ANTICIPATED GEOMORPHIC IMPACTS FROM MEKONG BASIN DAM CONSTRUCTION

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Abstract

The Mekong River is undergoing rapid dam construction. Seven mainstem dams are under construction in China and 133 proposed for the Lower Mekong River Basin (LMRB). We combined geomorphic assessments of the Mekong channel and delta with models of sediment trapping by reservoirs. We expect the biggest geomorphic changes to occur along alluvial reaches, though stripping of thin sediment deposits in bedrock reaches may also have significant consequences for benthic invertebrates, fishes, and other aquatic organisms dependent on the presence of alluvium in the channel. If all dams are built as proposed, the resulting 96% reduction in sediment supply would have profound consequences on productivity of the river and persistence of the Delta landform itself. Strategies to pass sediment past dams should be explored to reduce the magnitude of sediment starvation and resulting impacts.

Key Words: Mekong River, sediment load, reservoir sedimentation, channel change, dam construction

1 Introduction

The Mekong River basin is undergoing rapid and widespread dam construction (Grumbine and Xu, 2011). On its upper reaches in China (the Lancang), seven dams have been constructed or are under construction on the mainstem. In the Lower Mekong River Basin in Laos, Thailand, Cambodia, and Vietnam, another 38 tributary dams are considered certain to be built, with an additional 95 dams at some level of planning for tributaries and the mainstem. How will these dams alter the sediment load of the Mekong and how will the dams change the morphology of the downstream channel and delta? The Delta is currently home to 20 million people whose lives and economy are at risk from subsidence increased flood risk, and other changes in the delta. Previous authors have estimated the average annual suspended load of the entire Mekong as 160 million tonnes per year (Mt y^{-1}), and observed that about half of this amount was produced by the upper 20% of the basin, the Lancang drainage in China (Gupta and Liew, 2007; Walling, 2005). These values reflected conditions prevailing prior to ongoing construction of a cascade of seven dams on the Lancang, now mostly completed, and which will trap about 83% of the Lancang basin sediment when complete (Kondolf et al *submitted*). Thus, almost half of the natural sediment load of the Mekong will be lost in the reservoirs of the Lancang, and the sediment load of the Lower Mekong River will consist largely of sediment derived from sources within the LMRB itself. The hotspot of the river's extraordinary fish production is the Tonle Sap system. This tributary to the Mekong receives monsoon-driven, seasonal backwater flooding from the Mekong River mainstem, during which time fine-grained sediments deposit across the Ton Sap basin, making the Tonle Sap tributary basin net depositional (Tsukawaki 1997, Kummu et al. 2005) and potentially vulnerable to reduced sediment supply (Baran and Guerin 2012).

Most large rivers in the world are experiencing decreased sediment loads due to dam-induced sediment starvation. In the two millennia prior to widespread dam construction, human activities such as forest clearing and cultivation increased erosion and sediment delivery to the oceans ((Leopold 1921, Leopold 1923, Wolman and Schick 1967, Milliman and Syvitski 1992, Syvitski 2008). Worldwide, widespread dam construction has reversed this historical trend, and substantial reductions in the delivery of sediment to the oceans are now occurring in many of the world's rivers (Milliman and Syvitski, 1992). The Mekong, however, differs from other large Asian rivers, having produced a relatively consistent sediment yield over the past three thousand years (Ta et al., 2002), reflecting relatively modest levels of development that prevailed until very recently.

Reservoirs trap all the bedload and a percentage of the suspended load carried by a river. The supply of sediment to the river downstream is reduced by the amount trapped. Depending on the relative changes in sediment supply and transport capacity (Schmidt and Wilcock, 2008) erosion or deposition can occur, but most commonly the reach downstream of the dam is characterized by sediment-starved, or 'hungry' water, which can erode the bed and banks (Kondolf, 1997). These erosive flows threaten infrastructure and coarsen bed material, fundamentally altering physical habitat and aquatic food webs (Power et al., 1996). Sediment starvation typically affects downstream river channels and deltas by causing incision and bank erosion, habitat loss, and increased rates of land loss along the coast by reducing sediment replenishment.

