Deltas at risk

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Abstract The long-term sustainability of populated deltas is often more affected by large-scale engineering projects than sea-level rise associated with global warming and the global ocean volume increase. On deltas, the rate of relative eustatic sea-level rise is often smaller than the rate for isostatic-controlled subsidence and of the same order of magnitude as natural sediment compaction. Accelerated compaction associated with petroleum and groundwater mining can exceed natural subsidence rates by an order of magnitude. The reduction in sediment delivery to deltas due to trapping behind dams, along with the human control of routing river discharge across delta plains, contributes to the sinking of world deltas. Consequences include shoreline erosion, threatened mangroves swamps and wetlands, increased salinization of cultivated land, and hundreds of millions of humans put at risk.
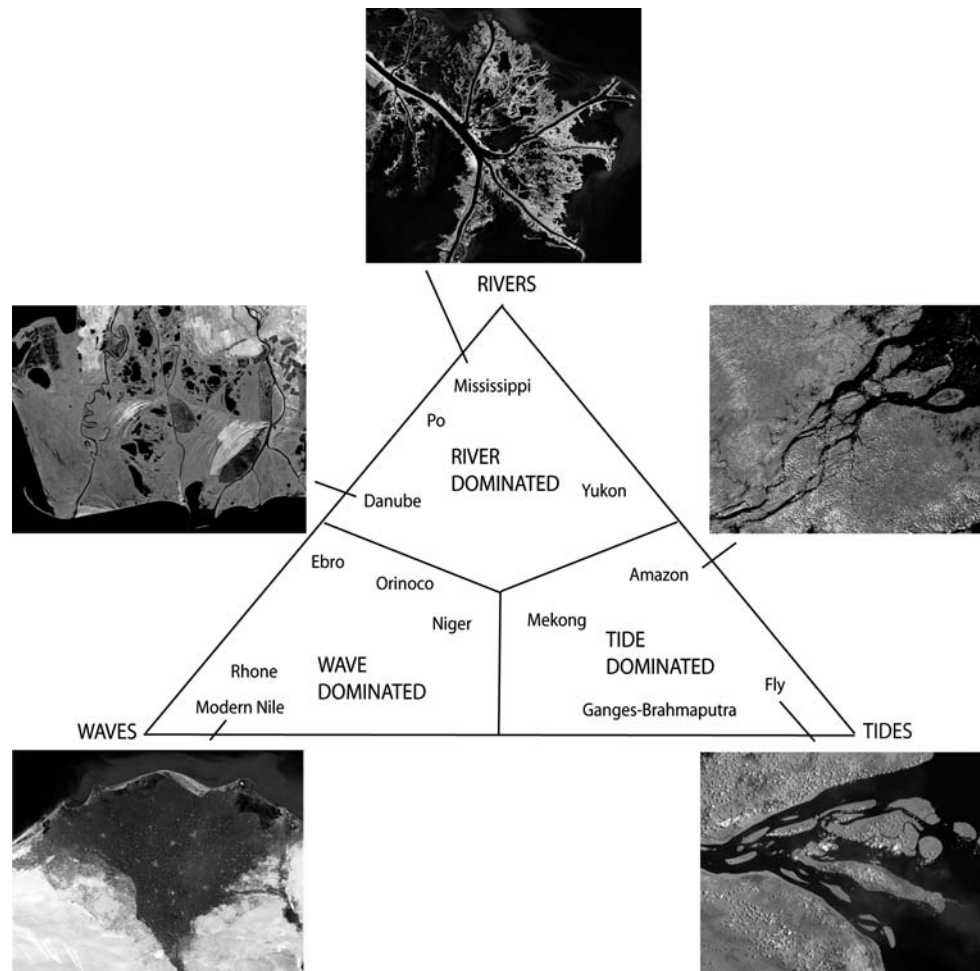
Deltas

River deltas are coastal features developed from the accumulation of sediment near the mouths of rivers. A delta's area may be defined as: (1) the seaward prograding land area that has accumulated since 6,000 years, when global sea level stabilized within a few meters of the present level (Amorosi and Miller 2001), (2) the seaward

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area of a river valley after the main stem of a river splits into distributary channels (Syvitski and Saito 2007), (3) the area of a river valley underlain by Holocene marine sediments (Kubo et al. 2006), (4) accumulated river sediment that has variably been subjected to fluvial, wave, and tidal influences (Overeem et al. 2005), (5) the area drained by river distributary channels that are under the influence of tides, or (6) any combination of these definitions. The aerial extent of a particular river delta therefore varies depending on the definition. Small rivers are associated with small deltas, usually of a few square kilometers; large rivers are associated with large deltas of tens of thousands of square kilometers—the largest being the Amazon delta at 467,000 km^2 (Syvitski and Saito 2007). In general, most deltaic features scale with the magnitude of a river's discharge, including the sediment load delivered by the river, the number of distributary channels, and the gradient of the deltaic plain, with larger deltas having the lowest gradients (Syvitski et al. 2005). Delta morphology is often accounted for in terms of the competing influence of waves, tides, and river discharge (Fig. 1, see Syvitski and Saito 2007).

