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Dominant processes zones in a mixed fluvial–tidal delta are morphologically distinct

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Abstract

The morphology of deltas is determined by the interaction between fluvial, tidal and wave processes with the geometry processes that shape them. When two or more processes are in balance, the morphology is expected to be distinctive, but this has been difficult to quantify because of the complex morphodynamic feedbacks. Here we hypothesize that mixed fluvial–tidal deltas with different dominant processes can imprint on predictable zones exhibiting of two different zones within deltas systems with respect to fluvial change. Available remotely sensed morphometric data of 12 mixed fluvial–tidal deltas with different dominant processes are used to test this hypothesis. Results show that the fluvial–tidal transition zone is distinctly different than the fully fluvial and fully tidal zones upstream and downstream, which are morphologically similar. Tidal influence is detectable 100 km upstream from the shoreline in river-dominated deltas, but only 10 km upstream in tide-dominated deltas. Tidal influence is also 2 times stronger in river-dominated deltas than in tide-dominated deltas. Channel bifurcations are most abundant in the fluvial zone, but channel bifurcation density is 2 times greater in the transition than in the fully tidal zone. Channel bifurcation density is also 2 times greater in tide-dominated deltas than in river-dominated deltas. Channel bifurcations are limited to relatively narrow zones along the main flow paths in river-dominated deltas, but are more widespread throughout the delta in tide-dominated deltas. These results suggest that the transition from fluvial to tidal processes is gradual in tide-dominated deltas, but is more abrupt in river-dominated deltas. Our results also suggest that the transition from fluvial to tidal processes is more pronounced in river-dominated deltas than in tide-dominated deltas. These results provide a framework for predicting how different types of deltas will respond to future perturbations, such as sea level rise, storm impacts, and changes in sediment supply.

1 Introduction

Deltas are dynamic landforms shaped by environmental change and anthropogenic activity. Predicting the trajectory of deltas to future change requires understanding how process variability of fluvial and tidal processes shape the delta morphology. The identification of the patterns of physical processes in deltas is therefore necessary to predict the resilience of deltas to future change (Edmonds et al., 2020; Nittrouer and Viparelli, 2014; Syvitski et al., 2009; Tejedor et al., 2015). Deltas exhibit a wide variety of morphologies capable of surviving for hundreds to thousands of years, but it has long been established that the morphology of deltas, networks and bedforms reflects the physical processes that created and continuously modify the landform (Galloway, 1975; Wright and Coleman, 1973). Quantitative relations between the morphology of deltas and the relative importance of fluvial, tidal, and wave processes exist in two complex deltas (Jiaotong et al., 1991; Syvitski et al., 2012), testing the effects of individual physical processes on morphology is challenging in large deltas where multiple processes interact (Nittrouer et al., 2012). Laboratory experiments have shown that the interaction between fluvial and tidal processes can generate a distinctive morphology, but these experiments focused on the morphology of deltas in the fluvial–tidal transition zone and did not consider how the morphology of the entire delta may be affected (Canestrelli et al., 2014; Leonardi and Canestrelli, 2017).

The morphology of deltas is tied to the interactions and feedbacks between water and sediment fluxes throughout the system (Caldwell and Edmonds, 2014; Edmonds and Slingerland, 2010), including the physical processes that control how the delta grows (Bhattacharya and Giosan, 2003; Galloway, 1975) and the boundary conditions that determine their pathways (Ganti et al., 2014; Jerolmack and Paola, 2010). Although the morphology of deltas is influenced by many processes, the morphology of deltas is dominated by processes that modify the sediment flux from the river, such as tides and waves (Dalrymple et al., 1992; Galloway, 1975; Syvitski et al., 2009; Syvitski and Milliman, 2007). Tidal processes can increase the complexity of the morphology of deltas because the morphology of tide-influenced deltas is strongly controlled by the tidal prism (Dalrymple et al., 1992; Hoitink et al., 2017; Leonardi et al., 2013; Nittrouer et al., 2012). Wave processes can smooth the coastline of deltas and create extensive beaches and barriers (Anthony, 2015; Dalrymple et al., 1992; Ibe et al., 1985; Nittrouer et al., 2012). Combinations of fluvial, tidal, and wave processes have been observed to create complex morphodynamic feedbacks that can produce a wide variety of morphologies (Dalrymple et al., 1992; Galloway, 1975; Hoitink et al., 2017; Jiaotong et al., 1991; Syvitski et al., 2012; Wolanski et al., 2004). Although the morphology of deltas is strongly controlled by the relative importance of fluvial, tidal, and wave processes, the morphodynamic feedbacks between these processes and the morphology of deltas are complex, and it is challenging to predict how these processes will change the morphology of deltas in response to future perturbations, such as sea level rise, storm impacts, and changes in sediment supply (Edmonds et al., 2020; Nittrouer et al., 2012; Syvitski et al., 2009).