The consequences 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 of costly disasters (Syvitski, 2008). Whereas eustatic sea level rise associated with global warming has received much focus and interest in recent years, the very land surface that meets the water has been subsiding more rapidly in recent years, as dam building reduces sediment supply needed for deposition on the delta plain, distributary channels are stabilized and dyked so that sediment-laden floodwaters can no longer disperse over the floodplain, and petroleum and groundwater extraction induce subsidence. Deltas that develop dense cities and industrial infrastructure become less resilient to tsunamis and hurricane-induced coastal surges. Lives and wetlands at risk today in coastal regions will be even more at risk in the future (Syvitski, 2008). The cumulative impacts of sea-level rise, sediment starvation from reservoir trapping and instream mining of construction aggregate, channelization of delta distributary channels, and groundwater extraction are common to many of the world's major rivers (Bucx et al., 2010), and have consequences that are broadly predictable (Table 1).

Prior Work on the Mekong River and Delta

Gupta et al. (2002), Gupta and Liew (2007), Carling (2005), Gupta (2008), and Carling (2009a) described the geomorphic framework of the Mekong River (Table 2), noted differences in geomorphic characteristics of reaches of the Lower Mekong, and to some extent, explored how reduced sediment supplies might affect different reaches. Following on Kummu et al.'s (2010) initial estimates of sediment reduction from planned dams, Kondolf et al. (*submitted*) developed geomorphically-based sediment yield estimates for the LMRB, calculated trap efficiencies for individual reservoirs, and compiling total storage capacity data for more accurate trap efficiency calculations. They then applied the 3W model (Minear and Kondolf 2009) to calculate cumulative sediment deficit from individual reservoirs under different reservoir development scenarios, accounting for reduced trap efficiencies as reservoirs fill, and accounting for multiple reservoirs in a given river basin. For the MRC's 'definite-future' scenario of 38 dams already constructed, under construction, or certain to be built, the sediment load reaching the Delta will be about half of its pre-1990 level. However, with full build of dams in the Lower Mekong River basin (Figure 1), including mainstem dams, the cumulative sediment trapping by dams will be ~96% of its pre-1990 load. Sediment starvation would actually be more severe owing to the mining of about 27 Mt y^{-1} of sand and gravel from the river channel, mostly in Cambodia (Bravard and Goichot 2012).

Flow alteration from existing and proposed dams is expected to be more modest than the sediment trapping. Typical of tropical rivers, Mekong River flow is seasonal, with a monsoon-driven high flow period from July to October that is responsible for 75% of the annual flow (Piman et al. 2013). Under a 41-dam "definite future" scenario, and a full-build scenario of 136 dams in the lower Mekong, Piman et al. (2013), predicted a dry season flow increase of 22% and 29% for definite future and full build scenarios respectively at the Kratie station. Wet season flows were predicted to decrease 4% and 13% for definite future and full build scenarios respectively. Similar estimates of hydrological changes were also presented by the Mekong River Commission (2010). These changes in flow regime may have significant impacts for the aquatic ecosystem and especially the fishery of Tonle Sap (Baran and Myschowoda 2009, Lamberts and Koponen 2008), but the small reduction in wet-season flow is unlikely to change the transport capacity of the Mekong. As such, the river will still have the capacity to transport a similar quantity of sediment with future hydropower development. Thus, sediment trapping by reservoirs is arguably the most important consequence of dams for the downstream channel.

Anthony et al. (2012) used sequential satellite images to analyze coastal retreat in the Mekong Delta from 2003 and 2011, finding an average of 4.4 m y^{-1} of coastline retreat across the entire delta, with higher rates of 12 m y^{-1} on the Ca Mau peninsula. Given the stable sediment supply and the growth of the Delta during the last ~6,000 years, Anthony et al. (2012) attribute this recent coastal retreat to the reduced sediment supply caused by massive extraction of sand and gravel from the river channel for construction aggregate (estimated to exceed 43 Mt y annually by Bravard and Goichot 2012), and by levees and channel straightening in the delta, which increase flow velocity and offshore sediment transport. To date, there has been a lack of analysis (and for that matter, a lack of data. To date, there has been a lack of analysis (and for that matter, a lack of data upon which to base analysis) to understand how the Mekong Delta is likely to respond to future sediment starvation. With better predictions of sediment starvation now available, it is clear that sediment starvation effects are likely to be severe, and thus there is an urgent need to draw upon available information for the Mekong Delta and analogous systems to make initial projections of likely impacts and identify critical data needs.

2 Methods

Our approach was twofold. We drew upon prior geomorphic work on the Mekong River basin by Adamson (2001), Gupta (2004) Gupta and Liew (2007), Gupta (2008), and Carling (2009a) to characterize channel reaches in terms of their likely response to sediment starvation We analyzed available data for other deltas as reported in the literature, and systematically compiled data such as degree of hydrologic alteration, percentage reduction in sediment supply, documented historical subsidence rates, and wave energy. Based on these analogous case studies, we made initial predictions for probable response of the Mekong Delta to the virtual elimination of its sediment supply.