Delta plains are incredibly flat: 0.005 (m/m) for steeper, mountainous river deltas, to 0.00001 (m/m) for the larger deltaic systems (Syvitski and Saito 2007). A delta's low gradient is both attractive and dangerous to human utilization. A large flat delta is attractive because it has the potential for easy agricultural development, made further attractive by its rich organic soil (e.g., Nile, Indus, Danube, and Po; Woodroffe et al. 2006). Deltaic sediments are at the finer-grained end of a river's flood plain (Syvitski and Saito 2007) and are generally rich in organic carbon (Keil et al. 1994, 1997; Beusen et al. 2005). Importantly, population centers are often located on deltas. Fifty-one of the world's deltas have a combined 2003 population of 325 million (Oak Ridge National Laboratory 2002), and this is

predicted to increase rapidly through the growth of megacities (e.g., Shanghai, Guangzhou, Bangkok, Yangon, Calcutta, Dhaka, Lagos, Ho Chi Min City, Hanoi: Woodroffe et al. 2006). The Nile delta alone has a population of ≈ 50 million people.

However, low delta gradients can contribute to a dangerous environment for human habitation, allowing river flooding to spread across the flat delta plains through distributary channels that often switch their location and direction. Twentieth-century engineering has partly ameliorated floods with upstream dams, dikes, levees, and other flood-control structures (Syvitski and Saito 2007). But these structures also encourage people to live in environmentally dangerous areas, putting themselves at risk when larger flooding events occur. Engineering often provides little protection from ocean-generated storm surges; ≈ 10 million people per year experience coastal flooding (Nichols 2004).

This paper reviews some of the latest findings on the sustainability of deltas in light of new findings on sea-level rise and land subsidence as applied to deltas, including the battle that humans are waging to control the way deltas behave naturally, and particularly the role of sediment supply in affecting delta stability.

Relative sea level and river deltas

Sea-level change along a coast is perhaps one of the most complex geophysical problems, involving many processes that intertwine with positive and negative feedback. The coastline of a delta moves as a function of the direction of global ocean volume (eustasy), more regional earth-surface load changes (isostasy), sediment supply, and compaction of the deposited sediment (Ericson et al. 2006). All deltas have experienced some level of sea-level fluctuations during the mid- to late-Holocene period (4000 BC to today) (Syvitski et al. 2005b). Below, we highlight the relevant relative sea-level processes impacting a delta but omit discussion on: (1) longer-term changes to the shape of ocean basins (producing a eustatic signal), (2) thermal subsidence (i.e., thermal contraction of the lithosphere) wherein a cooler crust becomes denser and sinks toward a new but deeper equilibrium level, and (3) local and

regional tectonic processes (e.g., fault displacement, hinge-line crustal-block instabilities, and mountain-building processes).

Six thousand years ago, the global ocean volume was largely what it is today (Peltier 2004). Over the last 1,000 years, with continued ocean-surface warming (the steric effect), along with polar ice cap and temperate glacier melting (adding water volume to the ocean), the global ocean has risen very slowly (≈ 0.1 mm/year). Since 1961, the global ocean has gained volume, rising another 7.6 cm (Bindoff et al. 2007). The rate of sea-level rise, as estimated from observations with satellite altimetry, has increased again to 3 mm/year since 1993 (Bindoff et al. 2007).

However, eustatic sea-level change is often overwhelmed by the regional isostatic signal, which may be a far more important control of delta development. Isostasy refers to significant regional load changes to the earth's crust. Load changes can arise from growth or shrinkage of a large ice mass, from the weight of new sediment added to a delta, and from the weight of coastal water added or subtracted with fluctuations in sea level. Tectonic forces ranging from fault-controlled subsidence to thermal subsidence may also influence Holocene deltas to varying degrees (Jouet et al. in press). The flexural response of the crust to these various changes: (1) occurs over thousands of years, because the viscous asthenosphere has to flow out of the way before the lithosphere can deflect (Hutton and Syvitski in press), and (2) extends over a region much larger than the area directly affected by load change (as influenced by the regional elastic thickness of the lithosphere and the properties of the mantle viscosity: Jouet et al. in press).

The relaxation rate depends on the exponential decay constant, varying between 1,500 and 5,000 years (Hutton and Syvitski, in press), e.g., a constant of 2,500 years would indicate that after a change in load, the lithosphere recovers 50% of its vertical displacement in 2,500 years. If a new load could vertically displace the lithosphere downward by 30 m, then in 5,000 years, 75%, or 22.5 m, of this displacement would have occurred, with the remaining 7.5 m taking thousands of years more to be fully displaced. The Holocene period of increase in global ocean volume, largely ending 6,000 years ago, still affects the coastal areas of the world today. For example, the Rhone delta in southern France is still being affected by Holocene ocean volume increase, where the weight of the Mediterranean Sea that flooded its continental shelf has increased the local rate of sea-level rise (Jouet et al. in press)—an effect known as hydroisostasy. In contrast, deltaic areas that formerly were under the weight of a Pleistocene ice sheet may still be experiencing uplift, as evidenced as a relative sea-level fall, even while the global ocean volume

has increased—an effect known as glacioisostasy (Syvitski et al. 2005b).

