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Sedimentation and Survival of the Mekong Delta

A Case Study of Decreased Sediment Supply and Accelerating Rates of Relative Sea Level Rise

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ABSTRACT. The Mekong Delta, early in the twenty-first century, is at a tipping point for sustainability. The delta is threatened by the implications of (1) damming and land-use changes in the drainage basin, (2) a burgeoning delta population in a nation (Vietnam) undergoing rapid development, (3) accelerating rates of rising sea level, and (4) an uncertain future climate that may impact tropical cyclone frequency and monsoonal precipitation patterns in the basin. These threats are present in other great rivers that emerge from the Himalayas. Two primary threats are examined in light of recent joint Vietnam-US studies in the largest distributary (Song Hau) of the Mekong River, in the shore-fringing mangroves, and on the adjacent subaqueous delta. We consider the implications of declining sediment loads from the catchment (as well as modification of the annual hydrograph) and flooding and salinity intrusion associated with relative sea level rise (eustatic + subsidence). This 2014–2015 study shows the interconnectivity in fluvial sediment supply to these parts of the delta: declining sediment loads and rising sea levels will likely impact distributary channel morphology and will alter estuarine circulation and sediment-trapping efficiency, all of which have feedbacks on sediment provision to the mangrove forests and the shelf.

THE IMPORTANCE OF HIMALAYAN RIVERS

Large rivers and their deltaic environments, home to millions of people, are under considerable threat from anthropogenic and natural processes. Eight of the 30 largest rivers on Earth in terms of water discharge, including the Mekong River, originate on the Himalayan Plateau at elevations >4,200 m (Table 1). While together they drain only 4.6% of the land surface area on the planet (6.8 million km^2), these rivers have an inordinate impact on the transport and delivery of sediment to the world ocean. These eight rivers together carry 3,360 million metric tons (MT) or 55% of sediment—more than the other 22 rivers in the top 30 combined—reflecting high seasonal precipitation associated with the monsoonal climate and a young, tectonically active terrain where they originate. The numbers reported in Table 1 summarize sediment discharges from the 1980s and early 1990s, numbers that are changing rapidly in these Himalayan river basins in the early twenty-first century in response to (1) human activities in the catchment, and potentially to (2) a changing global climate. The nine nations (including Tibet within China) through which these rivers flow were home to 45% (3.14 billion) of the world's people in 2011 (UNDP, 2015). Together, these nations, all classified as less developed by the United Nations, had a population growth rate in 2010–2015 that was more than 2.5 times that of the more developed world (1.07% versus 0.4%) and a much greater rural (non-urban) population than that in the developed world (68% versus 25%) (UNDP, 2015).

It is well documented in recent synthesis studies (Bianchi and Allison, 2009; Vörösmarty et al., 2009; Day et al., 2016) that rapid development in river drainage basins worldwide creates enormous perturbations to the passage of water, sediment, and dissolved ions to their deltas and adjacent coastal oceans. The most significant drivers of this development are construction of river dams for hydropower, water storage, diversion, and improved river navigation (Figure 1), and conversion of natural habitat (e.g., deforestation) for agriculture, aquaculture, and expanding urban footprints (Figure 2). With respect to water delivery from the catchment to the delta and river-ocean interface, deforestation and urbanization tend to reduce the catchment retention times of precipitation runoff, while damming increases water retention (Vörösmarty and Sahagian, 2000). By controlling releases to limit catastrophic flooding downstream and to maintain low-discharge channel navigability, damming tends to increase retention

TABLE 1. Characteristics of major Himalayan river systems. Data on water and sediment discharges are from Milliman and Meade (1983) and Meade (1996).

River	Water Discharge (10^6 m^3 yr^{-1}; global rank)	Sediment Discharge (10^6 tons yr^{-1})	Drainage Basin Area (10^6 km^2)	Maximum Catchment Elevation (m)	Nations in Catchment
Mekong	470 (9)	160	0.79	5,220	China, Myanmar, Thailand, Lao PDR, Cambodia, Vietnam
Ganges-Brahmaputra	970 (4)	1,050	1.48	3,890 (G) 5,210 (Br)	China (including Tibet), India, Bangladesh
Changjiang (Yangtze)	900 (5)	480	1.94	5,040	China
Ayeyarwady (Irrawaddy)	430 (12)	260	0.43	4,430	Myanmar, China, India
Thanlwin (Salween)	300 (17)	100	0.28	5,350	China, Myanmar, Thailand
Indus	240 (20)	50	0.97	4,260	China, India, Pakistan
Huang He (Yellow)	49 (30)	1,100	0.77	4,800	China
Honghe (Red)	120 (26)	160	0.12	5,830	China, Vietnam

duration as well as decrease water discharge extremes. Land-use change tends to increase sediment loads by accelerating soil erodibility, while damming serves as a sediment trap (Syvitski et al., 2005). Dissolved ion fluxes, in addition to being controlled by water discharge perturbations, are also impacted by point-source introduction of nutrients and pollutants resulting from use of agricultural fertilizers, pesticides, and herbicides, and from industrial byproducts released into the river. The potentially deleterious impacts of these flux changes to river deltas, adjacent shorelines, and their nearby coastal oceans are particularly contentious in multinational drainage basins: five of the eight large Himalayan rivers flow through more than one nation's boundaries (Table 1). Most notably, the Mekong River flows through six nations, creating potential political barriers to managed and wise development at the nexus of food, water, and energy.

The human footprint on the planet is accelerating in the early twenty-first century (Meybeck and Vörösmarty, 2005). Alterations to river drainage basins, as well as a changing global climate, may impact catchment water and sediment flux by modifying precipitation patterns and evapotranspiration rates associated with continental warming. These effects will be compounded by stressors originating in the deltas of these Himalayan rivers and others worldwide.

