Farming practices and anthropogenic delta dynamics

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Abstract Deltas are dynamic landforms that have been the foci of agri- and aquacultural development by humans for millennia. The dynamics of deltas are governed by changes in river discharge and reworking of sediment. While these dynamics make deltas highly productive areas, they also present challenges to farming practices, often resulting in complicated feedbacks. These dynamics include river and coastal flooding, compaction, subsidence, salinization, and moving land-water boundaries. Likewise, farming in a dynamic environment can lead to socio-economic conflicts. Adaptation to these constantly changing variables requires flexible farming practices that must keep pace with changing climate.

Key words river deltas; agriculture; Anthropocene; climate change

INTRODUCTION

Deltas are low-lying dynamic landforms created by the deposition of sediment where a river drains into an ocean basin. River processes interact with tides and waves to control a delta's form, and every delta reflects the balance of these controlling processes over time. Building laterally and vertically by sediments eroded from river catchments, deltas act as filters and repositories for continental materials, including carbon, on their way to the ocean (Giosan & Bhattacharya, 2005). The deposition of fine-grained river sediments also renders deltas highly productive sites for agriculture, aquaculture and fisheries. Their high productivity, rich biodiversity, low topography and easy transport along abundant waterways have attracted human inhabitants for millennia, arguably fostering the development of civilizations (e.g. Day *et al.*, 2007). Today, deltas remain a preferred human habitat with more than 500 million people living on them, including many heavily populated Asian megacities. The Ganges-Brahmaputra (Bengal) Delta, for example, supports an enormous population density because: its tropical monsoonal climate means it receives an unusually large amount of rain; the flat topography makes 80% of the land suitable for cultivation; and the quality of the soil, due to the huge sediment and carbon flux, makes it very fertile (Lewis, 2011).

A similar tropical monsoonal delta, the Niger, presents an instructive example of how discharge variability impacts a delta. The Niger River delivered across a 36-year period (1970–2006) a mean discharge of 4900 m^3/s with a standard deviation of 890 m^3/s. However, the monsoonal nature of the river system resulted in a peak discharge of 10 000 m^3/s to 24 000 m^3/s for the same period of record. Because of the vast amount of rain falling directly onto the Niger Delta, and its enormous size, the mean discharge of water to the coastal ocean is 19 235 m^3/s, many times more than the Niger River itself delivers to the delta. Peak discharges entering the ocean from all of the various Niger Delta rivers and tidal channels may exceed 56 000 m^3/s, making the Niger one of the most dynamic deltas worldwide. These kinds of dynamics force the population living on deltas to become highly adaptable — sometimes thriving, sometimes surviving.

The societies of the 20th century changed the nature of how deltas function, and downstream delta populations now need to adapt. Today's deltas commonly receive much less sediment due to river damming, in difference to the extraordinary sediment loads deltas received in historical times (Syvitski *et al.*, 2005). With less sediment carried to shorelines, they retreat and their distributary channels migrate faster (Syvitski, 2008). Furthermore, upstream reservoirs often change the nature of water discharge to a delta. In the case of the Nile River, low flow has more than doubled, and the seasonal flood wave has all but been eliminated as the result of water storage behind dams (*ibid*). While unwanted flooding is reduced, the lack of floods carrying river-borne sediment and organic matter to the delta forces farmers to rely on irrigation infrastructure and fertilizer. Examples such as this are common for many of the world's populated deltas.

The Anthropocene

The Earth is entering the Anthropocene, an epoch during which humans have produced permanent global signals on the planet (Steffen *et al*., 2011). Humans can intervene against gravity, decelerate and accelerate natural processes, focus energy, alter or destroy ecosystems, and have already altered the Earth's climate, chemistry, snow cover, permafrost, sea ice extent, glacial ice extent, ocean volume, and hydrological cycle (Syvitski & Kettner, 2011). Deltas are particularly sensitive to anthropogenic changes in their river basins. Human modification begins with far-field upstream measures causing changes in sediment and freshwater fluxes downstream. Fluxes are observed to change in both directions; damming and irrigation strongly reduces sediment delivery, whereas deforestation and other land-use changes can increase upstream erosion and thus sediment delivery to deltas. The hydrodynamics of many river systems are being altered to dampen high frequency floods and increase low water flow. But at the same time, the number of low frequency peak floods appears to be increasing and disastrous floods are becoming more common. The nexus between upstream river basin modification and downstream delta dynamics is expected to intensify with 21st century climate change (e.g. Nohara *et al*., 2006; Bianchi & Allison, 2009). Deltas are equally sensitive to farming related anthropogenic changes on their downstream surfaces: irrigation; tilling; embanking; crop or stock choice, and groundwater extraction. As deltas form the primary agricultural and population centres of many countries, these anthropogenic changes can influence socio-economic dynamics.