3 Results

Although the influence of reservoir-induced sediment starvation on downstream channel change will clearly be complex and varied, fundamental principles such as Lane's Balance (Lane, 1955) and the presence or absence of geologic controls can be used as preliminary predictive tools. The results of Kondolf et al. (*submitted)* suggest that sediment trapping will be substantial while reductions in high flows will be minimal (Mekong River Commission 2010). Therefore, the Mekong River will continue to have the capacity to transport sediment in large quantities, but the supply of sediment for transport will be reduced. Channel adjustment will be limited primarily by geologic controls.

3.1 Delineation of Reaches

The Upper Bedrock reach extends from the Chinese border downstream to about 5 km upstream of Vientiane. In this reach the Mekong River channel is bedrock controlled, with limited, and presumably transient, sediment storage (Figure 2). The channel gradient averages 0.0003, and channel width ranges from 200-2000m. This reach includes many wide, bedrock-floored reaches where bedrock is discontinuously overlain by a thin (ca 1-2 m) veneer of sand (Figure 3). The Middle Alluvial Reach extends downstream from Vientiane to Savannakhet. It is alluvial, with both single-channel and island-bar sections. Channel gradient averages 0.0001, and the channel is 800 to 1300m wide.

From Savannakhet downstream to Kratie, the Middle Bedrock Reach is again bedrock controlled. This reach includes a wide range of channel forms, as reflected in Gupta and Liew (2007) having broken this section of river into 4 reaches (their reaches 3, 4, 5, and part of 6). For our analysis, the key attribute of all these reaches is bedrock control (and thus we consider it a single reach), though a variety of sedimentary forms are present including sections with alluvial banks, anastamosed channels with rock-core islands covered with a relatively thin veneer of sand and silt (Meshkova and Carling 2012). For example, from Sambor to Kratie, the bedrock control is largely buried, so the river here displays many alluvial features. However, the underlying bedrock limits its potential response to sediment starvation. Channel gradient in the upper portion of Reach 3 is approximately 0.00006 and decreases downstream. Channel width ranges from 750 to 5000 m. The Cambodian Alluvial Reach extends from Kratie downstream to Phnom Penh. Here, the Mekong is again alluvial, crossing the wide floodplain of Cambodia to enter the depositional reaches of the delta. Channel gradient is 0.000005 and widths range from 3000 to 4000m. Some large-scale structural control is provided by bedrock, but channel planform and position is primarily set by channel migration through alluvium. Downstream of Phnom Penh is the Mekong Delta, by definition a reach of net deposition. The delta occupies an area of ~94,000 km^2 making it the third largest delta in the world (Coleman and Wright 1975). The delta begins ~330 km from the sea where the Bassac, the first deltaic distributary, separates from the mainstem. The two channels flow parallel for 200 km without additional distributaries or connecting channels. Ultimately, there are four main channels that reach the sea. As a result of groundwater extraction and limited sediment starvation, the Mekong is categorized as a "Delta in Peril" with late 20th Century aggradation at less than 0.5 mm y^{-1} and relative sea level rise occurring at approximately 6 mm y^{-1} (Syvitski et al., 2009). Sediment trapping under future dam building scenarios will further limit sediment delivery and distribution in the delta.

3.2 Potential effects on channel Reaches

Definite Future Scenario

Under the "definite future scenario", the Upper Bedrock Reach will have an 83% reduction in sediment at the upstream end of the reach, though as less regulated tributaries enter the reach the cumulative trapping decreases to 64% at the downstream end of Reach 1 (Kondolf et al. *submitted*). The relative reduction in sediment supply in this reach is the greatest of any reach in the definite future scenario, yet because the reach is bedrock controlled we anticipate only modest channel adjustment. Loose sediment deposits over bedrock as described by Carling 2009a (including slack-water deposits on bars, islands, inset floodplains and banks) (Figure 3) will likely be swept away in the first competent floods post-dam. Changes in bed-level will likely be confined to accelerated scouring of pools (Carling, 2009b)