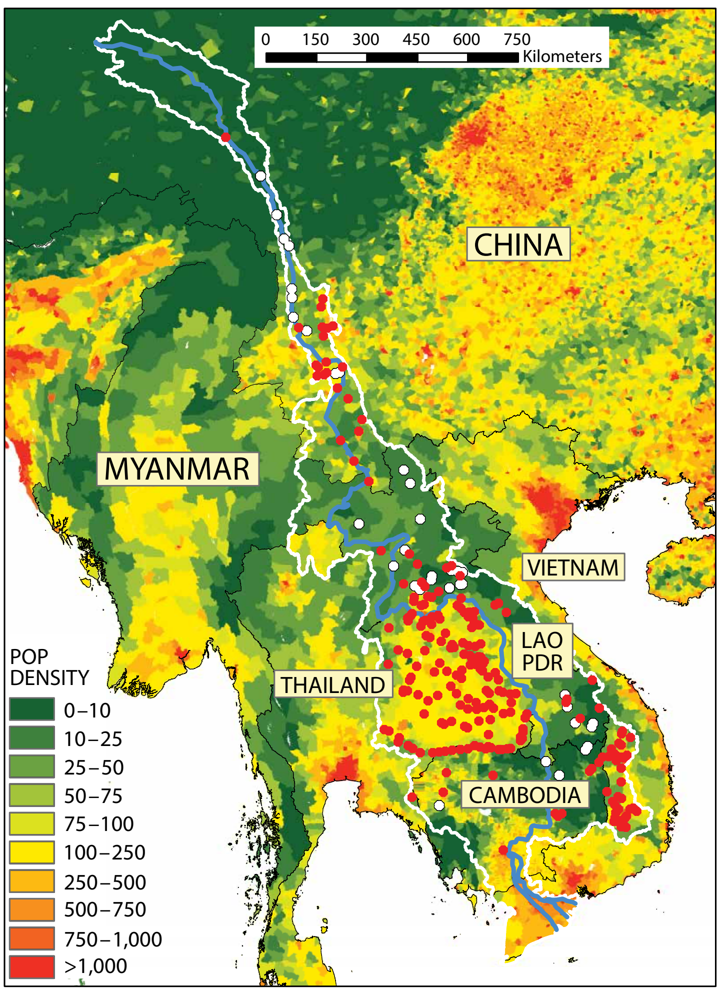

FIGURE 1. Map of the Mekong River drainage basin (solid white line) and main trend of the river (blue line) and the six nations through which it passes. The map plots 2015 population density from census data in the region (CIESIN, 2016) and locates all dams either commissioned (white circles) as of April 2016 or under construction (red circles) in the Mekong catchment (WLE-Greater Mekong, 2016).

STATUS OF THE MEKONG DELTA IN THE EARLY TWENTY-FIRST CENTURY

The great deltas associated with the major Himalayan rivers were a cradle for early humans attracted by rich native fisheries and enormous agricultural potential, as well as easy maritime linkage with other emerging cities and cultures in the Indo-Pacific region (Bianchi, 2016). This trio of activities was joined in the twentieth century both by the emergence of large-scale aquaculture of estuarine species on the saline lower delta plain and freshwater species farther inland, and by hydrocarbon exploration of the thick sedimentary sections that underlie the modern delta plain and adjacent continental shelf.

Each of these human activities has impacted the Himalayan deltas, and their impacts on the natural systems are increasing at a rapid pace associated with burgeoning populations and nation-scale development pressure. The Mekong Delta is an illustrative case study of these phenomena. The population of the Vietnamese section of the delta plain, which forms much of the lowest elevation section (Figure 3), rose from 15.5 to 17.6 million persons between 1995 and 2015 as measured by the General Statistics Office of Vietnam (GSOV, 2017). This growth equates to a delta-wide population density of 434 people per square kilometer in 2015, well above the rapid population growth rate of Vietnam as a whole (which increased from 110 to 296 persons per square kilometer between 1961 and 2015; FAO, 2015). Rapid urbanization is also predicted for the Mekong Delta region by 2030 (Figure 3). An example of the population's commercial activities is the rise in waterborne transport of goods in the Mekong's distributary channels and river-fed canal network. This transport rose from 17.9 MT to 73.6 MT between 2000 and 2014 (GSOV, 2017).

Although heavily utilized for agriculture dating back centuries (Figure 2), total agricultural land in the delta was still rising between 2009 and 2014 from

2,550 million hectares to 2,610 million hectares: this was mirrored by a reduction in forest cover to only 5.9% by 2014 (GSOV, 2017). In 2014, the largest agricultural components were almost equally balanced between cereal crops (4,280 thousand hectares) and rice paddies (4,250 thousand hectares) (GSOV, 2017). Aquaculture is also rising rapidly in the delta, with the total area set aside increasing from 289 thousand hectares to 759 thousand hectares between 1995 and 2014 (GSOV, 2017). Fish-farming production (2.5 times the volume of shrimp farming) rose by 1,480% in the same years (shrimp-farming production rose by 1,050%).

At the delta's ocean interface, mangrove acreage was in a long-term decline due to land use conversion and use of forest resources for fuel. A United Nations Food and Agricultural Organization report (FAO, 2015) indicates that mangrove acreage declined from an estimated 306 thousand hectares in 1943 to 253 thousand hectares by 1982, partially impacted by use of defoliants in the Indochina War of the 1960s and 1970s. Mangrove extent reached a minimum by 1999 (157 thousand hectares) before rebounding to 270 thousand hectares by 2015, due to replanting efforts by the Vietnamese government. There is also increasing fishing pressure in the coastal fishery adjacent to the delta. GSOV (2017) documents sea-fish production in the delta as increasing from 313 thousand tons to 736 thousand tons between 1995 and 2014. Oil and gas activities are also rising for the offshore Mekong in leased blocks that are undergoing seismic exploration, and in some cases initial drilling, by the Vietnam National Oil and Gas Group (PetroVietnam) and international partners. In April 2016, PetroVietnam and investors from Japan and Thailand broke ground on a $US 6.8 billion offshore gas field that is anticipated to produce 5 billion cubic meters of gas from 46 drilling platforms and 750 wells by 2020. An associated $US 1.2 billion, 400 km pipeline (including 290 km offshore) will supply gas to Kien Giang Province and the city of Can Tho. Hydrocarbon exploration in formations beneath the delta plain is ongoing in the Khorat Basin (Permo-Triassic fill) and Cuu Long Basin (Oligo-Miocene fill), both formed by rifting episodes in the Permian and early Oligocene.

