and (b) for the integration of this information into adaptive delta management strategies.

2. Delta Network as Distributor of Fluxes

As a system, the GBMD receives an estimated 500 MT (Islam et al., 1999) to 1037 MT (Rahman et al., 2018) of sediment per year, which is enough mass to aggrade the lower delta by >10 mm/yr if uniformly distributed (Figure 1). Yet, is this total flux the relevant measure for understanding sustainability in all parts of the system? Many of the poldered coastal areas, for example, where embankments were put in place in the 1960s, have shown significant land elevation loss due to sediment starvation, subsidence, and tidal-range expansion, lowering their elevation by 1–1.5 m relative to un-embanked land-surfaces (Auerbach et al., 2015). One such polder catastrophically breached during Cyclone Aila in 2009 and displaced 15,000 people over two-years of daily tidal inundation (Islam & Hasan, 2016). In contrast, rapid channel-bank

| Term       | Definition                                                                                                                                 |
|------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Sustainability | The persistence of delta landforms and their physical function, allowing shifts in location to maintain their role in water and sediment mass dispersal. Conflicts with the human need for stability. Requires network approach to link system to local scale behavior. |
| Stability | The preservation of existing delta landforms, but without the ability to shift location and maintain their role in water and sediment mass dispersal. Modifies the network dynamics in ways that can both inhibit and enhance local behavior, preventing sustainable delta functioning. |

Table 1
Definition of Terms as Used in This Paper
migration is the primary cause of severe land losses in the active, fluvially dominated parts of the delta (Jarriel et al., 2020). The GBMD is thus a clear example of how system-wide versus local-scale assessments of mass balance and landscape dynamics lead to different conclusions on the sustainability of the system. The result is a “paradox of scale” where a naturally dynamic delta system can be sustainable in the long run and as a whole, but cannot be simultaneously sustainable at human spatial and temporal scales that typically value static stability over longer-term persistence.

If we look at the size and complexity of the channel network that characterizes the GBMD, the cause of this paradox of scale becomes apparent--this network is responsible for the partitioning and transport of fluxes of 1,000 km$^3$ of fresh water, 500–1,000 Mt of solids, and 100 Mt of solutes over the delta plain and at the shore. The flux partitioning is not uniform; some areas of the delta receive more sediment than others, and human interventions, such as embankments, greatly exacerbate this heterogeneity. Local sediment starvation, whether natural or anthropogenic, results in increased exposure to flooding, economic loss, and impacts on the population. Enforcing local stability through embankment construction has resulted in a negative cycle leading to a decline in long term sustainability - a problem that affects not only the GBMD,
but many deltas in the world, including the Mississippi River Delta (Giosan et al., 2014; Tessler et al., 2015). Furthermore, sites of delta instability are not restricted to zones of sediment deficit; rather, even areas actively receiving sediment, such as along primary distributaries, at the river mouth estuary, and in upper tidal channels, can be morphodynamically unstable. Net land gains can still come at the cost of locally intense erosion, shifting navigation channels, loss of infrastructure, and overall community hardship and economic impact.

The exchange of water, solids, and solutes between the apex and the coast of deltas are still poorly known; due to logistical and cost reasons, fluxes have historically only been collected upstream of the delta apex. Furthermore, tides and storms can rework sediment from the offshore back upstream into the distributary network and wave-driven longshore drift can stabilize deltaic coasts or even construct new land (Giosan et al., 2013; Rogers et al., 2013). We lack information on the distribution of deltaic fluxes over second and higher order distributary channels, through overbank processes, and via marine transport pathways. These are large gaps in our knowledge of delta systems and our capabilities of managing them, which hinder the identification of areas that are sediment starved until negative effects are felt at larger scales and are almost irreversible. Nor do we know which areas receive enough sediment that can be leveraged by management solutions.

One aspect of river deltas that can help the estimation of flux partitioning is the network structure itself, which together with the resulting geometry of the islands (i.e., land masses surrounded by channels) reflects the main processes acting on the system (Passalacqua et al., 2013; Perignon et al., 2020). Statistical distributions of geometric characteristics of islands and channels show scaling breaks corresponding to process transitions making tidal, river, and upstream portions of the delta easily distinguishable from one another (Passalacqua et al., 2013) (Figure 2). Machine learning approaches based on metric analyses and clustering further identify process-related classes of islands (Perignon et al., 2020) (Figure 2). Work in other systems has shown that network structure can also be used to estimate flux partitioning and the delivery of fluxes at the shore (Tejedor et al., 2015) and that estimation of nutrient and sediment fluxes can be addressed in similar ways (Dong et al., 2020; Knights et al., 2020).