In the Middle Alluvial Reach, the sediment reduction decreases to 52% at the downstream end of the reach while sediment reductions in the Middle Bedrock and Cambodian Floodplain Reaches fluctuate between 51-56%. Under current conditions, bank erosion is not excessive (Darby et al., 2010) but we anticipate the most substantial post-dam erosion and channel adjustment in the Middle Alluvial reach and Cambodian Alluvial reaches, where bank erosion is currently occurring and where coarse bed sediment is exposed, suggesting Holocene incision (Carling, 2009a). Large island features are believed to result from chute cutoffs and suggest a dynamic river system (Carling, 2009a). Because upstream reservoirs will have a limited influence on flow regime, but will trap more than half of the total sediment load, we expect channel widening in alluvial reaches as the river seeks to recover its sediment load by eroding the channel margin, as commonly observed in sediment-starved rivers (Kondolf, 1997). Incision is also likely except where the bed elevation is controlled by bedrock. The Middle Bedrock reach has single-thread, bedrock-confined reaches, anastomosed reaches of bedrock islands, and also includes the base-level control of Khoné Falls (a Holocene lava flow that crosses the river) (Carling, 2009a). Future high flows of sediment-starved water may erode alluvium on bars, banks, and islands without replacing. Erosion into bedrock is not expected on the timescale of decades. The Cambodian Alluvial reach is a floodplain river with active meandering in anabranching and anastomosed sections. Individual islands are transient features, though the island complex is relatively stable (Carling, 2009a). Without replenishment, new islands will be less likely to develop and loss of the island features will likely occur. Erosion of the main channel bed and banks is also expected. The Mekong Delta will receive about half of its natural sediment load, and can be expected to experience accelerated subsidence and coastal erosion. Further research is needed on the size distribution of sediment transported by the river, and the size fractions most affected by the dams, but we expect the dams to disproportionately affect bed material load, notably sand, which is most important for building beaches and nourishing the coast. See further discussion of the Delta response to reduced sediment supply below.

Full Build Scenario

With all proposed dams constructed (full build scenario) and cumulative sediment reduction ranging from 83% below the Chinese boarder to 96% in Vietnam, we expect the most dramatic response in the alluvial reaches from Vientiane to Savannakhet and from Kratie downstream, where channel bed and banks will be susceptible to erosion.

While the bedrock-controlled reaches above Vientiane and from Savannakhet to Kratie will not downcut (except to remove any layers of erodible alluvium overlying bedrock, and/or to deepen pools) and will not have dramatic occurrences of erosion or channel instability, the extensive existing sediment deposits (bars, islands, inset floodplains and banks) will be stripped away, and bed material size will coarsen, all with potentially important ecological consequences. If the thin veneer of sediment in the bedrock reaches is removed, it can substantially alter the substrate, baseflow channel roughness, and water velocity that influence fundamental elements of habitat availability for the benthic macroinvertebrates, fishes, and other aquatic biota. Since little is known about many Mekong species, it is difficult to predict their response to channel change and consequent loss of habitat.

If the mainstem dams are constructed, they will inundate long reaches of the river and their backwater effects will extend further upstream. Within these reservoirs and back-water areas, rather than experiencing erosion from energetic flows, the channel will become a depositional zone. An important ecological feature of the river are the deep pools that provide essential habitat for native fishes and river dolphins (Poulsen and Vlabo-Jorgensen 2001, Baird and Flaherty 2005), and which are maintained by scour created by local hydraulics. Sediment starvation below dams is unlikely to negatively affect these pools through increased erosion. However, within the extensive zones of reservoir inundation and backwater, local hydraulics will change, likely eliminating the scouring currents that have maintained these features, and they will begin to fill with sediment and debris.

3.3 Potential effects on Mekong River delta from analogous cases

At present, approximately 21,000 km^2 of land in the Mekong Delta is less than 2 m above sea level and 37,000 km^2 is regularly flooded (Syvitski et al., 2009). The pre-dam sediment accumulation rate across the Mekong Delta was ~0.5 mm yr^{-1} while relative sea level is rising at ~6 mm yr^{-1} (Syvitski et al., 2009). While sediment delivery to the Mekong Delta has remained relatively constant over the 20th century, recent decades have seen accelerated rates sea level rise and more rapid compaction due to groundwater extraction. Thus, even under the pre-dam sediment regime, the delta was submerging and flood-prone areas expanding. Future reductions in sediment discharge from the Mekong River or channelization in the Delta will exacerbate the rate of land loss.