FARMING IN A DYNAMIC ENVIRONMENT

Every delta is "constructed" by sediment distributed by river flooding and coastal processes (Overeem *et al*., 2009). Overbank flooding of rivers adds freshwater and sediment to a delta's surface, whereas wetlands at the coastal zone help delta construction by efficiently trapping sediment and naturally protect against erosion. Freshly deposited sediment provides nutrients to flood affected areas, which was especially critical to farming before artificial petroleum-based fertilizers became available (e.g. Nixon, 2003). Despite the cyclic deposition of mineral-rich sediment and the abundance of freshwater, the constant interplay of water and sediment that characterizes deltas presents unique challenges for farming. Agriculture-based societies have for centuries adapted to, and attempted to control, delta dynamics for the benefit of feeding their communities and increasing their profits. In this paper, the unique physical dynamics that farmers in deltaic regions face is presented: flooding; subsidence and compaction; salinization; moving land-water boundaries, and storm surges. Adaptations and impacts of farming practices on deltaic landscapes, and how these practices may change with changing climate are discussed.

River and tidal flooding

Deltas experience frequent river flooding as a part of their dynamical regimes. Normal overbank flooding enhances sediment deposition and nutrient input, while extreme flooding events can lead to avulsion and erosion (Day *et al*., 1997). Syvitski *et al*. (2009) assessed 33 world deltas with satellite imagery and found that in the past decade, 85% of these deltas experienced severe flooding, resulting in temporary submergence of >260 000 km^2 of land area. Farming communities used the pulses of incoming freshwater, sediments and nutrients during floods to irrigate and fertilize crops before artificial petroleum based fertilizers became available (Nixon, 2003). Along the great river systems and deltas of the Yellow, Indus, Euphrates and Nile, irrigation systems that route floodwater to fields have sustained farming for centuries. Similarly, farmers in the monsoon influenced Asian megadeltas have optimized rice farming by seasonally rotating flood tolerant varieties with low water crops. For example, in the Bengal Delta three rice species form the dominant crops: Aman, Boro and Aus. Aman is cultivated during the monsoonal wet period and is resistant to modest periods of river flooding; Boro is a dry season species, and Aus is cultivated during the pre-monsoonal transition period (BBS, 2008). This agricultural production accounts for 20% of the Gross Domestic Product and employs 65% of the labour force in Bangladesh (Yu *et al.*, 2010). Rice produced in the Asian megadeltas feeds not just the inhabitants of these regions, but also an order of magnitude larger population in upstream river basins (Hoanh *et al.*, 2010).

Today, humans impact the incoming water and sediment fluxes to deltas, dampening river flooding and negatively impacting the sediment flux. Dikes and levees inhibit small annual floods, but may make delta and river systems more prone to catastrophic flooding from larger events (e.g. Chen *et al.*, 2012; Syvitski, 2012). Ruane *et al.* (2012) models future impacts of Ganges-Brahmaputra river flooding and the damages done to crops depending on flood duration, inundation depth and flood timing with regard to plant developmental stage. Their combined hydrology-land use model suggests 10% losses with river floods under a changing future climate. The study notes that mean flooding losses increase only slightly and the more important factor is the year-to-year variability in precipitation and river flooding associated with climate change.

Tidal flooding also plays an important role in irrigation. Rice farmers in tide-influenced deltas have adapted to daily tidal flushing by cultivating short grain, wet paddy rice with relatively high salt tolerance. Here, flood tides push water into fields and ponds, and sluice gates keep a quantity of the water from flowing back to the sea during the ebb tide. In other tide-influenced areas where salt tolerant rice varieties are not cultivated, farmers have historically controlled the flow of water onto their fields. For example, traditional agriculture from the 17th century until the late 1940s in the Bengal Delta involved small embankments that were built with gaps that would be opened at low tide to allow drainage and closed at high tide to prevent inundation with saline water (Islam, 2006). These embankments were torn down for the monsoon season when river salinity was low. This allowed relatively freshwater to wash salinity from the soil and allowed sediment deposition to keep the elevation constant, despite subsidence and soil compaction. However, a change to more permanent embankments in the 1950s starved the land of fresh sediment deposits. As a result, subsidence and soil compaction accelerated as buried organic matter oxidized, significantly lowering the land elevation behind the embankments. At the same time, reduced overland tidal flooding caused riverbeds to silt up. This led to widespread waterlogging, which was exacerbated as silt deposits blocked automated flap gates in drainage canals. In response, there has been growing interest in “Tidal River Management”, a return to something closer to the traditional practice of seasonal embankments in order to restore the regular supply of sediment to waterlogged lands (Islam, 2006; Kibria, 2011).