As an example of how isostasy can influence a delta's relative sea level in a spatially variable manner, Hutton and Syvitski (in press) modeled the deflection of the lithosphere due to load changes on the Mississippi delta, based on the history of sediment accumulation and the timing of lobe switches, as determined by Fisk and McFarlan (1955) (Fig. 2a). Due to discharge breakouts through the natural levees of the main stem, the Mississippi and most other deltas would normally change their locus of deposition from time to time (i.e., as witnessed by the various delta lobes in Fig. 2a). [An 1814 map by the cartographer Mathew Carrey, for example, shows where the Mississippi breakouts might have occurred (Fig. 2b) prior to engineering/stabilization of the levees in the twentieth century.] The model simulation incorporated the eustatic sea-level rise from the Last Glacial Maximum [18,000 before present (BP)] and the growth of various sediment lobes (Fig. 2a). Figure 3 shows the modeled subsidence rates keyed to five separate locations on the Mississippi delta (see red dots on Fig. 2a for locations). Each part of the Mississippi delta has a unique subsidence history (Fig. 3) depending on its distance to: (1) the continually changing coastline concomitant with Holocene sea-level rise and (2) the present and former sediment deposition centers. The modeled present-day sea-level rise, due to just isostatic subsidence, varied among these five sites from a high of 3.6 mm/year (position C) to a low of 0.3 mm/year (position B) (Fig. 3).

In addition to eustatic and isostatic effects, sediment compaction can also add to the overall rate of subsidence. Using a combination of numerical modeling and field observations, Meckel et al. (2007) determined typical compaction rates of deltaic sediment. As new sediment (weight) is added to a sedimentary deposit, the underlying sediment reduces in water content due to reduced between-grain-void space. Compaction rates vary over three orders of magnitude, but 80% of the rates are between 0.7 and 2.2 mm/years (Meckel et al. 2007). These compaction rates slow with the depth of burial (Bahr et al. 2001). The fastest compacting sediment layers are composed primarily of peat and bar sand, whereas the slowest compacting layers are composed of prodelta mud and natural levee deposits (Meckel et al. 2007). Thus, compaction is also variable across a deltaic plain and influences a delta's evolution by controlling accommodation space. Heterogeneity in sediment layers increases the rate of compaction (Meckel et al. 2007).

In summary, competing processes control the natural rates of sea-level fluctuations relative to a coastline. Prior to the 1950s, sea-level rise due to ocean volume changes (eustasy) were minor (0.1 mm/year). Since 1961, this rate has increased to 1.8 mm/year and may have doubled to
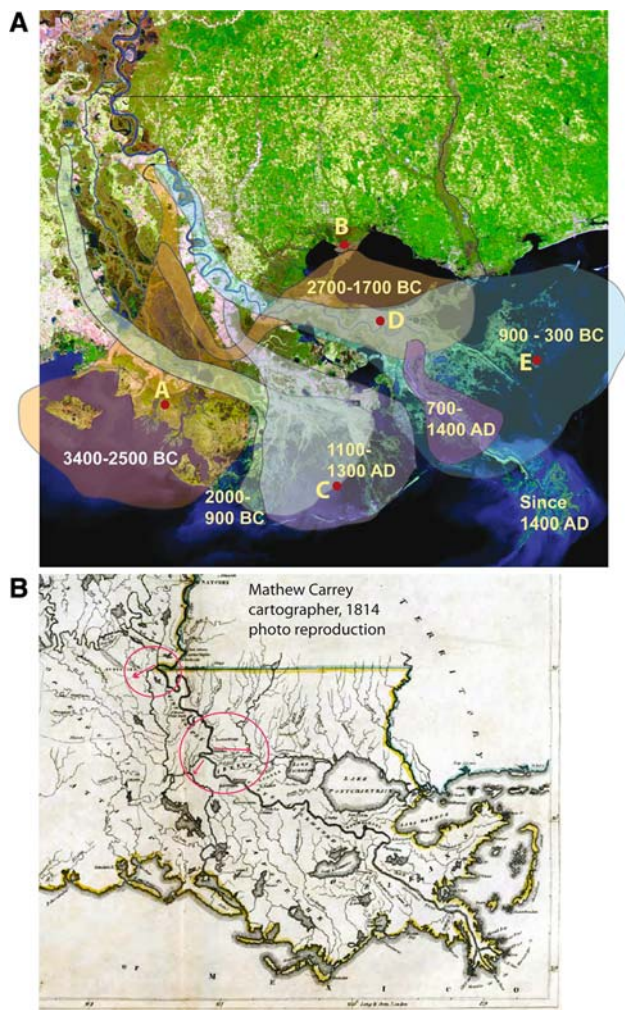
Fig. 2 a Historical sediment lobes of the Mississippi delta as mapped by Fisk and McFarlan (1955) showing the dates associated with their time of formation. The lobes are superimposed on a Moderate Resolution Imaging Spectroradiometer satellite image of the delta. Also shown is the location (*A–E*) of sites used to model isostatic subsidence (cf. Fig. 3). **b** Photo reproduction of the 1814 cartographic map by Mathew Carey of the Mississippi delta. Highlighted on the map are major distributary channels that might have shifted the locus of deposition to form a new lobe. Twentieth-century engineering has reduced the likelihood of such a shift