Similar to "full-build" predictions for the Mekong River by Kondolf et al. (*submitted*), the Colorado, Ebro, Indus, Krishna, Nile, and Yellow River deltas have all experienced sediment reductions of 90% or more (Table 1). Since those deltas have comparable or lower rates of relative sea level rise than the Mekong and similar intensities of wave energy, they provide a reasonable framework for understanding the likely impacts of unmitigated dam construction. The Indus, Nile, and Yellow River deltas were all prograding prior to dam construction and subsequently were net erosional. For example, the Indus coast was prograding ~100 m y^{-1} before dam construction and retreating ~50 m y^{-1} in recent decades. Pre-dam delta growth is not reported for the Colorado, Ebro, and Krishna, but all are actively eroding in the post-dam period (see Table 1 for citations). Rates range from 1-90 km^2 y^{-1} of area lost per year and from 10 to 70 m y^{-1} of coastline retreat. Detailed modeling of the delta is required to make quantitative predictions of erosion, but experience from around the world suggests a high likelihood of widespread erosion unless sediment management practices are implemented for proposed Mekong dams.

4 Discussion

Deltas evolve through a complex interplay of river, tides, waves, biological and human factors. For example, mangrove communities slow wave velocities, thereby efficiently trapping sediment, and improving water quality and preventing coastal erosion. The extent of mangrove ecosystems in the Mekong delta has remained stable in recent decades (Shearman et al., 2013). Elsewhere, mangroves are at risk from rapid sediment deposition (Ellison 1999) (not likely in the Mekong), as well as sea-level rise and increased storm intensity, aquaculture and water quality impacts, and sediment reductions from dams (Thampanya et al., 2006). Such interactions exemplify the challenges posed to modelers of deltaic systems. These are extremely difficult and important processes to understand, yet likely impossible to parameterize accurately given the unpredictable nature of storm events and other stochastic processes. However, given the magnitude of sediment starvation likely to occur in the near future, our review of experiences elsewhere, combined with fundamental geomorphic principles, can provide an initial prediction of likely effects. In a data-limited, poorly understood system such as the Mekong, implementation of detailed models may be unrealistic due to the lack of long-term and/or reliable data for calibration. By relying on the global dataset we hope to inform decision makers and stakeholders in the Mekong River basin while advances until accurate modeling and forecasting tools become available.

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References

Adamson, P. 2001. Hydrological perspectives of the Lower Mekong. *International Water Power Dam Construction*, March 16-21.

Adamson, P.T. 2009. An exploratory assessment of the potential rates of reservoir sediment in five Mekong mainstream reservoirs proposed in Lao PDR. Unpublished report, Mekong River Commission, Vientiane.

Alexander, J.S., Wilson, R.C., and W.R. Green, 2012. A brief history and summary of the effects of river engineering and dams on the Mississippi River system and delta: U.S. Geological Survey Circular 1375, 43 p.

Anthony, E.J., Goichot, M., Brunier, G., Dussouillez, P., Provansal, and M. F. Dolique (2012). Widespread erosion of the Mekong River Delta: from construction to destruction phase? Conservation of Nature and Culture for the Sustainable development of the Mekong Delta, Ca Mau City, April 12, 2013.

Baird, I. G. and M. S. Flaherty, 2005. Mekong River fish conservation zones in southern Laos: assessing effectiveness using local ecological knowledge. *Environmental Management* 35: 1-17.

Baran, E., and C. Myschowoda, 2009, Dams and fisheries in the Mekong Basin, *Aquatic*