Fish farming in tidal areas is primarily focused on migratory species that follow tides into irrigation systems and can be trapped in narrow tidal creeks and canals. Additionally, fish and shellfish are caught in tidal pools at low tide in the deltaic mudflats beyond the farming fields. This is still common practice in Asia, but a similar system was in use for silver eels in the Rhine-Meuse Delta until their populations sharply declined (Bruijs & Durif, 2009). The disappearance of economically important anadromous and catadromous fish is partly due to barriers on tidal rivers such as barrages and hydroelectric facilities.

Compaction and subsidence

River deltas are composed of sand, silt, clay and peat deposits that compact naturally under their own weight. New sediment exerts pressure on underlying layers, which consolidate by expelling water from the pore spaces between individual grains. In a pristine delta, the fastest compacting areas become low-lying bowls that capture sediment rich distributary channels, eventually re-levelling the ground. The result is an extraordinarily flat landform; large river deltas such as the Amazon can have gradients of just 1 to 10 cm/km (Syvitski & Saito, 2007).

A delta surface lowered through compaction is more susceptible to flooding. Natural compaction and associated inundation can hinder agricultural operations on deltas, while certain farming practices can accelerate compaction. In the Netherlands, for example, it has long been recognized that draining peatland (e.g. to establish pastures or facilitate the use of heavy machinery) can induce rapid oxidation of organic material in the soil. Under sufficient weight, saturated (anoxic) peat can lose 40–50% of its volume over the course of a century; when the soil is drained and begins oxidizing, peat layers can lose an additional 10–20% volume, and compaction rates can become three times faster (van Asselen, 2010). Compaction of drained areas, combined with sediment starvation, adds to or accelerates any baseline subsidence that may already be taking place.

Groundwater pumping can also drastically accelerate sediment compaction by creating empty, underpressurized spaces between grains. Excessive groundwater pumping in California's San Joaquin Delta lowered the water table more than 120 m in the 20th century (Planert & Williams, 1995), causing 9 m of subsidence (Rojstaczer *et al*., 1991). Most of the delta now lies below sea level, and more than 1600 km of levees struggle to protect the land (Ingebritsen *et al*., 2000). Similarly, groundwater pumping in the city of Bangkok, which lies within the Chao Phraya Delta, caused more than 100 mm/year of subsidence in the 1980s (Sabhasri & Suwanarat, 1996). This subsidence affected millions of people and drove considerable shoreline retreat, converting entire villages to open ocean. Extraction-induced sediment compaction is gaining worldwide recognition as a serious hazard, and steps are being taken to prevent further subsidence (e.g. Shi *et al*., 2012). The California government now regulates groundwater extraction in the San Joaquin Delta, and heavy taxes on groundwater pumping have been enacted in Bangkok. Studies by Thailand's Department of Groundwater Resources show that subsidence rates have dropped to 10% of their 1980s values. While these measures can prevent additional subsidence, they cannot undo compaction that has already occurred. Sunken land can only be recovered if new sediment is deposited. Consequently, compaction and subsidence increase the low-lying area of a delta already vulnerable to flooding and storm surges.

Salinity

Another consequence of delta subsidence is salinization of river channels, groundwater aquifers and soils. As the ground surface in a delta lowers through subsidence caused by tectonics or human impacts, the tidal incursion moves inland, saturating soils, damaging plant roots and raising the salinity of channels (Day & Templet, 1989). To compensate for this increase in salinity, farmers in the tide-influenced western Bengal Delta build embankments to prevent tides from infiltrating fields and trap rainfall for irrigation. However, embanked paddy fields then receive minimal new sediment and therefore subside due to natural compaction. In the eastern Bengal Delta, which is closer to the active Ganges-Brahmaputra River mouth, crops are irrigated by natural flooding. Flood-irrigated fields receive new sediment each time they are inundated, building up over time and compensating for compaction and other subsidence. In essence, salinization of cultivated areas, while sometimes damaging, can also inform agricultural decisions that may slow the rate of deltaic subsidence.