Complicating factors prevent network structure alone to be sufficient for estimating flux partitioning; first off, these approaches cannot yet incorporate tidal and marine contributions of sediment to the delta plain. However, the network could be envisioned in two dimensions, with not only network structure, but also fluxes and their directions. Essentially, a step up is required from a purely structural connectivity analysis to a functional connectivity analysis in which flux direction and magnitude are accounted for (Passalacqua, 2017). Additionally, natural (and to a lesser extent even embanked) delta networks are leaky (Hiatt & Passalacqua, 2015; Rogers & Overeem, 2017), as discharge is not contained within the channel but rather transferred in part to delta islands through overbank processes. This hinders the applicability of a purely network based model for flux estimation (Passalacqua, 2017) and points to the importance of the secondary network of transport pathways that connect the main rivers to the island interiors. Recent efforts using multiplex networks to capture these patterns are promising (Tejedor et al., 2018), but ultimately complementary field and remote sensing measurements and modeling are required at large scales. It would also be essential to capture impacts of agricultural practices, especially crop irrigation, that are a mechanism to trap sediment from turbid delta channel water.

3. Delta Network Connections and Landscape Dynamics

In most of the world’s deltas, active land construction (i.e., progradation) is restricted to areas of the delta proximal to the main river mouth receiving direct fluvial sediment input (Nienhuis et al., 2020), or also locally from principal distributaries (e.g., Giosan et al., 2013; Shaw & Mohrig, 2014). However, areas of the delta more distal from the river channels can nevertheless receive sufficient sediment delivery to offset land losses driven by subsidence or erosion (e.g., Carlson et al., 2020). As mentioned in the previous section, sediment needed to sustain these areas is delivered through secondary components of the transport network, driven by overland flow, along-shelf currents, waves, or tides (Wilson & Goodbred, 2015). Thus, both non-fluvial and non-channelized components of the transport network can be effective at maintaining
land-surface elevations and delta sustainability, but at the same time foster morphodynamic changes to the delta landscape (Shen et al., 2015). Taking the GBMD as an example, areas of active landscape construction in the upper fluvially dominated portion of the delta occur primarily through channel levee and braid-belt deposition close to the mainstem Ganges and Brahmaputra channels (Allison, 1998). Away from the main channels, though, active sediment deposition in the upper delta is still supported by secondary mechanisms. Large distributaries, such as the Madhumati-Gorai and Arial Khan, divert $\sim 10 \pm 5\%$ of discharge from the main channels to remote delta-plain areas, serving to offset slow subsidence (Bomer et al., 2019). Additionally, effective sediment redistribution in the distal floodplain is driven by local runoff and overland flow due to intense seasonal precipitation (Goodbred & Kuehl, 1998). Field results (e.g., Pickering et al., 2014; Sincavage et al., 2018) and modeling studies (e.g., Reitz et al., 2015) show that collectively, these primary and secondary mechanisms of sediment dispersal and aggradation lead to a $\sim 2$-kyr period for major channel avulsions. Associated with this network dispersal, $\sim 1/3$ of the total fluvial sediment load is sequestered onto the upper reaches of the delta (Goodbred & Kuehl, 2000).
On the lower delta plain below the backwater transition, the construction of new land occurs primarily in the main river mouth estuary (Allison et al., 1998). There, distributive mouth-bar development is fed by suspended fine sand from the two main rivers (Rogers & Overeem, 2017), accounting for 12–18 km$^2$/yr of net land growth (Sarwar & Woodroffe, 2013). Much of the river’s silt-dominated mud fraction bypasses the river mouth estuary to the inner shelf (Barua et al., 1994), where wave, tide, and storm transport disperse the sediment plume to the subaqueous delta-front and canyon (Kuehl et al., 1997; Michels et al., 1998; Rogers et al., 2015). About 40% of total fluvial sediment discharge can be accounted for through deposition in the river mouth estuary (20%) and subaqueous delta (20%).