3 mm/year since the 1990s. Isostasy can be as important in controlling today's delta surfaces relative to ocean levels. For example, the Mississippi delta has variable isostatic subsidence rates that vary between 0.3 and 3.6 mm/year. Finally, a shorter-lived phenomenon is natural compaction that can lower the base level of a delta's surface at rates between 0.7 and 2.2 mm/year. If these various rates are cumulative, as they are on many deltas, then relative sea-level rise may range from 2.8 to 8.8 mm/year, in agreement with other estimates on natural subsidence rates (Jelgersma 1996; Stanley and Warne 1998).
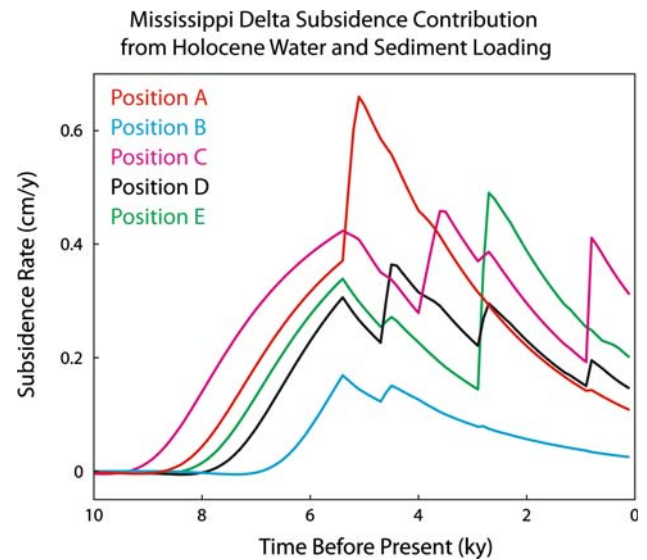

Fig. 3 Modeled isostatic subsidence rates from Holocene water and sediment loads for five locations (cf. Fig. 2a) on the Mississippi delta. Each site is unique, reflecting distance from the site to the sea, during a rising sea level and given the shifting lobes of sediment deposition (cf. Fig. 2a)

Anthropogenic influences on relative sea level

A number of anthropogenic influences exacerbate the natural rates of sea-level rise on deltas, more so than for most other coastline types. Accelerated compaction can occur with groundwater withdrawal or hydrocarbon extraction. For example, in the Po delta of Italy, methane production began in 1938 and reached a maximum in 1960, generating 0.3 km^3/year from 81 wells (Rinaldi 1961). Subsidence from this accelerated compaction reached rates of 60 mm/year (Fig. 4a: Caputo et al. 1970). Shortly after the methane production ended, subsidence rates decreased by a factor of five, and subsidence shifted to where sedimentation was more active (Fig. 4b: Bondesan and Simeoni 1983). Other deltas with significant oil and gas accumulations and extraction include the Niger, Magdalena, Mahakam, MacKenzie, and Mississippi deltas (Ericson et al. 2006) and the Yellow River (Huanghe) (Syvitski and Saito 2007). High subsidence of the Niger delta, due to oil and gas extraction, may reach between 25 and 125 mm/year (Abam 2001). In the Mississippi delta, loss of coastal wetlands peaked between 1955 and 1978 at 11,114 ha/year and declined to 2,591 ha/year from 1990 to 2000 (Morton et al. 2005). Massive extraction of gas from the Mississippi delta subsurface peaked in 1970 and declined rapidly thereafter and is suspected of being the cause of the rapid subsidence and possible fault reactivation (Morton et al. 2003).

The Chao Phraya River delta of Thailand has experienced serious coastal erosion since 1970 due to accelerated
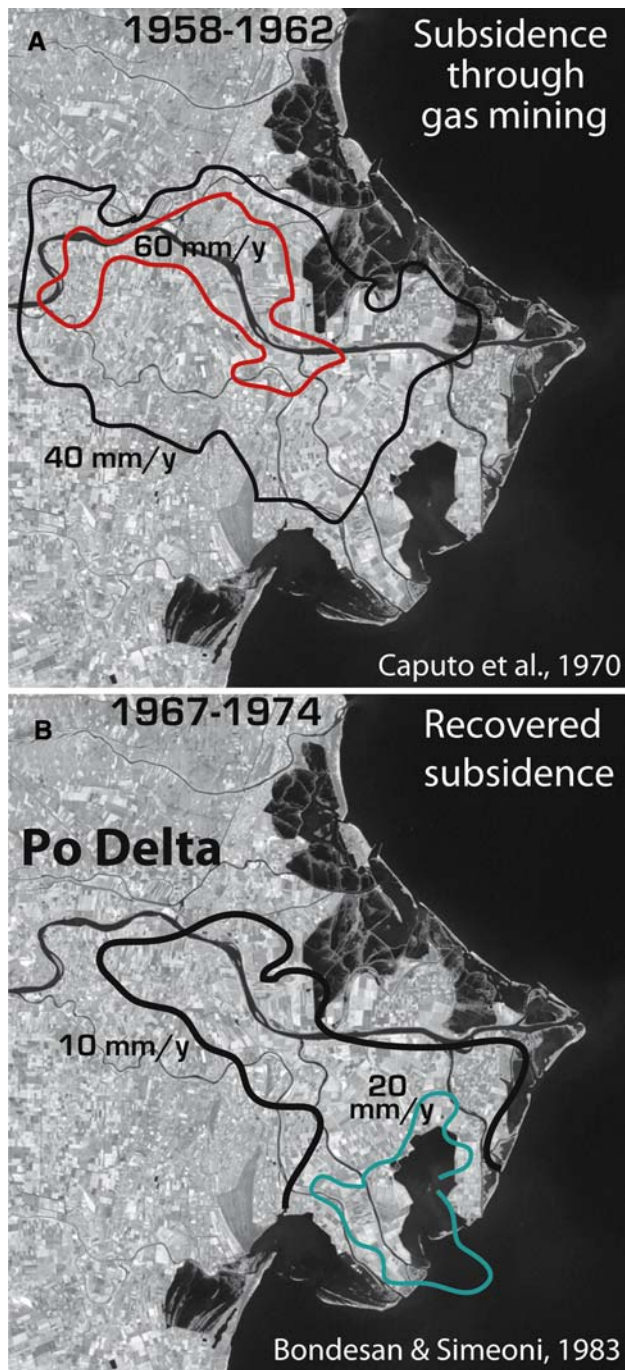
Fig. 4 a Contours of subsidence (40 and 60 mm/year) over the Po delta, Italy, showing the impact of methane production resulting in accelerated compaction (after Caputo et al. 1970). **b** Contours of subsidence (10 and 20 mm/year) over the Po delta, Italy, after gas mining had ceased and accelerated compaction ended (after Bondesan and Simeoni 1983). The contours are superimposed on a Landsat Enhanced Thematic Mapper Plus image of the Po delta