With fast-evolving land use and damming in the Mekong catchment, and with increased stressors on the natural system in the Mekong Delta associated with population and development pressures, what are the key risks to the delta in the twenty-first century? How do global climate change effects, which may impact monsoonal precipitation, raise eustatic sea levels, and change the paths of tropical cyclones in the region, come into play with these regional stressors? The Mekong Tropical Delta Study of the distributary channels, coastal mangrove forests, and continental shelf deposits in 2014–2015 provides much new information about how these natural systems function, and hence, how they may be responding, or will likely respond, in the future to anthropogenic alterations. Given the study's focus on water and sediment-transport dynamics in the distributary channels, their interaction at the seaward boundary with shelf dynamics and subaqueous delta evolution, and their exchange through mangrove fringes, two issues will be the focus for the remainder of this paper. The first objective is to examine how the Mekong Delta would likely respond in the near future to alterations in the timing and magnitude of water and sediment flux from the catchment. The second objective is to outline a likely scenario of future delta response to rising relative sea levels that result from a combination of eustatic mechanisms and land subsidence of the delta plain. A final objective will be to suggest future research needs and adaptation strategies based on the premise that, in the long run, delta restoration is more expensive than preservation.

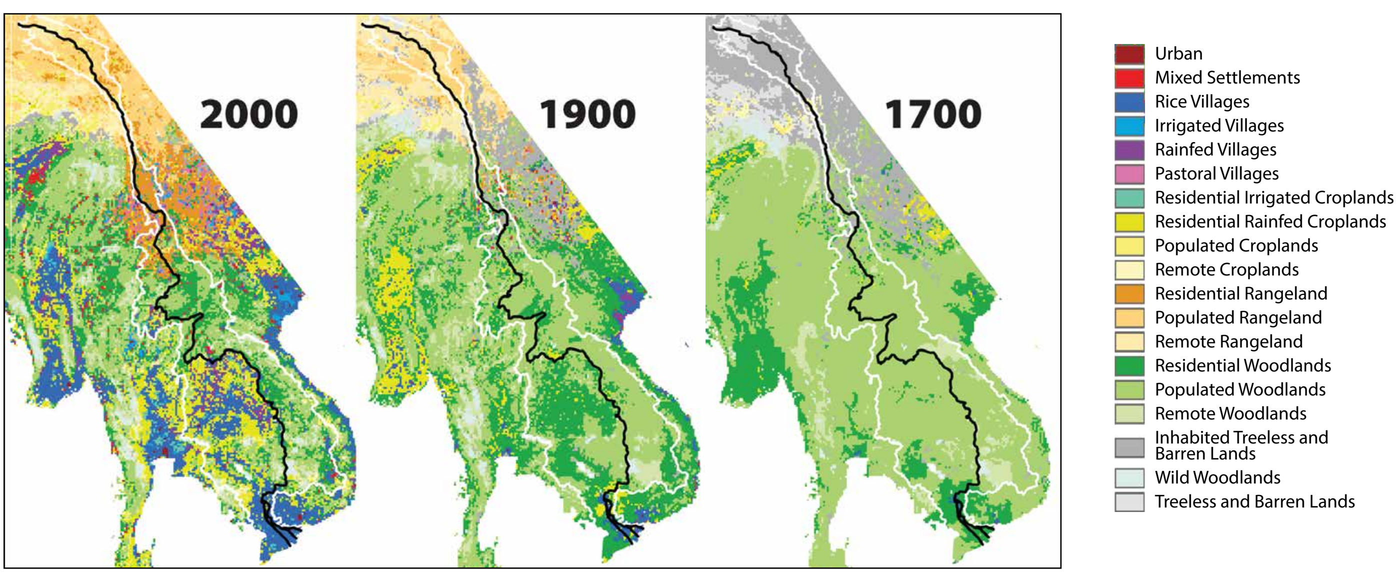

FIGURE 2. Land-use maps for the Mekong Basin (white line) in the years 1700, 1900, and 2000. *From Ellis et al. (2013a, 2013b, 2013c)*

POTENTIAL ALTERATIONS TO RIVER WATERS AND SEDIMENT FLUX

The concept of source-to-sink linkage is well known in the fluvio-deltaic scientific community: actions in the drainage basin impact the river channel and floodplain farther downstream, and, ultimately impact the delta, including its subaqueous component, where the majority of new sediment delivery is sequestered. Hence, damming and land-use change in the rapidly developing Mekong drainage basin potentially may cause major deleterious changes to the delta region that was the focus of the 2014–2015 study. Additional alterations might be caused by global-climate-induced changes in basin precipitation patterns and rising sea levels (see next section). At this key time in the history of the Mekong basin, we can ask two questions. First, are changes in the supply of water and sediment from the Mekong River to the basin already evident, and, if so, do the results of the 2014–2015 effort show them? Second, given the results and the knowledge of how other deltas responded to alterations in riverine water and sediment supply that took place a half century or more ago (e.g., Mississippi, Nile, Rhine, Ebro, Colorado, Huang He), can we predict a future impact for the Mekong Delta?