Seasonal salinity variations can also influence crop rotation**.** In the Mekong Delta, salinity varies with the annual monsoon. During the dry season, which can last up to eight months, freshwater river flows are low and intrusion of saline coastal water affects half of the delta's 39 000 km^2 (Huu-Thoi & Das Gupta, 2001). Many farmers utilize these variations by farming shrimp in the dry season and growing rice in the wet season when river discharge is high (Tran *et al*., 1999). As the price of shrimp rises, more farmers may make the choice to switch from rice to year-round shrimp farming. However, confining salt water in a shrimp pond increases the salinization of the soil; soil contaminated by shrimp farming remains saline even after the pond is drained. Farmers in the Ca Mau province of Vietnam, for example, began year-round shrimp production in 2000. The soil water salinity is now 4–8 times higher than critical limits. Many farmers in this district have attempted to revert back to rice cropping, although the soils remain too saline for successful rice cultivation (Tho *et al.,* 2008). The time required for agricultural land to return to normal salinity levels after extensive shrimp farming is uncertain and debated in the literature, and may be highly variable between areas (e.g. Neiland *et al*., 2001).

When salinity is high, groundwater is also commonly pumped to supplement irrigation. Just as with subsidence due to reduced sediment input, subsidence from pumping can exacerbate salinization by pulling ocean water into river channels and aquifers. This creates a feedback where agricultural practices amplify natural salinity perturbations. Under a future rising sea level scenario, we expect the salinity of delta groundwater and river channels to increase. In the Mekong, the 2.5 g/L saline front is predicted to shift 10 km upstream by 2030, and may move up to 20 km inland in the paddy fields (Khang *et al*., 2008). These changes could drive a conversion from flood-irrigated agriculture to rainfall-irrigated agriculture in some deltas, and a conversion from agriculture to aquaculture in others. However, if a warmer climate intensifies precipitation (e.g. Schewe *et al*., 2011), rainfall and river discharge may likewise increase, shifting the saline front seaward. Any of these changes could affect the deltas' agricultural production.

There can also be strong feedbacks between agricultural practices, local economies, and the changing landscape. When embankments are breached or land becomes waterlogged, converting rice fields to brackish ponds for shrimp aquaculture can make unprofitable land profitable. But as shrimping and associated soil salinization spreads, it can make nearby agricultural land less fertile and sicken livestock. Shrimp ponds need to be flushed regularly with fresh river water so shrimp farmers often cut into embankments with improvised sluice gates or drainage pipes. This weakens embankments and makes them more prone to breach under storm surges or exceptionally high tides. These environmental stresses combined with political and economic pressures may create a bi-stability in local agriculture, where either rice farming or shrimp aquaculture can persist, but a combination of the two cannot (Chowdhury *et al*., 2011).

Storm surges

Deltaic coastlines are susceptible to flooding from storm surges. Agriculture systems have been designed to accommodate river flooding in deltas, although farming in cyclone prone regions where arable land is at risk of coastal flooding presents different challenges. One means that farmers cope with the threat of coastal flooding is by avoiding planting profitable crops in low-lying areas outside of seawalls and protective levees, and instead reserve these areas for livestock grazing and fodder production. This practice results in a tradeoff between having less land to grow crops, and reducing the likelihood of costly storm-related flood damage.

Another adaptive practice by farmers working in cyclone prone coastal zones is building protective embankments. For example, tropical storms make landfall every few years along the Bengal coast, and over the last decade two major cyclones impacted the delta: Sidr in 2007 and Aila in 2009. Inhabited areas close to coastal fringes are protected by ~4–5 m high dikes of clay reinforced with bricks, and the land directly below is highly cultivated with rice or shrimp farms. However, the storm surge height during Cyclone Aila was >6.2 m, causing many of the embankments to fail. This resulted in widespread flooding and the deposition of a thick (<1 m) layer of sand that devastated fields and farms. It took over two years to rebuild the dikes and drain fields; farming has not yet fully recovered (Fig. 1). Other farming communities in the Bengal and Mekong Deltas have found that land rendered highly saline by tidal inundation after storms breached embankments can be restored to fertility after several years of flushing with fresh monsoon water. After two seasons of flushing, a crop progression that begins with salt-tolerant crops such as watermelon gradually expands to include a greater variety of crops as the soil recovers.