Fig. 5 Contours of subsidence (5 and 10 cm/year) superimposed on a Landsat Enhanced Thematic Mapper Plus image of the Chao Phraya delta, Thailand. Just to the *left* of the loci of peak subsidence is the town of Bangkok, which has grown to a population of >10 m in 30 years. Water withdrawal around the coastline has retreated by 1 km during this period (Saito et al. 2007)

compaction (Syvitski et al. 2005b). Excess groundwater pumping in the Bangkok area has caused rapid subsidence, to more than 100 mm/year (Sabhasri and Suwanarat 1996), and the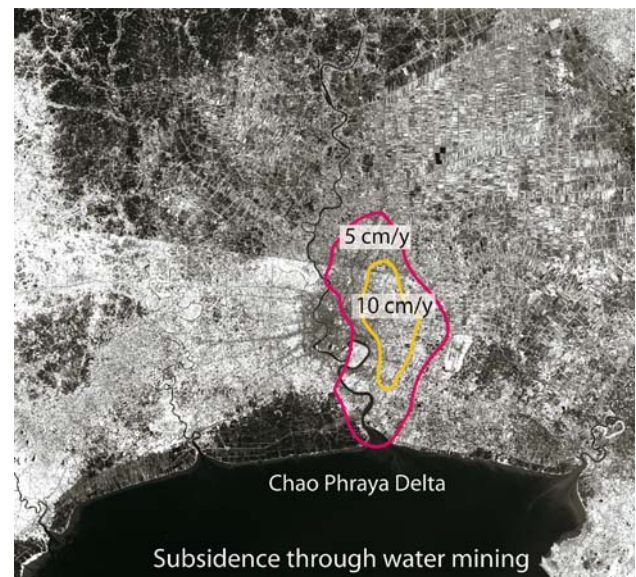 delta's surface has subsided by more than 2 m, not only in the Bangkok metropolitan area, but also in the coastal region south of Bangkok (Fig. 5). Between 1970 and 1990, sea level rose 0.5 m in the coastal region and the shoreline retreated 0.7 km (Saito 2001). The shoreline retreat occurred even during the early stage of land subsidence, indicating that even a 100-mm subsidence (equivalent to a 100-mm relative sea-level rise) can induce serious coastal erosion (Saito et al. 2007).

Similarly, accelerated compaction associated with groundwater extraction was associated with the subsidence of Shanghai (on the Yangtze delta) at rates of 28 mm/year—a rate since reduced to 3–4 mm/year by regulating the withdrawal of groundwater (Han et al. 1995). Central Shanghai now lies 2–3 m below storm surge levels and is dependent on the embankment built around the city (Chen and Wang 1999).

In summary, accelerated "anthropogenic" compaction through either petroleum production or groundwater mining can increase the subsidence of delta plains by up to an order of magnitude over natural background rates. Cessation of accelerated subsidence can be quick (years), concomitant with ending of petroleum or groundwater withdrawals. Whether ambient or anthropogenic-induced subsidence is common on most deltas, outside of areas near former ice sheets, and other tectonically active settings. The impact of coastal erosion is rapid: shorelines retreat, wetlands drown, and large tracks of land become vulnerable to storm surges (Nicholls 2004).

Oceanographic impacts on relative sea level

Areas of the coastal ocean that are warming at a rate greater than other parts of the ocean or that experience the impacts of a migrating western boundary current, such as the Gulf Stream, may also experience an anomalous and gradual sea-level rise (≈ 1.5 mm/year) due either to the local steric effect or dynamic topography (for discussion, see Cabanes et al. 2001; Miller and Douglas 2004). Shorter-term adjustments of a delta's relative sea level include the effects of a coastal-hugging Kelvin wave set up by the seasonal river plume (Morehead and Syvitski 1999) and the plume's hydraulic head near the river mouth (Syvitski et al. 1987, p. 114). These may increase local sea level by several centimeters for days to weeks. The gravitational pull of the moon and sun provides daily tidal waves in the range of a few meters (e.g., Amazon, Colorado, Fly, Fraser, Indus, Irrawaddy, Parana, and Yangtze deltas: Syvitski and Saito 2007). Many deltaic coasts also experience wind-induced surface-gravity waves and swells up to a few meters in amplitude (e.g. Copper, Limpopo, and Rhone deltas: Syvitski and Saito 2007). All of these ocean mechanisms contribute to the long-term development of a delta's coastline: deltas take on morphodynamic forms that are in equilibrium with these ocean forces.

The largest oceanographic impacts to a delta's surface are from unusual or rare events—from a short duration (hours) tsunami wave (Edwards 2005) or from a hurricane/typhoon-induced coastal surge (hours to days) (Murty and Flather 1994). In both cases, the direction of the ocean wave cannot be predicted precisely and is likely to be different for each event. Because of the rareness of these powerful events, a delta's morphodynamic form does not adjust to them. The associated rise in sea level can be measured in meters and can exceed 10 m. The impact of such events can be magnified by other oceanographic conditions, e.g., high spring tide, large breaking waves, and coastal flooding by the delta's river.