Major dam construction began in the Mekong basin with construction of China's Manwan Reservoir in 1993; by April 2016, 35 dams had been commissioned for hydropower of >15 megawatts, for irrigation reservoirs (>0.5 km^2), for water supply, or for mixed purposes (Figure 1; WLE-Lower Mekong, 2016). A further 226 dams are under construction with even more planned (WLE-Lower Mekong, 2016). Pre-damming best estimates of suspended sediment load delivered to the delta are about 160 MT (Milliman and Syvitski, 1992). Wang et al. (2011) recognize a steady increase in suspended sediment load in records from the upper Mekong to the Manwan Reservoir, where a sharp decrease in load is observed post dam. However, they acknowledge that station data sets from the lower Mekong are of too limited spatial and temporal resolution to determine how much of the natural sediment supply reached the delta versus what was stored on floodplains of the middle Mekong. Kummu et al. (2010) and Kondolf et al. (2014) estimated 15%–18% of the annual suspended sediment load is already being trapped behind dams in the catchment. Nowacki et al. (2015) utilized measurements of the Song Hau distributary in the 2012–2013 water year and flow partitioning with the other distributaries (from A. Nguyen et al., 2008) to suggest total suspended loads may be as low as 40 MT yr^{-1}. The 2014–2015 study calculated a total sand export from the delta at about 6.5 MT yr^{-1}, and McLachlan et al. and Stephens et al. (both in press) estimate sand to represent 5%–20% of total suspended sediment transport; these studies also suggest sediment supply to the delta may already be declining. Given the rapid pace of dam construction in the Mekong basin, and the balancing effects of land use changes (e.g., deforestation) that may have increased Mekong tributary sediment inputs to the main stem, it is difficult to quantify the degree that sediment (and water) discharge has been affected. This difficulty is compounded by limited monitoring at discharge stations in the lower Mekong Basin compared to other global rivers, as well as natural interannual variability in runoff rates that make access to multiyear records necessary in order to define a baseline trend in river water and sediment discharge.

Changing global climate may also affect the future water and sediment supply to the Mekong Delta. A study by Darby et al. (2016) used river monitoring station data reinterpretation combined with hydrological modeling to estimate

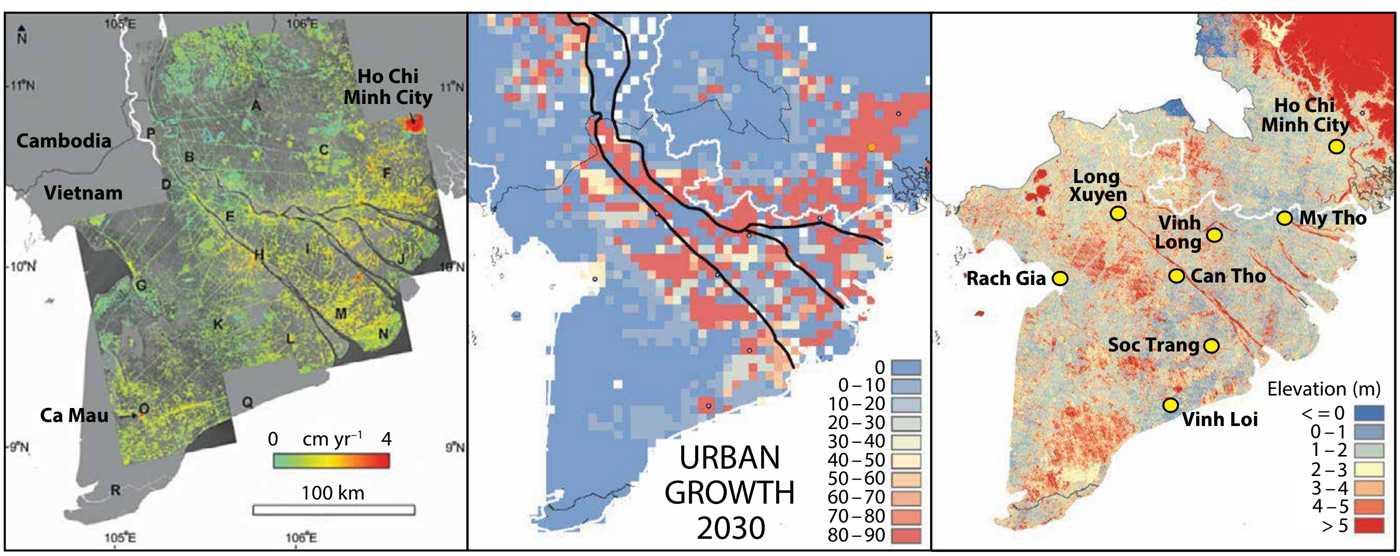

FIGURE 3. Maps of the Mekong Delta in Vietnam and Cambodia. (left) Map of annually averaged (2006–2010) InSAR-based line-of-sight land subsidence rates (Erban et al., 2014). (middle) Map shows the probability of an area becoming urban by the year 2030 (grid cell values 0 to 90) from Seto et al. (2015). (right) A 30 m digital elevation model of the Vietnam portion of the Mekong Delta locates major cities in the region.

that 32% of the suspended sediment load reaching the delta is associated with rainfall from tropical cyclones. While climate modeling suggests the number and intensity of tropical cyclones reaching the East Sea (also known as the South China Sea) are likely to increase due to future anthropogenic climate change, track locations are likely to shift away from the latitude of the Mekong Basin (Redmond et al., 2015). Darby et al. (2016) suggest this change has already begun, and they calculate sediment loads between 1981 and 2005 declined by approximately 53 MT, of which 33 MT were ascribed to a shift in tropical cyclone climatology. Other regional to global climate patterns may also be expected to impact precipitation, and hence runoff, in the Mekong Basin. Due to the two distinct monsoon seasons—a rainy southwest monsoon and a dry northeast monsoon, the period of June to November accounts for nearly 80% of the yearly Mekong River discharge (Gupta and Liew, 2007). Possible links between monsoon and the El Niño-Southern Oscillation (ENSO) in the western Pacific led Xue et al. (2011) to suggest there may be a strengthened ENSO-runoff relationship (6.6-year periodicity) in the post-dam period.