For distal areas of the lower delta plain, land surface elevations are sustained by secondary transport processes, as they are in abandoned areas of the upper delta. Indeed, the same distributaries from the upper delta do contribute some sediment and freshwater to the lower delta as well (Bomer et al., 2019); however, on the lower delta plain tides are the principal mechanism of sediment transport. There, flood-dominant tidal transport extends 100 km inland of the coast and efficiently imports sediment from the river plume and resuspended sediment from the inner shelf (Bomer et al., 2020; Hale et al., 2019; Rogers et al., 2013). This sediment import is sufficient to offset relative sea-level rise in un-embanked areas of the tidal delta plain, the natural mangrove forest of the Sundarbans, which otherwise receive little direct fluvial input. There is also indication that some sediment settles even within the embanked polders due to the irrigation practices that support intense local rice and shrimp agriculture (Rogers & Overeem, 2017). In all, the areal extent of land in the tidal delta plain is relatively constant, but intense morphodynamics cause areas of acute local change (Auerbach et al., 2015; Jarriel et al., 2020) (Figure 3), largely promoted by feedbacks with prior embankment construction (Bain et al., 2019; Pethick & Orford, 2013). Inland reaches of the tidal channels are found to be infilling at a rate of >2 km$^2$/yr in response to the reduction in tidal prism from widespread poldering (Wilson et al., 2017), whereas modest rates of land loss are occurring at the coast (4 km$^2$/yr, <0.1% of land area) due to sediment redistribution by waves and storms (Sarwar & Woodroffe, 2013).

In sum, high river discharge and energetic transport processes make the GBMD relatively effective at broad scale sediment dispersal, and thus at maintaining delta elevation across a large area. These conditions favor overall sustainability of the GBMD as a unit-scale delta system but at the same time require locally intense morphodynamic changes to uniformly distribute sediment over longer time periods (i.e., decades to millennia). The sediment supply and transport networks of all delta systems must similarly evolve to reach a balance between unit-scale growth and the local morphodynamics needed to sustain it or to respond to allogenic or anthropogenic perturbations.

4. A Network View of Delta Sustainability

The precarious interaction between sustainable delta construction and morphodynamic responses means that perturbations at the system-wide level can tip local areas of a delta into states of land gain, loss or intense change. System-wide delta degradation is typically to be expected in response to upstream reductions in river sediment supply (e.g., Tessler et al., 2015), or due to widespread embankments and river control structures that starve the delta plain of nourishing sediment (Auerbach et al., 2015; Corthell, 1897; Higgins et al., 2018) and the exacerbation of subsidence from compaction and fluid extraction (Higgins et al., 2014; Syvitski et al., 2009). On the other side of the spectrum, the mass balance can be disturbed by changes in marine controlling factors, increases in ocean storm frequency and intensity, or sea level rise encroaching slowly. Classification systems of deltas have carefully assessed delta sustainability on the system-wide scale as a mass balance and have found many deltas appear at risk (Tessler et al., 2015). Yet, coastline change mapping from 30-year record of remotely sensed imagery finds that at the coastline boundary extensive land loss due to this degradation cannot yet be corroborated (Nienhuis et al., 2020).

Modern societies rely on engineering and relatively fixed infrastructure, and thus struggle with dynamic landforms. The construction of embankments and similar interventions aim to make river systems stable, often resulting in a false sense of safety for those living next to engineering structures, the so-called “levee effect” (Di Baldassarre et al., 2009; Lane et al., 2011; White, 1945). Besides the cost associated with classic engineering interventions, which may or may not be affordable in the future (Tessler et al., 2015), there is a limit to what engineering structures alone can achieve, particularly as rates of sea level rise increase.
The lack of connectivity, or dis-connectivity, of the river to its floodplain can have dramatic effects on system functioning, as seen in the GBMD leading to channel infilling (Wilson et al., 2017) and reduction of secondary channels (Bain et al., 2019), amplification of tides (Pethick & Orford, 2013), and land loss in island interiors (Auerbach et al., 2015). Nature-based engineering solutions (Giosan et al., 2013; Temmerman & Kirwan, 2015) aim instead at leveraging the natural landscape capabilities of building land by reconnecting rivers and their floodplain at specific locations, identified as part of the design. The ongoing restoration of coastal Louisiana with river diversions and tidal river management in Bangladesh are examples of this type of strategy to reestablish connectivity. While we often aim at achieving stability, stability does not imply sustainability, particularly over longer time scales. As a matter of fact sustainability is not achieved via stability; stability, as imposed by engineering interventions in the past, has led instead to lack of sustainability and land loss.

