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Approaches to defining deltaic sustainability in the 21st century

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ABSTRACT

Deltas are among the most productive and economically important of global ecosystems but unfortunately they are also among the most threatened by human activities. Here we discuss deltas and human impact, several approaches to defining deltaic sustainability and present a ranking of sustainability. Delta sustainability must be considered within the context of global biophysical and socioeconomic constraints that include thermodynamic limitations, scale and embeddedness, and constraints at the level of the biosphere/geosphere. The development, functioning, and sustainability of deltas are the result of external and internal inputs of energy and materials, such as sediments and nutrients, that include delta lobe development, channel switching, crevasse formation, river floods, storms and associated waves and storm surges, and tides and other ocean currents. Modern deltas developed over the past several thousand years with relatively stable global mean sea level, predictable material inputs from drainage basins and the sea, and as extremely open systems. Human activity has changed these conditions to make deltas less sustainable, in that they are unable to persist through time structurally or functionally. Deltaic sustainability can be considered from geomorphic, ecological, and economic perspectives, with functional processes at these three levels being highly interactive. Changes in this functioning can lead to either enhanced or diminished sustainability, but most changes have been detrimental. There is a growing understanding that the trajectories of global environmental change and cost of energy will make achieving delta sustainability more challenging and limit options for management. Several delta types are identified in terms of sustainability including those in arid regions, those with high and low energy-intensive management systems, deltas below sea level, tropical deltas, and Arctic deltas. Representative deltas are ranked on a sustainability range. Success in sustainable delta management will depend on utilizing natural delta functioning and an ecological engineering approach.

1. Introduction

Deltas are important ecosystems in the global context. They contain the largest areas of coastal wetlands and support large fisheries and societal development. They support large human populations, as in the case of the Yangtze, Yellow, Ganges, Mekong, Nile, Rhine, and others. One in fourteen people globally live in deltaic regions. Deltas are often regions of intense economic

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activity that include agriculture, navigation and trade, fisheries, forestry, fossil energy production, and manufacturing. Because of their ecological richness, deltas have among the highest values of ecosystem goods and services in the world (Day et al., 1997, 2007a,b; Costanza et al., 1997; Batker et al., 2014; Kuenzer and Renaud, 2012; Vörösmarty et al., 2009; Syvitski et al., 2009; Chen and Saito, 2011).

Deltas are also among the most stressed and degraded natural systems (Day et al., 2007a,b, 2014; Syvitski et al., 2009; Vörösmarty et al., 2009; Renaud et al., 2013; Giosan et al. 2014; Tessler et al., 2015; Ibañez, 2015). Medium- and large-sized deltas suffer from retreating shorelines due to upstream damming that reduce sediment input that counteract subsidence and accelerated sea-level rise (Giosan et al. 2014). Large areas of deltaic wetlands have been "reclaimed" for agriculture, aquaculture, urban, and industrial use (Kuenzer et al., 2014). Deltas often receive heavy loads of sediments and pollutants (Chen et al., 2010a,b), as is the case for excessive nitrogen levels (Rabalais and Turner, 2001). Deltas are especially vulnerable to sea-level rise because of their low elevation and commonly high rates of natural subsidence, often exacerbated by the extraction of subsurface ground water, natural gas, and petroleum, and peat oxidation (Sestini, 1992; Morton et al., 2005; Chen et al., 2008; Day et al., 2011b; Wang et al., 2012; Kuenzer et al., 2014; Higgins et al., 2013, 2014; Ibañez, 2015). Both climate change and increasing energy costs will limit options for sustainable management and restoration because many restoration approaches are energy intensive and climate change mediation will make sustainable restoration more challenging (Day et al., 2005, 2007a,b, 2014; Giosan et al. 2014; Tessler et al., 2015).

Objective: This paper summarizes the status of threats to deltaic sustainability and presents a context in which sustainability can be addressed, and suggests some ways forward. We review different approaches to defining deltaic sustainability, develop a conceptual framework, and discuss the sustainability of a number of representative deltas.

