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Wave influence in the construction, shaping and destruction of river deltas: A review

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A B S T R A C T

Waves are an important agent in the construction, shaping and destruction of river deltas. Notwithstanding the commonality of waves in oceans and seas, wave influence on deltas varies considerably depending on the coastal morphology and nearshore bathymetry. Although there have been advances in understanding the way waves approaching a delta shape its shoreline, much still remains to be known of the interactions between waves and river deltas. Deltas are built essentially from sediments supplied by rivers. Sand-sized and coarser sediments may also be derived from nearby abandoned delta lobes or from older relict near-shore deposits, transported by wave reworking and longshore currents. Alternatively, delta erosion by waves can also release sediment that is redistributed alongshore or that accumulates offshore. The extent to which bedload is supplied to and sequestered in, or lost by, deltas through waves and longshore transport strongly depends on interactions between waves and fluvial discharge at the river mouth. These interactions and the mutual adjustments they engender are not only important in the overall balance between delta retreat, progradation or aggradation but also in processes such as avulsion and channel switching, as well as in the eventual survival of a delta in the face of sea-level rise. Where waves are important, fluvial liquid discharge is high, and sediment supply is rich in bedload, two important aspects are the blocking of waves and longshore currents by strong river discharge and the formation of bars at the river mouth. Field studies of the complex interactive processes prevailing where river flows encounter waves are, however, non-existent and numerical modelling, though promising, hampered by scale constraints and the difficulty of replicating them and generating mouth bars in the presence of longshore currents. This interaction influences the seaward extent of the delta mouth protuberance and its stability; this protuberance then forming the regional shoreline template to which waves and longshore currents adjust. Longshore currents can redistribute wave-reworked mouth bar deposits emplaced during strong river flow. Transport may be either divergent from the mouth or may be regionally unidirectional but wherein the symmetry of some deltas, probably rare, may be maintained by a strong river blocking effect on transport from the updrift flank. The mouth protuberance may be such as to foster transport reversal (counter-drift) at the delta margins that contributes to sediment sequestering within the delta. These interactions largely contribute in shaping delta shorelines, and together with the abundance of sediment supply and grain size, determine the resultant wave-formed shoreline barrier types, which include spits, more or less closely-spaced beach ridges, and barrier islands and cheniers in situations of punctuated progradation or retreat. Where several distributary mouths occur, pronounced longshore variability in wave processes and wave-induced sediment transport may ensue, resulting in multiple drift cells that assure the retention of sand and coarse-grained sediments within the delta. Waves can also be an important agent in the reworking and retreat of mud-rich deltas that generally conform in morphology to the 'river-dominated' (such as the Mississippi) or 'tide-dominated' (such as the Ganges–Brahmaputra or Chao Phraya) types, resulting in the episodic formation of sandy cheniers and beach ridges.

Although sea-level rise is likely to lead to enhanced wave reworking of deltas, the possible prevalence of aggradation (in lieu of progradation), channel switching and avulsion, and washover processes, may contribute to the disorganization of waves and longshore transport, fostering deltaic sequestering of sand and coarser-sized sediment and delta survival. The weakening of river discharges resulting from human activities will invariably lead, however, to enhanced wave reworking of deltas and to deltaic sediment redistribution by longshore currents. The massive swing towards significant reductions in fluvial sediment supply today may signify the ultimate demise of many deltas in the coming decades through a process of delta

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shoreline straightening by waves, in addition to accelerated sinking. These various foregoing aspects of the relationship between waves and river deltas are reviewed here across a range of timescales, and new interaction concepts proposed, using numerous examples of deltas in the world and on the basis of case studies, conceptual studies and numerical modelling studies in the literature spanning more than forty years.

1. Introduction

River deltas are characterised by low topography, by commonly high productivity, and potentially rich and biodiverse ecosystems, and may offer a wide range of ecosystem services such as coastal defence, drinking water supply, recreation, green tourism, and nature conservation. Many deltas support rural settlements, agriculture and fisheries, and are food baskets for many nations. Industry and transport in some deltas can also be very important, leading to the development of major urban centres, ports, and harbours. These potentially rich economic and ecological functions are assured by the ability of deltas to trap fluvial sediment en route from upland sources to coastal, nearshore, continental shelf and abyssal plain sinks (Fig. 1). The retention of river-borne sediments essential to the growth of deltas on the world's present coasts under conditions of a stable eustatic sea level depends on numerous conditions such as the morphological and tectonic characteristics of the coast, subsidence, but also the relative influence of the parent river, waves and tides (Coleman, 1981), the three cornerstones of delta morphological classification (Galloway, 1975). This classic tripartite classification scheme (Fig. 2) has formed a simple conceptual basis for categorizing deltas in many studies throughout the world. Deltas prograde on coasts where waves and currents are either not energetic enough to disperse all of the sediment brought down by rivers, or where the fluvial liquid and solid discharge are so high as to dampen even large waves. Even where the nearshore wave climate is important in terms of energy, delta morphology can be as much a product of fluvial as of marine processes. Since, by far, the most important sources of sediments to the world ocean are rivers (Milliman and Farnsworth, 2011), the redistribution of this sediment from river deltas to adjacent coasts is primarily vested in waves and wave-generated longshore currents. Delta erosion by waves can also release sediment that is redistributed alongshore or accumulates offshore. Whilst modern river deltas are primarily products of fluvial sediment sequestering on the present coasts, they may also trap exogenous sediments transported alongshore by currents and/or derived from the inner shelf by wave reworking. This sediment trapping capacity is fundamental to their maintenance in the face of climate change and sea-level rise. Although deltas may develop resilience and adapt to changes in sediment supply and sea level, commonly through re-organization of their channels and their patterns of sedimentation, they have become increasingly vulnerable economic and environmental hotspots (Foufoula-Georgiou, 2013). The hundreds of millions of people living in deltas today are increasingly exposed to the hazardous impacts of a large range of events to which deltas are usually exposed, such as flooding, subsidence, and coastal erosion, but the intensity of which is being exacerbated as a result of reduced sediment flux from rivers caused by humans (Evans, 2012; Anthony, 2014). This reduction in fluvial sediment flux, sometimes combined with lower liquid discharges, is becoming detrimental to the balance between the river and wave influence in delta dynamics, thus rendering many of the world's deltas vulnerable to the aforementioned hazards (Syvitski et al., 2009).