While it is not possible to predict at present the impact of all commissioned and planned Mekong damming on water and sediment loads, we can say that modeling scenarios developed by Kondolf et al. (2014) predict a cumulative sediment reduction in the Mekong ranging from 51% (resulting from all dams built or under construction as of 2013) to 96% (resulting from full build-out of all dams planned as of 2013). We know from studies of other altered large-river source-to-sink systems that the magnitude of sediment reductions associated with basin alteration and their effects on associated deltas has been profound. For example, in the Mississippi basin, major dams constructed in the 1940s and 1950s on the Missouri and Arkansas tributaries resulted in ~50%–70% reduction compared to pre-development loads in the river (Meade and Moody, 2010); in an extreme example, as much as 99% of the sediment that previously reached the Nile Delta is now sequestered behind the Aswan Dam and downstream barrages (Stanley and Warne, 1993). The degree to which regulated storage and release of water from reservoirs affect the magnitude and timing of water supply to a delta is different in each system, depending on climate (which impacts degree and timing of storage), drainage-basin size and relief (which impact timing of tributary precipitation), and water usage (e.g., hydropower, irrigation). However, several recent Mekong studies suggest that, in addition to reducing sediment loads, dams will decrease maximum (flood) flows, increase minimum annual flows (Kummu and Varis, 2007; Xue et al., 2011; Lauri et al., 2012), and increase discharge fluctuations during the dry season (Lu and Siew, 2006).

Studies of other deltas subject to a reduction in sediment load show that the system responds by erosion of the river channel bed, the banks, and the delta shoreline. In the 2014–2015 study of the Song Hau distributary below Can Tho, Allison et al. (in press) found that the river's channel floor was relatively sediment starved, exhibiting thin, modern sand sheets (~19% of the total channel area) interspersed with large areas (~80%) of relict substratum composed of older fluvio-deltaic sedimentary units likely deposited with the progradation of the delta seaward in the last 3,500 years and incised by the channel. At low discharge during the northeast monsoon in February to March 2015, Allison et al. (in press) found that the estuarine section of the channel floor (Figure 4) was mantled by modern, soft mud layers

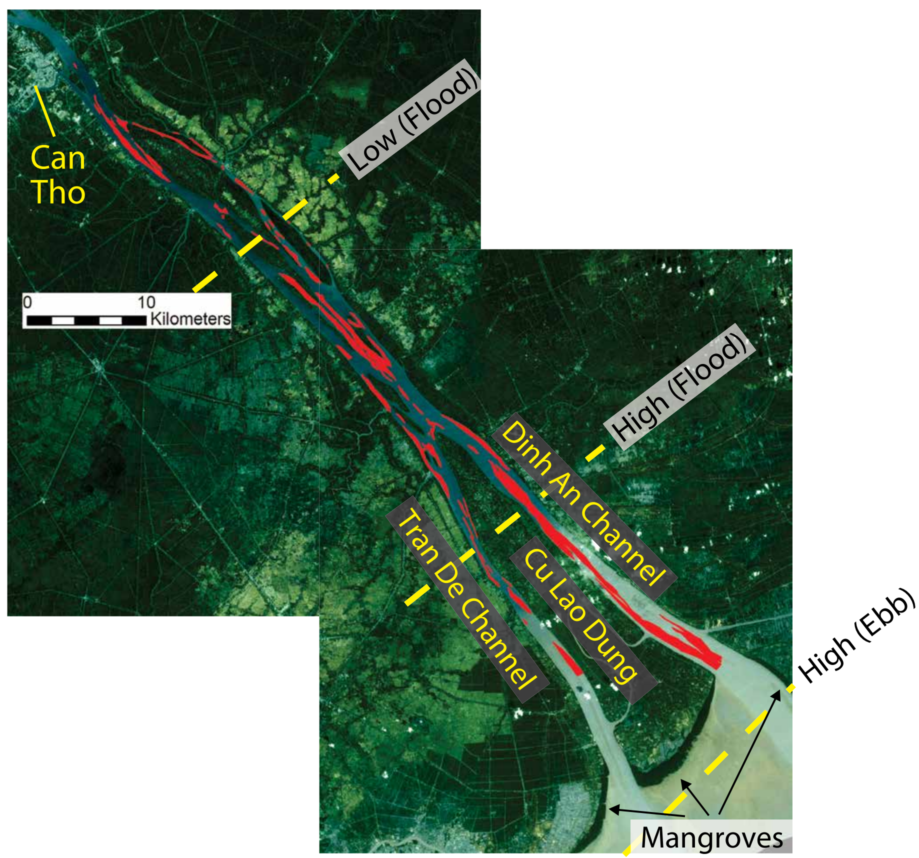

FIGURE 4. Map of the Song Hau distributary channel of the Mekong River below Can Tho, Vietnam. Modern sand extent on the bed is shown in red (from Allison et al., in press). Approximate estuarine limits at high discharge (flood tide) and low discharge (ebb and flood tide) are shown for the period 2012–2015 (from Nowacki et al., 2015; McLachlan et al., in press). At high discharge, much of the channel floor is composed of exposed relict units, while at low discharge, the zone downstream of the estuarine flood limit is partly mantled by soft muds trapped by estuarine circulation.

0.25–1 m thick that likely are a result of stratification-induced estuarine trapping (Nowacki et al., 2015; McLachlan et al., in press). These fines are removed during the subsequent high-discharge period to the adjacent subaqueous delta. Hence, it could be anticipated that a future reduction in sediment supply might have a limited impact on the channel floor and the banks, as the system is already not in an aggradational state other than ephemeral, seasonal deposition.

The estuarine regime is expected to change with respect to the key parameters of river discharge and estuarine circulation (Figure 5) as damming decreases river discharge, and conditions will be more conducive to salt-wedge formation in the distributaries. The location of ephemeral seasonal mud deposition will also change. Less sediment arriving from the catchment will be balanced against more efficient trapping (due to increased stratification), and most sediment trapped at the lower discharge rate will come from the inner shelf (Eidam et al., in press; McLachlan et al., in press). Together, these factors will determine the size of the fine sediment reservoir stored in the lowermost distributary channels of the Mekong River at lower discharges.