Knowledge of delta network dynamics is lacking, partly due to lack of data and tools (Table 2). The example of the GBMD reviewed above illustrates the importance of the scale and approach taken to assess the sus-

Figure 3. Channel response variance computed on the Ganges-Brahmaputra-Meghna Delta Landsat data indicating morphological change over the period 1989–2019 (Jarriel et al., 2020). Areas in red indicate channelized water loss, while areas in blue indicate channelized water gain. In addition to the highly dynamic rivers, the poldered area (gray boundary) shows larger morphological change than the adjacent natural Sundarban forest (located directly downstream). Human modifications drive channel infilling and increased rates of channel migration in the embanked area.
tainability of a delta system. When a mass balance is performed over the whole system, the system appears able to respond to current rates of sea level rise. However, the complex network of rivers that characterizes this system controls the distribution of fluxes of water, solids, and solutes over the delta plain. This flux distribution is not uniform; certain areas receive very little sediment and experience land loss. Thus, quantifying the distribution of fluxes along the network with observations, particularly from remote sensing, and modeling, is key to delta management. While models may not be able to simulate water and sediment transport over large systems at high resolutions, analysis of surface patterns, for example, based on machine learning (Perignon et al., 2020) can identify subareas of the delta that behave similarly. It may also help to identify which areas are suitable for building land, and which are too sediment-starved to feasibly be nourished. Once these clusters are identified, high-resolution modeling can be performed in representative islands and the results extrapolated to the whole cluster to capture larger scale patterns of sediment aggradation of erosion.

The other important aspect that emerges from the GBMD analysis, and currently missing for many delta systems, is the quantification of riverbank and island migration dynamics, both in terms of magnitude as well as timescale associated with the movement. Remotely sensed data can be employed to quantify the magnitude of change and hotspots, locations where the rivers are most active (Jarriel et al., 2020), and this information should be accounted for when designing delta management strategies (Table 2). With the current remotely sensed data, timescales associated with river dynamics can be estimated over an interval of time, but more frequent observations will be needed to distinguish between abrupt changes and more gradual channel migration.

The Landsat record is long enough to quantify changes over time in the network structure. At the same time, retrieval algorithms developed with machine learning techniques quantify patterns in suspended sediment load in distinct river stretches over the Landsat or MODIS record (Dethier et al., 2020; Long & Pavelsky, 2013; Miller & McKee, 2004). But for either of these applications, cloudy conditions often experienced at the coast, including during flood seasons in deltas, limit the amount of imagery that can be analyzed. The upcoming SWOT mission will allow the detection of water surface elevation over rivers globally at unprecedented spatial scales. Airborne simulators of these upcoming missions, AirSWOT and UAVSAR (for NISAR), in addition to AVIRIS-NG, are being tested as part of the NASA Earth Venture Mission Delta-X, which is focused on understanding the key drivers of soil accretion in coastal Louisiana. These upcoming remotely sensed observations are poised to revolutionize the way we analyze rivers globally, opening up the opportunity for quantifying water flux partitioning along networks. With this detailed information on flux partitioning, numerical models would be much better constrained to quantify associated suspended sediment loads, although in situ-experiments may be needed to further understand sediment distribution along distributary channels links and nodes across scales. Knowledge of network dynamics and flux partitioning along the network will have to be integrated into adaptive delta management strategies.

| Table 2 | Recommended Steps to Connect Network Approaches, Remote Sensing, and Field Observations Required to Take a Network View of Sustainability |
| Box: Call for action |
| • Analyze remotely sensed data through time to identify hot spots of change (and associated rates of change) where field observations are needed and predictive morphodynamics models can be tested. Systematic identification of decadal-scale changes can inform local restoration or maintenance efforts. |
| • Expand local, ground-based observations to link remote sensing data with system’s physical dynamics. Remotely sensed data can be combined with targeted deployment of in-situ sediment sampling or turbidity measurements to obtain preliminary water and sediment flux partitioning based on network information. |
| • Leverage machine learning approaches to identify spatial/temporal similarities within deltaic networks that can aid in designing model simulation domain and guide model experiment duration and time-step choice. |
| • Integrate surface network, ground-based observations, and subsurface analysis approaches to quantify past sedimentation patterns and lobe switches and project future large scale network dynamics. |
| • Integrate knowledge of network dynamics and flux partitioning into adaptive delta management strategies. |
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