Sediment supply to deltas

Whereas subsidence increases a delta's vulnerability, the impact is made much worse by anthropogenic control on the supply and routing of sediment to and across a delta (Ericson et al. 2006; Syvitski and Saito 2007). Subsidence on a delta can be seen as providing accommodation space for newly arrived sediment from upstream sources. In a pristine world, the seasonal flood would sometimes over-bank levees and deposit a layer of sediment, often centimeters or greater in thickness. Year after year, decade after decade, these delta top deposits (topsets) would aggrade, keeping pace with a delta's subsidence. The

shoreline position would adjust with changes in either the rate of sediment supply or rate of subsidence. Under such a balance, a delta's shoreline would remain fixed only if the sediment supply was able to fill the accommodation space generated by subsidence. If subsidence slowed or if the sediment supply increased, then the shoreline would prograde seaward. If subsidence increased or if the sediment supply decreased, then the shoreline would retreat landward.

Above we have discussed ways that humans have changed the rate of subsidence on deltas. Human control on sediment supply and routing is even more common. In a global analysis of sediment delivery by rivers to the coast, Syvitski et al. (2005c) calculated that humans have altered the natural sediment yield on most landscapes (e.g., deforestation, poor agricultural practices, mining activities, urbanization). Syvitski and Milliman (2007) noted that the footprint of this anthropogenic impact is associated with high population density (PD) and is strongly influenced by the gross national product (GNP). For drainage basins with a PD > 200/km^2 and a per capita GNP > \$15,000/year (e.g., western Europe and eastern United States), rivers are well regulated and contained by stop-banks hardened by raft and concrete. The sediment yield for these basins has decreased by half relative to prehuman times. For basins where PD > 200/km^2 but per capita GNP is low ($\leq$\$1,000/year: parts of Asia, Africa, the Philippines, and Indonesia), the sediment yield has doubled. These basins have either not received the resources to solve problems of soil erosion or represent areas where deforestation is near its historical peak, farming practices are poor, or open-pit mining is intense.

Whereas many rivers are getting dirtier (sediment concentration is increasing), an every-increasing portion of this sediment transport is intercepted before the river debouches across its delta plain, influenced by impoundments, water diversions, and seasonal flood-wave control. The rate of sediment reduction is geographically varied depending principally on the number and location of upstream reservoirs. European, African, and North American rivers transport far less sediment than before the impact of humans (at −26%, −39%, and −19%, respectively; Syvitski et al. 2005c).

For many rivers, the history of sediment delivery to their deltas has been one of a slow developing rise in sediment conveyance followed by a rapid twentieth-century fall (Fig. 6). For example, the pristine sediment load of the Yellow River was ≈ 0.1 BT/year prior to 2,000 years BP (Wang et al. 2007). Due to accelerated soil erosion on the Loess Plateau, the load increased to ≈ 1 BT/year about 1,000 years BP, reaching a maximum level of ≈ 1.8 BT/year in the 1950s (Wang et al. 2007). Since then, the load has steadily decreased back to its pristine level of
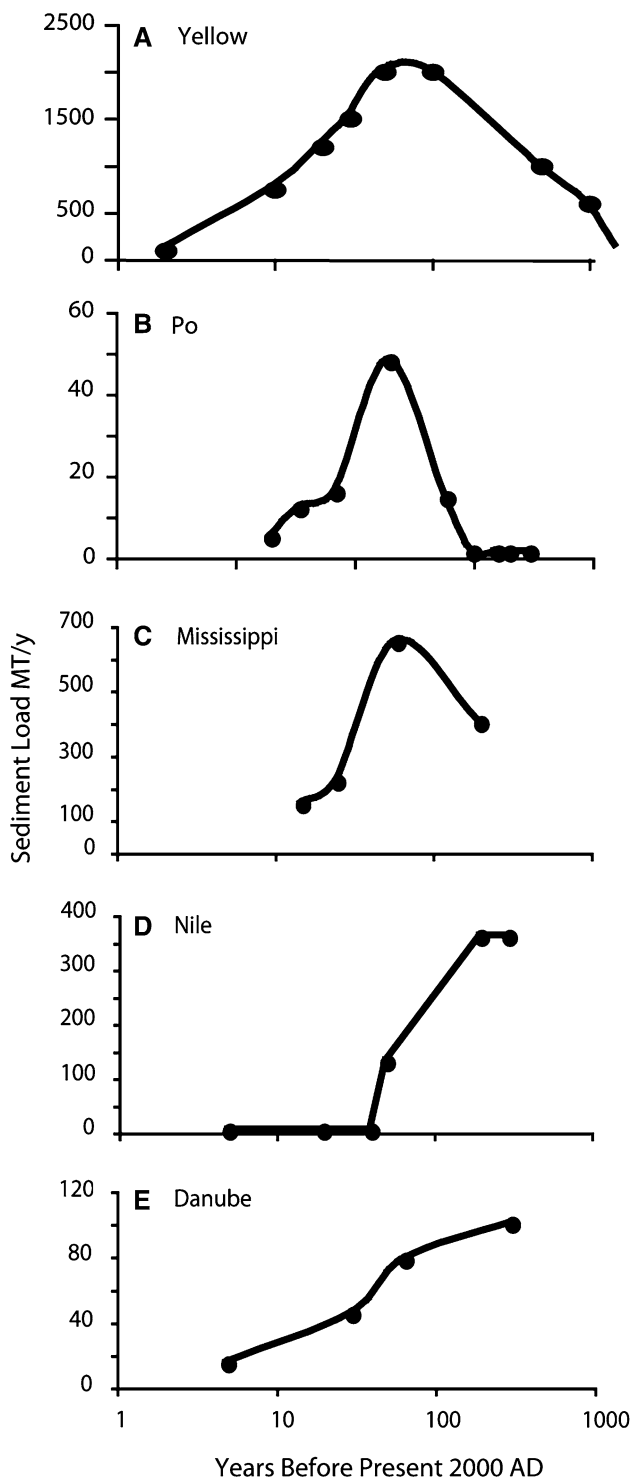
Fig. 6 Change in the sediment load (MT/year) delivered to the deltas of five rivers over a period of 1,000 years. **a** Yellow River (data from Wang et al. 2007), **b** Po River (data from Syvitski and Kettner in press), **c** Mississippi River (data from Meade 1986; Walling and Fang 2003; Syvitski and Saito 2007), **d** Nile River (data from Milliman and Syvitski 1992; Syvitski et al. 2005c), and **e** Danube River (data from Walling and Fang 2003; Syvitski et al. 2005c). Note: the time before present (BP) is plotted on a log scale to allow for the rapid change in the twentieth century to be expanded