Though damming favors the trapping of larger particles of sand, studies of systems like the Mississippi show that, while suspended fine sediments reaching the delta drop by more than half, suspended sand loads remain stable (Biedenharn et al., 2000). This is ascribed to the presence of a local bottom source for sand that is resuspended during high-energy flood events (Ramirez and Allison, 2013) rather than to primary sourcing from the catchment. In the 2014–2015 Mekong study, Stephens et al. (in press) and Allison et al. (in press) demonstrate a strong connection between presence of a local bottom source for sand and suspended sand concentration. Significant sand in suspension is confined to high-energy tidal periods in the high-discharge phase of the river: estuarine mud deposition during the lower discharge phase mantles the bottom sand source, even though tidal energies remain sufficient for sand resuspension. Although sand trapping behind dams can be anticipated, it may take years to decades for sand-sized particles entrained below the dam to travel thousands of kilometers from the upper Mekong to the delta. Thus, it will take considerable time before sand supply to the delta will decline. Complicating the picture, channel-bed incision with longitudinal profile adjustment below the dams may erode sand from underlying strata and inject it into the modern transport system. Any decline in sand supply may be deleterious to the large channel-sand mining industry that operates in the distributary channels of the Mekong Delta: this sand mining may also be reducing sand supply to the ocean interface (Bravard et al., 2013; Brunier et al., 2014; Allison et al., in press).

The estuarine regime shift and the size of the fine-sediment reservoir trapped in the lowermost river channel at low discharge impacts the release of fine-grained sediment to the coastal zone in the East Sea where mangrove shorelines and the subaqueous delta are located. For example, Fricke et al. (in press) show links between the more physically mixed river waters in the Tran De sub-distributary and the delivery of sediment to the mangrove forests and enhanced progradation on the southwest end of the island of Cu Lao Dung. In contrast, more stratified channel waters in the Dinh An sub-distributary and less-turbid waters bathing the northeast mangrove fringe will likely result in lower sediment accumulation and reduced progradation of the mangrove edge. Changes in the location and size of the fine-sediment reservoir stored during the low-discharge period will change the sediments delivered to the mangrove forests and the shelf during

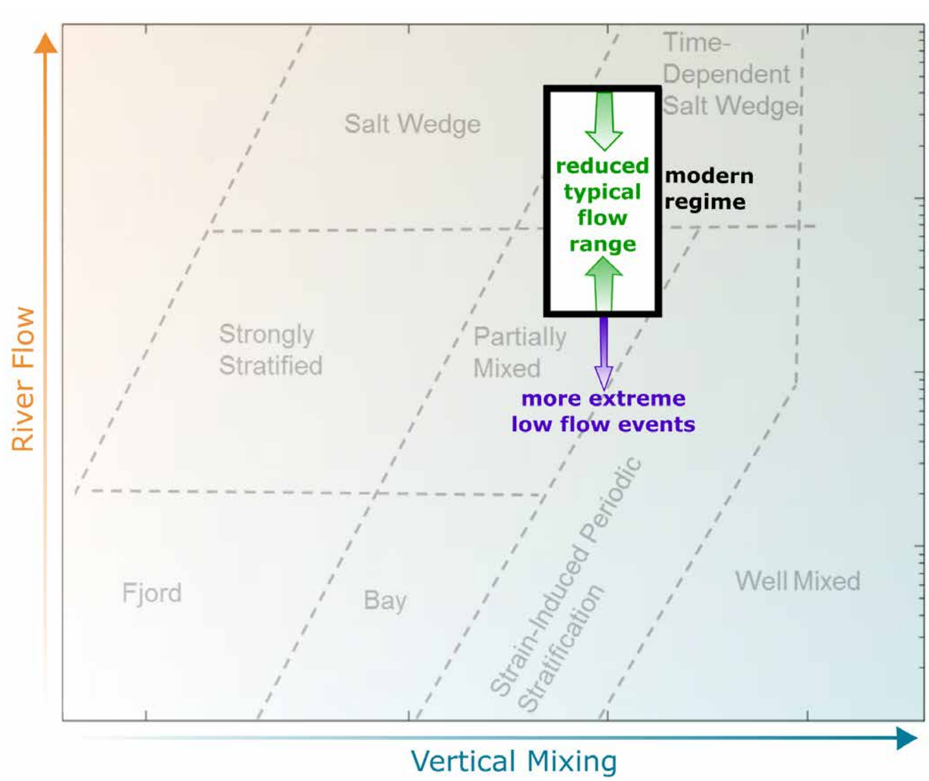

FIGURE 5. The lower Song Hau distributary studies of 2014 and 2015 mapped into estuarine parameter space based on river flow and vertical mixing (diagram modified from Geyer and MacCready, 2014; McLachlan et al., in press). Modern seasonal and tidal variations typically map the study region as a time-dependent salt wedge to partially mixed estuary (black box). Continued dam installation throughout the drainage basin will reduce the typical flow range (green arrows), while extreme low-discharge events are expected to become more common and sporadically shift the study region more toward a partially mixed estuary (purple arrow).

the following high-discharge period. Sediment arriving at the topset area of the subaqueous delta on the inner shelf is presently producing clinoform aggradation at rates of 1–3 cm yr^{-1} (DeMaster et al., in press; Eidam et al., in press). This rate is likely to diminish simply due to reduction in sediment supply from upstream, but in addition, the reworking and movement of muddy sediment from the shelf back toward the mangrove shoreline and into the distributaries as a result of wave resuspension and enhanced buoyancy-driven shelf circulation (Fricke et al., in press) may be reduced during the low-discharge period (Figure 6).

Rapid coastal erosion rates in deltas worldwide provide the most dramatic evidence of declining sediment inputs from their catchments (Coleman et al., 2008; Syvitski et al., 2009) as the marsh and mangrove wetlands along their shorelines become sediment starved. Destructive processes such as wave attack then reverse the aggradation and progradation characteristic during delta lobe growth. In Asian deltas where sediment reductions from damming are only in their early stages, this process is not yet prevalent (Shearman et al., 2013). At the distributary mouths of the Mekong Delta, Anthony et al. (2015) show net shoreline change is still progradation, at rates of 4–5 m yr^{-1} in the 2003–2012 period. Farther southwestward along the coast, down drift in the sediment dispersal system, shorelines have been eroding since at least 1973, predating dam-induced reductions in sediment flux (Besset et al., 2016). The authors attribute this loss in part to land-use change and the reduction in mangroves in the delta that date back several centuries (Figure 1). A complicating factor is the rise in eustatic and relative sea level in the Mekong Delta that is the focus of the next section. The possibility of future shoreline erosion associated with a combined decline in sediment delivery and increase in the rate of sea level rise has resulted in several studies that suggest strategies such as (1) non-structural adaptation of coastal populations (Boateng, 2012), (2) creation of barriers using natural materials (Albers and Schmitt, 2015), and (3) increased planting of mangroves on sea-facing shorelines (Phan et al., 2015).