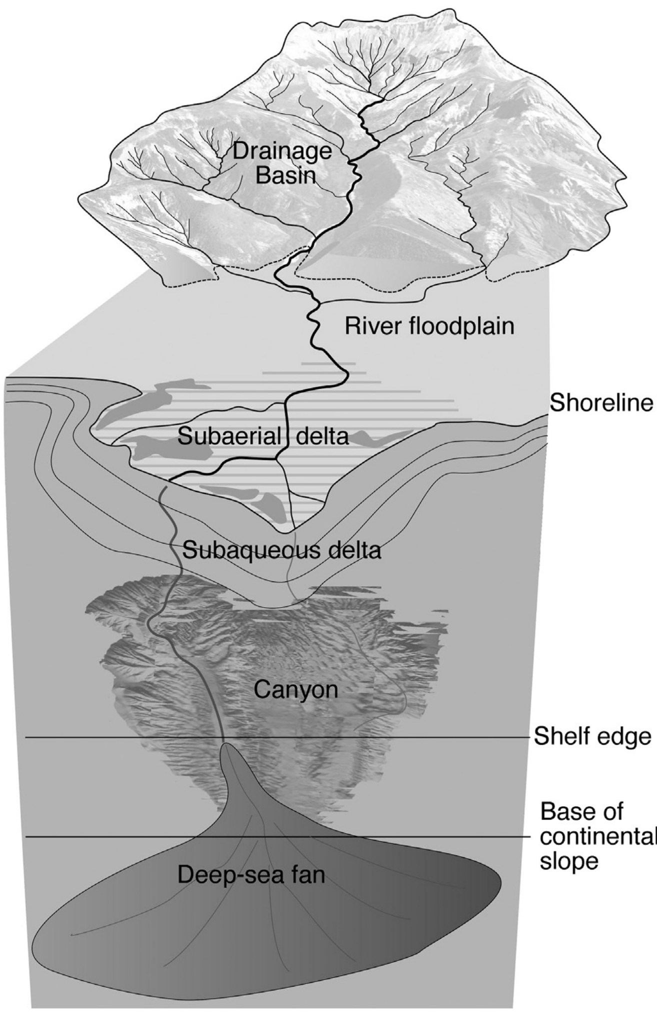

Fig. 1. River deltas in the fluvial source-to-sink continuum from catchment to deep-sea fan.

From a process point of view, the early works of Wright and Coleman (1972, 1973) and Galloway (1975) provided the basis for many case studies in considering the extent to which waves influence the development of individual river deltas. With regards to this process approach, which is central to our review, attempts to understand the role of waves in shaping the shorelines of river deltas and in modulating large-scale delta development have essentially revolved around the extent to which waves approaching the delta shoreline can generate currents that redistribute fluvial and coastal sediments. Based on work on the strongly wave-influenced coast of Brazil, Martin et al. (1987) and Dominguez (1996) drew attention to the importance of the ‘groyne’ effect caused by river flow in obstructing longshore currents and in generating accumulation of what they considered as inner shelf-derived sand on the updrift flanks of four river deltas in Brazil, whereas downdrift shoreline growth was generated by sediment of fluvial origin. The hydraulic groyne effect refers to the ebb jet effect on longshore currents across tidal inlets (Todd, 1968), and the term was later employed by Komar (1973) in his model of river delta growth under the influence of longshore currents. Bhattacharya and Giosan (2003) conceptualised the role of oblique wave approach on delta evolution in terms of delta asymmetry that reflects the extent to which adjustments between wave-generated longshore currents and river liquid discharge determined the plan shape of the delta shoreline. More so than a case study, the example of the Danube delta in the Black Sea has been used by Giosan et al. (2005) and Giosan (2007) to draw attention to the highly non-linear nature of the morphodynamics involved in delta lobe growth. These authors showed that the evolution of the Danube delta