Despite human attempts to protect their lives and livelihoods from coastal flooding, deltas worldwide may experience a trend of increasing vulnerability to storm surges. This is due to: (a) rapid sinking of the land surface due to compaction and subsidence; (b) lack of replenishment of constructive new sediment, and (c) loss of protective natural coastal wetlands. Vörösmarty *et al*. (2003) have estimated that >40% of global river discharge is currently intercepted by large reservoirs and dams to regulate flow and manage water for irrigation in upstream river basins. Syvitski *et al*. (2005) estimated that on a global scale 26% of sediment that would otherwise flow to the coast and deltas has been intercepted by retention in reservoirs. Based on this estimate of reduced sediment discharge, the area of deltaic coasts vulnerable to flooding could increase by 50% under the projected values for sea-level rise in the 21st century. While the need for incoming sediment as a nutrient source is diminished by modern fertilizers, the constructive force of sediment accumulation is still of essence to farmers in low-lying lands, and even more so with human-induced subsidence accelerating the sinking of deltas.

Fig. 1 Breaching of coastal embankments by storm surges destroys arable cropland. Following Cyclone Aila (2009) up to 1 m of coastal sand was deposited on paddy fields in southwest Bangladesh, forcing hundreds of people to abandon their land and migrate to other areas.

DYNAMIC SYSTEMS REQUIRE DYNAMIC RESPONSES

While floods, compaction, subsidence, salinization and storm surges can significantly alter delta landscapes, the most dynamic aspect of deltas is their numerous moving land–water boundaries. "Moving boundaries" is a well-established geomorphic concept, along with their associated computational methods (e.g. finite element methods, Stefan problems). The shoreline boundary for example, is in a constant state of movement, responding to changes in the supply of sediment from local rivers or from alongshore or cross-shore currents set up by wave action. There are many moving boundaries for a river delta beyond the shoreline associated with migrating bars, channel avulsion, *char* island development, and tidal channel migration. Even if a delta has reached some equilibrium condition with respect to water or sediment movement through its environment, these boundaries are likely to shift. For instance, rivers meander even if zones of deposition balance zones of erosion. The very nature of hydrology is predicated on the concept of moving boundaries, otherwise known as morphodynamics.

River deltas are not steady state sedimentary coastal environments. They are, in fact, the cumulative end product of highly variable boundary conditions and forcing factors (e.g. upstream water and sediment supply, offshore tidal or wave energy, frequency and intensity of tropical cyclones and storm surges, monsoon conditions, and rates of sea level rise). Thus, farmers have been adapting to living with moving boundaries for thousands of years. Agriculture-based societies face many challenges when they farm along a moving water-land boundary. These include issues related to ownership (land loss *vs* land acquisition), crop management (salinization of soils and groundwater, and access to freshwater), and loss of infrastructure (roads, bridges, docks, housing, electricity, schooling).

In general, farming communities on deltas (e.g. Yellow, Godavari, Krishna, Mahanadi, Ebro) favour the constancy of an engineered water supply, but they have become less able to cope with the rarer floods that can overpower the infrastructure (e.g. Indus, Syvitski and Brakenridge, 2013). With less variable hydrographs, farmers seldom encounter the frequent moving boundaries of a normal wetland and are overwhelmed when climate driven floods re-occur. Though some movable boundaries have been slowed or tamed by reinforced stop-bank levees, barrages, engineered canals, or decreased floods waves from upstream dams, movable boundaries on many deltas remain a challenge to farming communities.

Often, attempts to control moving boundaries trigger consequences that increase crop vulnerability. For instance, on the Chao Phraya Delta protective mangrove forests were removed at rates of >100 ha/year and replaced by more profitable shrimp farming. As a consequence, shoreline retreat has averaged 30 m/year over the last four decades, exposing shrimp farms to coastal storms and flooding (Fig. 2). The decision to clear-cut mangrove forests to create farmland is motivated by the economics of shrimp and rice farming. These cash crops reap a farmer 3 or 4 times greater profit when compared to livestock rearing or wetland-mangrove fishing (Can *et al.*, 2010). Western countries (e.g. Netherlands, Spain, USA) spend large sums of money to continually add sand and gravel to their coastal environments as beach nourishment in order to mitigate shoreline retreat. Other countries (e.g. Japan, Korea, China) invest heavily in hardened coastal structures to limit shoreline retreat.