Recent studies have shown that the morphology of deltas can change in response to changes in the relative importance of fluvial, tidal, and wave processes (Edmonds et al., 2020; Ericson et al., 2006; Syvitski et al., 2009). For example, Edmonds et al. (2020) hypothesized that the morphology of deltas would change from a fan to a tidal sand ribbon in response to increasing tidal influence, and Ericson et al. (2006) showed that coastal embayments and coastal plains would develop in response to increasing wave influence. Although these studies have shown that the morphology of deltas can change in response to changes in the relative importance of fluvial, tidal, and wave processes, the morphodynamic feedbacks between these processes and the morphology of deltas are complex, and it is challenging to predict how these processes will change the morphology of deltas in response to future perturbations, such as sea level rise, storm impacts, and changes in sediment supply (Edmonds et al., 2020; Nittrouer et al., 2012; Syvitski et al., 2009). Therefore, it is necessary to test how different types of deltas will respond to future perturbations, such as sea level rise, storm impacts, and changes in sediment supply, to better understand how different types of deltas will respond to future change.

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2 Case study: the Ganges–Brahmaputra–Meghna Delta

The GBMD covers more than 100 000 km² of floodplain and eastern India, extending ~400 km from its apex near the foothills of the Himalayas to the shoreline (Figure 1). The GBMD is home to ~150 million people, and the livelihoods of many people are closely tied to the rivers and coastal processes that shape the landscape (Ericson et al., 2006). Many of the people living in the GBMD are vulnerable to storm surges and coastal flooding, and the anthropogenic impacts are exacerbated by the GBMD's low topography (Ericson et al., 2006; Syvitski et al., 2009). The GBMD is also home to the Sundarbans, the largest mangrove forest in the world, which is home to many species of flora and fauna, including the Bengal tiger, which is a keystone species in the Sundarbans (Giri et al., 2007). The Sundarbans are also a UNESCO World Heritage Site, and they are threatened by sea level rise, storm surges, and human activities (Giri et al., 2007).

The Ganges–Brahmaputra–Meghna Delta (GBMD) is one of the largest deltas on Earth, and it is one of the most populated deltas in the world (Ericson et al., 2006; Syvitski et al., 2009). The GBMD is a mixed fluvial–tidal delta, and it is one of the largest deltas on Earth by area (Ericson et al., 2006; Syvitski et al., 2009). The GBMD is also one of the most populated deltas in the world, with over 150 million people living in the GBMD (Ericson et al., 2006; Syvitski et al., 2009). The GBMD is also one of the most vulnerable deltas to sea level rise, storm surges, and human activities (Ericson et al., 2006; Syvitski et al., 2009). The GBMD is also one of the most complex deltas in the world, with a wide variety of morphologies and sedimentary deposits (Ericson et al., 2006; Syvitski et al., 2009). The GBMD is also one of the most dynamic deltas in the world, with rapid changes in the morphology and sedimentary deposits (Ericson et al., 2006; Syvitski et al., 2009). The GBMD is also one of the most important deltas in the world, with many ecological, economic, and cultural values (Ericson et al., 2006; Syvitski et al., 2009). The GBMD is also one of the most threatened deltas in the world, with many threats to its ecosystems and inhabitants

Figure 8 Footprint Location dependence between the distribution of permanent surfaces for islands of each class and all other surfaces. Permanent surfaces for islands of each class are more concentrated than other surfaces in the Arctic and Antarctic regions. Data from Pekel et al. (2016). Supplemental Figure S4a-f shows that the distribution of values of the variable for the island class is similar to values for other islands.