2. The intimate delta-human connection

Perhaps the greatest challenge facing deltas is the human occupation of an otherwise transient environment. Many modern river deltas began to form 6500 to 8500 years ago, as global mean sea level stabilized (Coleman and Wright, 1971; Van Andel, 1967; Kazmi, 1984; Xue, 1993; Stanley and Warne, 1993; Ibañez et al., 1996, 1997, 2010; Tornqvist et al., 1996; Kazmi, 1984; Roberts, 1997; Giosan et al., 2006b). Other deltas such as the Po, Ebro, Rhone, and Yellow deltas owe their current existence to increased flux of sediment that was liberated from uplands due to human disturbance - deforestation, agricultural practices, mining, and urbanization in general. While deltas were rapidly growing and shorelines were shifting seawards, delta dwellers were mostly concerned with the ephemeral nature of water routes distributed across the delta since distributary channels would shift every few years to decades. So while deltas offered lush vegetation, diverse forests, wildlife and fisheries, and rich organic muddy soils, movement through these ultra-flat environments remained difficult. Ultimately, the richness of deltas led to the establishment of the first city states that used their richness (Kennett and Kennett, 2006; Day et al., 2007a,b; 2012; Pennington et al., 2016). Tropical and sub-tropical infections, particularly from disease-carrying insects, also kept human populations low. While annual river-floods were needed for nourishing agricultural soils, the Nile Delta being the type example, floodwater inundation also destroyed habitats and livelihoods. Some cultures adapted to these episodic floodwaters, such as in the Ganges delta, where growing population centers were often found upstream and off of the delta. To control floods and reduce risk, human-fortified levees surrounding the large branches of the river became popular to construct. In the case of the Mississippi Delta, embankments were made with the full knowledge that future land might be lost to the sea (i.e., National Geographic, Dec. 1897). Constraining floodwaters by levees also forced sediment-laden water to enter and exit the delta largely intact, with most sediment being deposited at mouth bars, as shallow marine deposits, within the channels and along shorelines. Where delta swamplands were drained for agricultural purposes, soil and subsoil peats rapidly oxidized and the land surface compacted and subsided (Knights, 1979; Sestini, 1992; Morton et al., 2005; Olea and Coleman, 2014).

During the 20th century, deltaic environments were radically transformed by human activities (Syvitski and Saito, 2007; Syvitski et al., 2009). Upstream dams sequestered billions of tons of sediment, and the flux of sediment delivered to most deltas was greatly reduced. In some rivers, such as the Colorado, Ebro and Nile, little sediment is now delivered (Stanley and Warne, 1993; Ibañez et al., 1996; Carriquiry et al., 2011). Even where distributary channels were not embanked and floodwaters could still inundate the land, sediment aggradation did not always occur. As the land surface subsided, farmlands were fertilized using commercial fertilizers. Where wetlands were drained, delta lands were transformed into important agricultural areas, as in the Nile, Rhone, Ebro, and others. Civil engineering transformed many deltas. Coastal barriers and river levees presently protect the subsided Rhine-Meuse delta as 25% of the Netherlands is below sea level. Windmills and other pumping mechanisms continue to keep the Dutch soils from flooding, particularly from the sea. In essence, the Dutch approach to a large proportion of their citizenry living below sea level was to engineer their way to safety and, in fact, prosperity (Borsje et al., 2011; van Koingsveld and Mulder, 2004; van Wesenbeeck et al., 2014). Future risks would be met with future solutions but as discussed below, this will likely become increasingly difficult.

When modernity began, the growth of megacities on deltas began in earnest. Cities like Bangkok, Jakarta, Rangoon, Dhaka, Alexandria and Cairo, Seoul, Tokyo, Shanghai, Guangzhou, Tianjin, New Orleans, and arguably Mumbai, Kolkata, Karachi, Lagos and Ho Chi Minh City all owe their existence to the very flat land that river deltas provided in combination to the rich resources of the delta and the importance of large rivers as arteries of trade. Today, over 600 million people live on or very near deltaic environments (Higgins 2016; S. Higgins, Pers. Comm., University of Colorado, U.S.A.). Roadways and railways cross deltas, leading away from port cities capable of receiving large ocean-going vessels through the efforts of near-continuous coastal dredging. As the population of delta megacities skyrocketed — an order of magnitude growth in the last few decades — the need for fresh, potable water increased. The draw of groundwater became industrialized, particularly as many of the agricultural areas producing rice transformed into protein bowls through the growth of 21st century shrimp farming and other aquaculture operations. Poor engineering and/or maintenance of the water infrastructure beneath these megacities led to further subsidence; New Orleans being a prime example of a city plagued by water pipe leakage. Delta subsidence was additionally accelerated by: 1) petroleum mining, with the Po, Mississippi, Yellow and Niger deltas being typical examples (Sestini, 1992; Morton et al., 2005; Olea and Coleman, 2014), and 2) peat oxidation, with the Mississippi, Po, and Rhine deltas being representative (Knights, 1979; Sestini, 1992).

Today, many of the world's populated deltas are subsiding (Syvitski et al., 2009; Ibañez, 2015). Global mean sea level is rising at rates now exceeding 3 mm/y due to climate warming (e.g., Koop et al., 2016) and delta land surfaces are sinking at rates of 10 s—100 s of mm/y due to the combination of sea level rise and subsidence