The effectiveness of mangroves as sediment traps was demonstrated in the 2014–2015 studies of the Song Hau mouth (Mullarney et al., 2017, and Fagherazzi et al., 2017, both in this issue). It is difficult to predict how future reduced sediment supply, combined with sea level rise, will impact the Cu Lao Dung mangrove forest, as responses seen in other locations have been highly site specific (Lovelock et al., 2015). However, what is clear is that sites not following the overall global trend of mangrove retreat have ample sediment supply (e.g., Firth of Thames, New Zealand; Swales et al., 2015). Therefore, a reduction in Mekong sediment supply will likely slow down the rapid progradation observed on the southwest side of Cu Lao Dung (Nardin et al., 2016), while an extant dike on the landward side of the mangrove forest will prevent landward retreat (Winterwerp et al., 2005). Moreover, salinity change has been shown to alter mangrove root architecture and hence sediment trapping ability (Krauss et al., 2014). Therefore, changes in the upstream extent of salinity penetration owing to sea level rise could lead to mangrove distributions extending farther upstream.

If sediment supply is reduced due to less supply from upstream and/or more efficient sediment trapping in the distributary channels, this will affect the rapid rates of sediment accumulation on the inner shelf (>1 cm yr^{-1}; DeMaster et al., in press; Eidam et al., in press). However, the oceanic processes (surface waves, wind-driven currents, tidal currents) will remain active, or possibly intensify, with climate change (Nittrouer et al., 2017, in this issue). The shelf surface could become erosional, as observed for some areas today near the Ca Mau Peninsula (Liu et al., in press).

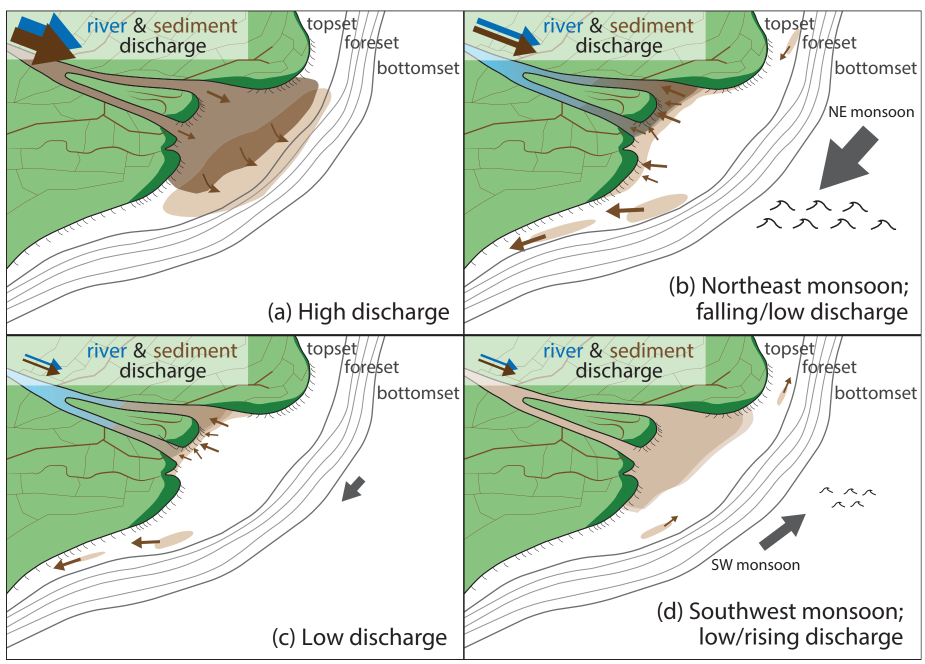

FIGURE 6. Conceptual diagrams of seasonal sediment transport patterns. (a) During peak river discharge, sediment bypasses the channels and mangroves and is delivered to the shelf. (b) Northeast monsoon winds promote landward and southwestward sediment transport on the shelf. Sediment is re-imported into the river channels (where it becomes trapped in the estuarine turbidity maximum) and is deposited in the coastal mangrove forests. (c) Some residual southwestward sediment transport on the shelf and delivery to the mangroves/channel likely occurs during the waning phase of the windy northeast monsoon. (d) During the southwest monsoon, rain drives increasing river discharge, and some sediment delivered to the shelf migrates northeastward.

THREAT OF RISING SEA LEVEL

Based on the 5th Assessment Report of the International Panel on Climate Change, global sea levels are projected to rise from a rate of about 3.2 mm yr^{-1} in 1993–2010 to as much as 10 mm yr^{-1} or more by 2100 (Church et al., 2013). This rate threatens future inundation for the Mekong Delta plain, which has an average elevation of less than 2 m (Figure 3). The problem is made more severe by coastal subsidence that is characteristic of many deltas: the thick, young sedimentary packages underlying delta plains are subject to subsidence by compaction and other mechanisms (Allison et al., 2016). In the Mekong Delta, this natural process has been compounded by groundwater extraction for domestic, agricultural, and industrial needs. Erban et al. (2014) used well data and inferograms from the ALOS PALASAR satellite (inferometric synthetic aperture radar, or InSAR) to measure total subsidence rates of 10–40 mm yr^{-1} active over large areas of the subaerial Mekong Delta (Figure 3). Together, eustatic sea level rise and anthropogenic-natural subsidence may subject the Mekong Delta to ~1 m of additional inundation hazard by 2050. Multiple recent studies examine the threat posed by this inundation to coastal populations and to agriculture-aquaculture from increased soil salinities (Wassman et al., 2004; Balica et al., 2013; Smajgl et al., 2015; T. Nguyen and Woodruffe, 2016). In this tidally dominated delta setting, inundation will interact in a complex manner with the timing and magnitude of river floods and tidal periodicities (Takagi et al., 2014).