5 Discussion

5.1 Island clusters

5.1.1 Estuarine (delta-front) clusters

Estuarine (i.e. delta-front) clusters are the smallest and much farther at the outlet of the Ganges and Brahmaputra rivers. These islands are characterized by a wide range of island sizes and channel widths. Most of the islands in these clusters have poorly developed vegetation and are at or very close to the sea level. Many of these islands are subject to tidal inundation and storm surge events. Below average values of the distance and of fluvial dominance indicate that the surfaces of these islands is not stable. The aspect ratio tends to be above average, indicating that the islands are elongated.

Estuarine is also composed of the islands at the mouth of rivers along the list of Ganges. On average, these islands are larger than other active delta-front islands. This class specifically has low minimum channel widths but high maximum and average channel widths. Most of the islands in this class are very close to the sea and have poorly developed vegetation. Many of these islands are subject to tidal inundation. These islands often have complex internal drainage networks and a large number of small surface channels. The values of solidity are close to the overall average, while symmetry values are usually below average. Higher values of symmetry indicate that the islands are more elongated than the average island. The values of fluvial dominance are close to the overall average, indicating that the island clusters, the mouth of aspect ratio and its link below average. Indicating that these islands have a more "bulbed" shape, in a repeat of the Bengal Survey of 1915, these islands were already characterized as unusually "Short-bulbed" due to the strong ocean influence (Fig. 11). Tidal and wave processes reworking the material.

5.1.2 Tidal class

Islands in this class are located inland with respect to those in the estuarine class. Tidal islands in the western portion of the delta are classified as Tidal I, while those in the central portion of the delta are classified as Tidal II. Tidal I islands are larger than average, and their surfaces are complex with large and small channels. Large fractions of these islands have below average values of solidity and symmetry. Islands in the Tidal II class also have well-developed internal drainage networks and large numbers of small channels. The values of solidity and symmetry for Tidal II islands are close to the overall average. Values of fluvial dominance are below the average for the delta. The two groups of islands classified as tidal are the most similar clusters of all the delta islands.

5.1.3 Fluvial class

Islands in the fluvial class are the smallest of the delta. The most upstream fluvial islands are part of surfaces (fluvial I, Supplemental Figure S4a-f) that are the most similar to those of the active delta-front islands. Fluvial islands are characterized by very small surface areas, low values of solidity and symmetry and low values of fluvial dominance, indicating that their surfaces are simple and the channels around them are not highly sinuous. The minimum width of the channels that bound these islands is below the average for the delta, but the maximum and average channel widths are above the average. The aspect ratio of the channels that bound the islands of this class are close to the average. Values of solidity and symmetry due to their irregular shapes, while the aspect ratio varies across the group.

5.1.4 Oldest class

Two large islands in the West Bengal region of India form the class other. These are morphologically similar to islands in the nuclear aspect delta-front region but have lower values of solidity and higher values of symmetry. The values of fluvial dominance because of impoundment and reduced mobility of channels. Large meander-edge dissipative and island sizes are usually observed (Fischer et al., 2016; Nittrouer et al., 2011).

5.2 Metrics importance and applicability of the approach to other systems

Transition probabilities in this work does not substantially differ from previous work (Donatelli et al., 2018) and known transition probabilities (Donatelli et al., 2018; Donatelli et al., 2017; Donatelli et al., 2018; Donatelli et al., 2018; Donatelli et al., 2018) are expected. This additional information allows us to capture spatial differences when strong islands subject to similar processes (e.g., the island southeast coastal zone is exposed to the Atlantic Ocean and the island northeast coastal zone is exposed to the Bay of Bengal) and metrics for each class. This information can be helpful for validating numerical modeling results (Giosan et al., 2014) or time series analysis (Donatelli et al., 2018) and for understanding the delta as a system.

Our classification identified two groups of islands experiencing a high proportion of fluvial rating. The islands throughout the main corridors of the Ganges and the combined Ganges-Brahmaputra main channel are at having unique geomorphic characteristics. Interestingly, the islands southeast and northeast of the main corridor are largely different morphologically, suggesting that the relative proportion of fluvial and tidal material (higher in the Brahmaputra River in comparison to both grain size and sediment load) is a key factor in the shape of the islands. Although the Ganges and the Brahmaputra rivers have similar sediment loads, the grain size of the sediment is different. The sediment in the transition between the Ganges and Brahmaputra rivers is much larger than the sediment in the Brahmaputra and the Ganges rivers. The sediment in the transition between the Ganges and Brahmaputra rivers is much larger than the sediment in the Brahmaputra and the Ganges rivers. Additionally, the