≈0.1 BT/year, largely related to interception of the sediment load by upstream dams and reduction in water discharge to the delta (Fig. 6a: Wang et al. 2007). The Po River underwent a similar cycle in the history of its sediment load (Fig. 6b: Syvitski and Kettner in press). The Mississippi sediment load likewise increased due to human activity; however, the 45,000 reservoirs in the Mississippi River basin have since reduced the load below pristine conditions (Fig. 6c: Meade 1986; Walling and Fang 2003; Syvitski and Saito 2007).

Longer-term fluctuations in a river's load may certainly be influenced by climate variability and other drainage-basin changes (see Kettner and Syvitski 2008). However, for many of the world's rivers, their historical sediment load has been changing in one direction—reduction due to sediment impoundment behind dams (Fig. 6d, e: Syvitski et al. 2005b; Vorosmarty et al. 2003). A reservoir's trapping efficiency may range from extreme (e.g., Nile, Fig. 6d, Milliman and Syvitski 1992; Syvitski et al. 2005b), to large (e.g., Danube, Fig. 6e, Walling and Fang 2003; Syvitski et al. 2005c), to continually reducing as newer dams are brought on line (e.g., Yangtze, Yang et al. 2006; Mekong, Saito et al. 2007). Dams along the Colorado, Nile, Indus, and Yellow rivers have effectively stopped sediment discharge, whereas previously, these four rivers alone accounted for 10% (1.5 BT/year) of sediment flux to the global ocean (Syvitski and Milliman 2007).

River-delta systems where the sediment load is increasing include, for example: (1) the Kolyma, in Siberia, attributed to mining activities (Bobrovitskaya et al. 2003) and (2) the Magdalena in the tropics, where the increase in flux is attributed to a combination of deforestation, agricultural practices including poor soil conservation and mining practices, and increasing rates of urbanization (Restrepo and Syvitski 2006). For these systems, the soil erosion increase has not been accompanied with damming of the various river branches.

Sediment routing across deltas

Humans commonly control the number of functioning distributary channels and the movement (avulsion) of these distributary channels. Without flood controls, the seasonal flood wave will overbank its levees every few years, providing a nutrient-enriched layer of sediment to the delta surface. The Nile delta provides a classic example on how through the nineteenth century (and before) river distributary channels naturally irrigated the delta surface. Figure 7a shows the geolocation of the numerous distributary channels across the Nile delta from four higher-resolution cartographic surveys. The channel locations