Sea level rise issues are often compounded by sediment supply issues that could result in deeper effective channels within the Mekong River distributaries, and this would affect the extent of saline water intrusion into the distributary channels. At present, the 2012–2015 Song Hau studies suggest that saline water can intrude up to 40 km from the river mouth at low river discharge (Nowacki et al., 2015; McLachlan et al., in press). Numerical modeling studies in other Himalayan large rivers, such as the Changjiang (Qiu and Zhu, 2013), that face similar rates of relative sea level rise suggest that the intensity of saltwater intrusion and stratification both increase as sea level rises, with distinct partitioning of the effect between individual distributary channels.

Greater channel depths may result in reduced bed stress associated with estuarine processes that are located farther up the distributary channel, along with greater aggregation, decreased bed erosion, and enhanced mud deposition within the channels (e.g., Wolanski et al., 1996; Chernetsky et al., 2010). Alternately, sea level rise and increased channel depths may promote bed erosion due to the greater tidal prism accommodated along the tidal river (e.g., Canestrelli et al., 2010; Xing et al., in press). The net result from the combined effects of channel depth increases, tidal velocity changes, and the shifting of estuarine regimes is not as yet clear. However, increased efficiency for seasonal trapping of fine-grained sediment within the distributaries (even if the total load of fines from the catchment is decreased) seems likely, giving rise to less sediment available to the shorelines and prograding clinoform.

Although rising sea levels coupled with a reduction in sediment supply might intuitively lead to predictions of mangrove decline, in many cases mangroves act as "ecosystem engineers," promoting vertical accretion, thus allowing the forest to keep pace with sea level rise (Krauss et al., 2014). However, these processes of deposition or erosion exhibit strong ecogeomorphic feedbacks, and the precise thresholds beyond which mangrove forests become converted to open water, or conversely can accrete, are not known. In the case of sea level rise, a higher tidal prism can lead to longer inundation periods and greater deposition rates. The balance between deposition and erosion within mangrove forests also depends heavily on the local wave climate. A more energetic wave climate could potentially transport more sediment to the system; however, increased water depths also reduce wave energy dissipation and consequently promote sediment resuspension. Mangroves can also vertically accrete through incomplete decay of organic matter from belowground biomass production (Kirwan and Megonigal, 2013).

During Mekong low-discharge periods today, estuarine circulation and landward bottom flows are effective in bringing suspended shelf sediment into distributary channels where it is trapped in the estuarine turbidity maximum. Most of this sediment is resuspended and returned to the shelf during Mekong high-discharge periods. However, future locations of the turbidity maximum will be progressively farther upstream with rising sea level. If the high-discharge flow is modulated by dams, the return of this sediment to the coastal shelf system (including the mangrove shorelines) could be severely reduced or eliminated. In future times, the Mekong coastal environment could receive a net negative sediment flux from the river (i.e., sediment eroded from the shelf seabed and transferred into distributary channels).

RECOMMENDATIONS

If the goal for the future of the Mekong Delta is to maintain and even strengthen a natural ecosystem and, at the same time, maximize its utility to the people who make it a home, then strategic planning will have to navigate a web of stakeholder issues. Planning initiatives undertaken in similar settings, such as the Mississippi Delta (LACPRA, 2012), indicate that the result is often a compromise that balances on cost:benefit calculations. The benefits of decisions by managers and others must be calculated, or at least weighed, based on their impacts on the sustainability of ecosystems and delta communities, as well as their economic impacts on the region and the nation. Measures of economic impact can be a complex set of stakeholder issues surrounding (1) agriculture/aquaculture, (2) navigation, (3) fisheries, (4) forestry, (5) hydrocarbon production, (6) manufacturing, and (7) ecotourism.

Examination of these issues goes far beyond the scope of the present paper, but use of several clear strategies could help ensure Mekong Delta sustainability. We suggest the following:

1. More comprehensive fixed-station monitoring of water and sediment discharge through the lowland reach and deltaic plain of the Mekong is required to better monitor any reduction in sediment loads from the catchment and any modification to the annual hydrograph. These data will also be critical to refining numerical models that can predict the evolution of the distributary channels, the delta plain, and the coastal zone. These numerical models must be expanded delta-wide to examine the interactions of freshwater and sediment among the multiple distributary channels, intervening coastlines, and the subaqueous delta. Hydrogeomorphological modeling will also have to be coupled with ecosystem modeling (and improved monitoring of vegetation and fisheries) to anticipate how the delta's natural systems will reflect these changes.
2. Extremely deleterious effects have been observed in other deltaic systems where >50% of the sediment load has been intercepted by drainage basin dams. These include shoreline erosion, morphological modification in the distributary network, and harm to coastal ecosystems. Given the rapid pace of dam construction in the Mekong Basin, compounded by the inundation potential posed by rapid relative sea level rise, basin-wide management plans need to be developed to minimize sediment starvation (and annual hydrograph modifications). These strategies might include use of engineered sediment passage around dams. Within the delta, reducing channel sand mining would also be advantageous to maintaining the supply of coarse sediment to the river-ocean interface.
3. The sediment aggradation observed in mangrove forests in the 2014–2015 study at the mouth of the Song Hau distributary is at or above relative sea level rise rates. Given the likely future of rising sea levels and declining sediment at the distributary mounts, expanded use of mangrove plantations provides a means of minimizing future delta shoreline degradation by maximizing near-range sediment capture. This would have to be accompanied by measures to protect vulnerable new plantations that would aid substantially in expanding the width of coastal mangrove belts.
4. The acceleration of relative sea level rise in the delta engendered by water-withdrawal-induced subsidence (e.g., Erban et al., 2014) is one potentially harmful future effect that can be mitigated. This could be accomplished by improvements to agricultural practices and by reducing groundwater extraction.

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