In more rural or agricultural societies, farming has to be flexible. Where farms are small and individually owned, channel avulsion can destroy the livelihood of farming village (e.g. Indus, Bengal, Burma). Social structures need to be in place such that shifting lands do not create homelessness**.** Temporary sandbars, called *chars*, often develop in the Bengal Delta. These small

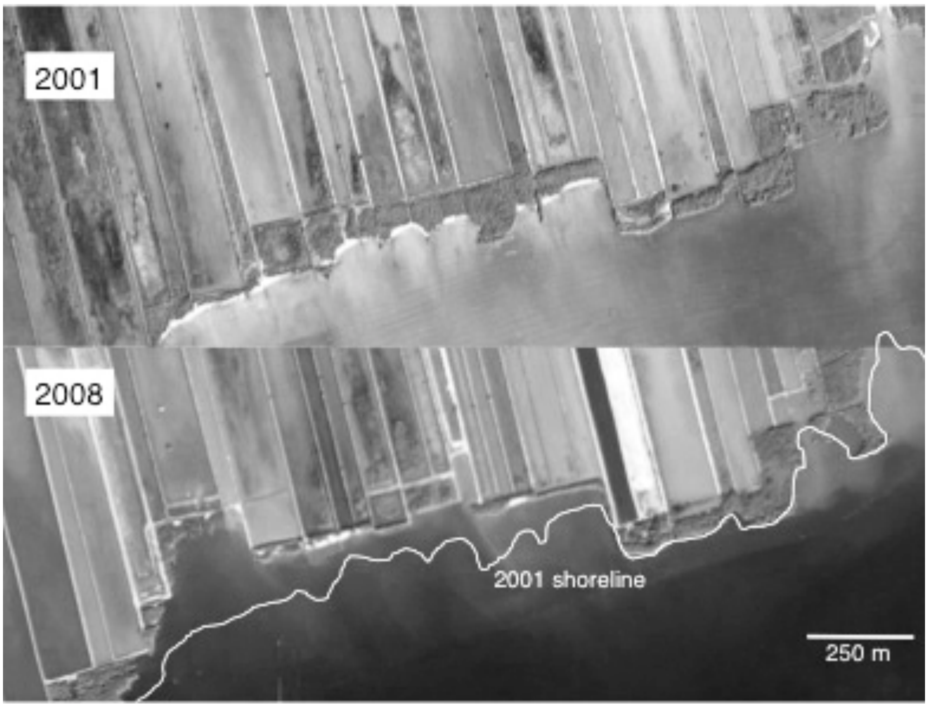

Fig. 2 Google Earth images of the uneven shoreline retreat along the Chao Pharya coast lined with reduced mangrove forest area and shrimp farms.

islands are >100 m across with lifespans of ~10 years. Communities often claim a char and farm it until it erodes away. The main Meghna River channel is migrating 100–200 m/year, forcing villagers to migrate and re-establish their crops in other locations (Fig. 3). Moving boundaries at the coast and within rivers and delta distributaries are expected to become more dynamic as the frequency of climate-related floods increases in the 21st century. In response, agricultural societies on deltas must develop dynamic practices and technologies that strengthen their resilience to climate change variability.

Fig. 3 Erosion along the banks of the Meghna River in Bangladesh during the 2012 summer monsoon season resulted in the collapse of an average of one palm tree per week into the river. Breaching of the riverbanks resulted in flooding of village fishponds, as seen behind the villagers in this image.

CONCLUSIONS

Deltas all over the world are identified to be among the most important sources of ecosystem goods and services. They are a reflection of past and current global change phenomena along our coasts, as well as the societal dimensions associated with these changes. In terms of spatial and temporal scales, deltas are an expression of the complex geomorphic interplay between natural and human forcing, and thus provide a mirror of the multiple feedbacks between man and the environment. The relevant spatial extension of deltas and the processes that govern their geomorphologic dynamics and shape encompass the water continuum from source areas in the river catchments down onto our continental shelves. Along this continuum, anthropogenic pressures exact their toll, involving changes and responses.

The deterioration of world deltas is caused by the increasing pace of human development that alters the functionality of ecosystems, producing escalating socio-economic impacts in these food-producing areas. The human dimension and ecological implications of deteriorating or disappearing deltas cannot be overstated. Leading delta researchers are calling for the international community to develop a focused effort towards a holistic physical-socio-economic understanding of deltas as critically delicate and vulnerable systems undergoing change. This effort is a basic requirement for the management, protection, and restoration of deltas.

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