Fig. 7 a Superimposed on space shuttle radar altimetry (Shuttle Radar Topography Mission) of the Nile delta, Egypt, are geolocated distributary channels mapped out before the Aswan Dam was built and the seasonal flood wave existed. Colored distributary channels are from the following cartographers: (1) *pink* for Pinkerton 1813, with a registration error of ±3 km; (2) *red* for Lizars 1831, with a registration error of ±2.6 km; (3) *brown* for Rand McNally 1897, with a registration error of ±1.5 km; and (4) *black* for Bartholomew 1922, with a registration error of ±1.6 km. **b** Moderate Resolution Imaging Spectroradiometer near-infrared image of the Nile showing the post-Aswan Dam situation of only two functioning distributary channels and many smaller engineered canals. **c** Landsat Enhanced Thematic Mapper Plus image of the Damietta promontory showing the impact of postdam sediment reduction of the Nile and coastal erosion
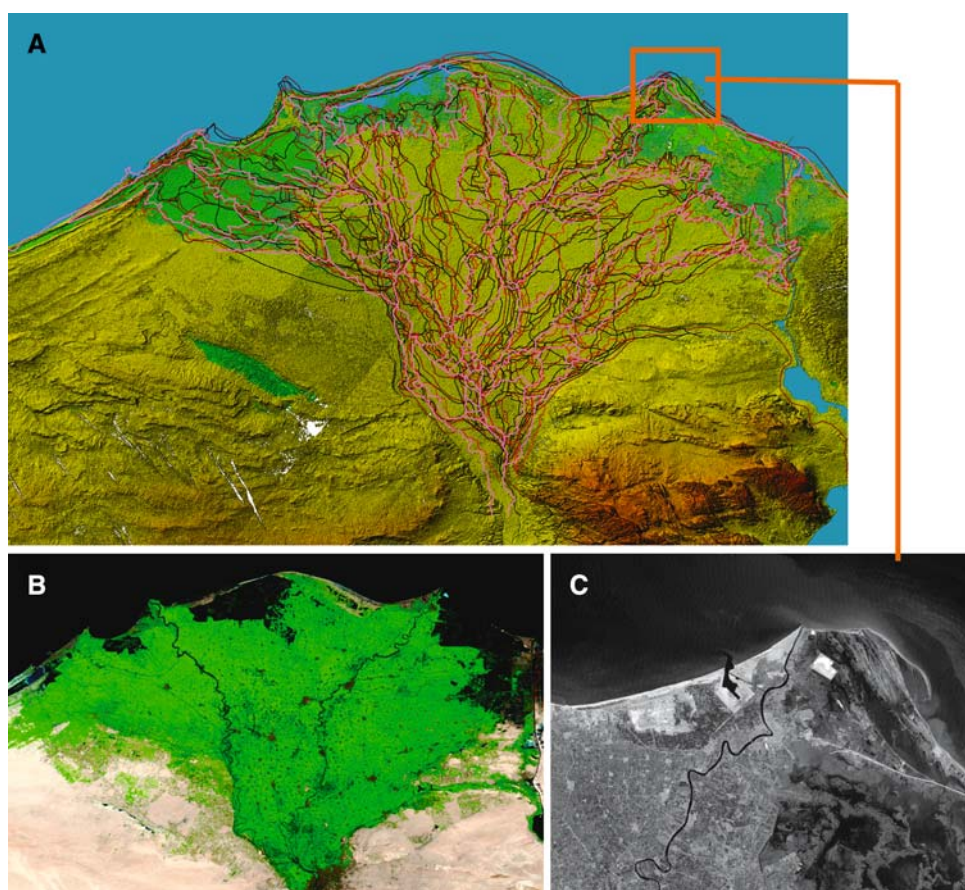
have a geolocation error of between 1.5 and 3 km, being less accurate in the earliest 1813 Pinkerton survey. In all cases, the distributary channels were numerous (≈16), and between-year surveys suggest the channels were mobile (Fig. 7a). However, the seasonal flood waves often caused infrastructure damage and loss of life and were an important justification for building the original dams (Syvitski et al. 2005b). After the Aswan Dam was constructed, the seasonal flood wave disappeared and the number of functioning distributary channels dropped to two (as seen in the near-infrared Moderate Resolution Imaging Spectroradiometer (MODIS) image, Fig. 7b). River barrages and diversions redirect river water across the delta along canals (Syvitski and Saito 2007). However, the method is largely ineffective for providing sediment to the delta surface given the river's greatly reduced sediment concentration (Syvitski and Saito 2007).

For many inhabited deltas, the number of distributary channels has fallen dramatically: e.g., Ganges, Magdalena, Indus, Mahanadi, Mississippi, Po, Nile, Rhone, and Vistula (Syvitski and Saito 2007). The few active distributary channels often have their natural levees stabilized with riprap (armored shoreline). A stabilized channel allows for a perceived sense of safety of the riverside towns and cities. They also allow for seagoing ships to supply these

centers of trade and commerce. Often, to maintain flow depth for this river traffic, water discharge along secondary distributary channels is reduced or cut off.

Taken together, channel stabilization and flood-wave mitigation do not allow sediment to be dispersed across the subsiding delta. The Yellow River, for example, once trapped 82% of the annual load delivered to the delta plain (Syvitski et al. 2005b). With greatly reduced discharge, the little sediment that is still delivered to the delta is now funneled to its main river mouth with little trapping (Syvitski and Saito 2007). The five Po distributary channels still trap ≈16% of the sediment delivered to the delta, but the sedimentation occurs within the distributary channels themselves and not on the surrounding flood plains (Syvitski et al. 2005a). As a consequence, the distributary channels are becoming superelevated in relation to the flood-plain surfaces, which are now partly below sea level, protected from the ocean and storm surges by coastal protection walls (Syvitski et al. 2005a).

Consequences

The consequence of delta subsidence, both natural and accelerated, in combination with discharge control,

sediment-load reduction, and channel stabilization, is to accelerate shoreline erosion, threaten the health and extent of mangrove swamps and wetlands, increase salinization of cultivated land, and put human populations at risk (Syvitski et al. 2005b). Between 1800 and 1900, the main river mouths of the Nile—the Rosetta and Damietta promontories—prograded seaward by 3.6 and 3.0 km, respectively (McManus 2002). Today, the entire Nile coastline is retreating landward (Fig. 7c), infilling the many small harbors (McManus 2002). The same is true for the Indus, the Ebro, and the Rhone (Jimenez and Sanchez-Arcilla 1997; Syvitski et al. 2005b). The Yellow River delta, which was growing at a rate of 20–25 km^2/year, now suffers from a net loss of land to the ocean (Saito et al. 2007). Whereas eustatic sea level associated with global warming has received much focus and interest (Bindoff et al. 2007), large-scale engineering projects (dam building, petroleum and groundwater mining, distributary-channel stabilization, water-diversion schemes) can have even greater consequences to the world's deltaic coastal regions. Under a subsistance scenario, the fragile infrastructure of most deltas becomes less resilient to rare events such as tsunamis and hurricane-induced coastal surges. Lives and wetlands at risk today will be even more at risk in the future.

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