Ecosystem Health & Management, 12(3), 227-234.
Baran E. and E. Guerin E. 2012. Fish bioecology in relation to sediments in the Mekong and in tropical rivers. Report for the Project "A Climate Resilient Mekong: Maintaining the Flows that Nourish Life" led by the Natural Heritage Institute. World Fish Center, Phnom Penh, Cambodia.
Bravard, J.P. and M. Goichot. 2012. Sand and gravel mining in the Mekong river: Results of the 2011 WWF survey. Presentation to the workshop, 'Decision Support for Generating Sustainable Hydropower in the Mekong Basin: Knowledge of sediment transport and discharges in relation to fluvial geomorphology for detecting the impact of large-scale hydropower projects', 22-23 May 2012, Phnom Penh, Cambodia. Sponsored by WWF (World Wildlife Fund).
Brune, G. (1953), Trap efficiency of reservoirs, *Trans. AGU*, *34*(3), 407-418.
Bucx, T., M. Marchand, A. Makaske, C. van de Guchte, 2010. Comparative assessment of the vulnerability and resilience of 10 deltas – synthesis report. Delta Alliance report number 1. Delta Alliance International, Delft-Wageningen, The Netherlands
Carling P. 2009a. The Geomorphology and Sedimentology of the Lower Mekong River, pp 77-11 in: The Mekong: Biophysical Environment of an International River Basin edited by IC Campbell, Elsevier.
Carling, P. 2009b. Impacts on River Morphology. Assessment of basin-wide development scenarios, Technical Note 4. Mekong River Commission Secretariat, Vientiane, Laos.
Carling, P. 2010. International Consultants for Sediment Management Principles Sediment Trapping: Geomorphologic Changes. Report prepared for: Mekong River Commission Secretariat, Vientiane, Laos.
Clift, P. D., G. D. Layne, and J. Blusztajn, 2004. Marine sedimentary evidence for monsoon strengthening, Tibetan uplift and drainage evolution in East Asia, in *Continent-Ocean Interactions Within East Asian Marginal Seas*, pp. 255-282, AGU, Washington, DC.
Coleman, J. M. and O. K. Huh, 2003. Major world deltas: A perspective from space, Lousiana State University.
Coleman, J.M.; Huh, O.K., and Braud, D., JR., 2008. Wetland loss in world deltas. *Journal of Coastal Research*, 24(1A), 1–14.
Couvillion, B.R., Barras, J.A., Steyer, G.D., Sleavin, et al., 2011. Land area change in coastal Louisiana from 1932 to 2010: U.S. Geological Survey Scientific Investigations Map 3164, scale 1:265,000, 12 p. pamphlet.
Dai, S. B., S. L. Yang, and A. M. Cai, 2008. Impacts of dams on the sediment flux of the Pearl River, southern China, *Catena*, *76*(1), 36-43.
Dang, T. H., A. Coynel, D. Orange, G. r. Blanc, H. Etcheber, and L. A. Le, 2010. Long-term monitoring (1960- 2008) of the river-sediment transport in the Red River Watershed (Vietnam): Temporal variability and dam-reservoir impact, *Science of The Total Environment*, 408(20), 4654-4664.
Darby, S. E., H. Q. Trieu, P. A. Carling, J. Sarkkula, J. Koponen, M. Kummu, I. Conlan, and J. Leyland, 2010. A physically based model to predict hydraulic erosion of fine-grained riverbanks: The role of form roughness in limiting erosion, *J. Geophys. Res.,* 115, F04003, doi:10.1029/2010JF001708
Ellison, J.C. 1999. Impacts of sediment burial on mangroves, *Marine Pollution Bulletin*

37(8-12): 420-426.
Encyclopedia Britannica Online, 2013. http://www.britannica.com/EBchecked/topic/448059/Pearl-River-Delta
Frihy, O.E., Nasr, S.M., El Hattab, M.M. and M. El Raey, 1994. Remote sensing of beach erosion along the Rosetta promontory, northwestern Nile delta, Egypt. International *Journal of Remote Sensing* 15:1649–1660.
Gamage, N., and V. Smakhtin, 2009. Do river deltas in east India retreat? A case of the Krishna Delta, *Geomorphology*, 103(4), 533-540.
Giosan, L., S. Constantinescu, P. D. Clift, A. R. Tabrez, M. Danish, and A. Inam, 2006. Recent morphodynamics of the Indus delta shore and shelf, *Continental Shelf Research*, 26(14), 1668-1684.
Grillas, P. 2013. The Camargue, Rhone River Delta, France, in Encyclopedia of Wetlands: Wetlands of the World (ed. M, Finlayson). Springer
Grumbine, R. E., and J. Xu, 2011. Mekong Hydropower Development, *Science*, 332(6026), 178-179.
Gupta, A. 2004. The Mekong River: morphology, evolution and paleoenvironment. *Journal of the Geological Society of India,* 64(4) 525-534.
Gupta, A. 2008. The Mekong River: morphology, evolution, management. In Large rivers: geomorphology and management (Ed. A. Gupta). Chichester, Wiley & Sons: 435-455
Gupta, A., and S. C. Liew, 2007. The Mekong from satellite imagery: A quick look at a large river, *Geomorphology*, 85(3,-4), 259-274.
Gupta, H., Kao, S.J. and M. Dai. 2012. The role of mega dams in reducing sediment fluxes: A case study of large Asian rivers. Journal of Hydrology 464–465:447–458.
Haq, B. U. 1999. Past, present and future of the Indus delta, in The Indus River, Biodiversity, Resources, Humankind. Linnaean Society of London, Oxford University Press, Oxford, UK, edited, pp. 231-248, Oxford University Press, Oxford, UK.
Hedley, P. J., Bird, M. I., and R. A. J. Robinson, 2010, Evolution of the Irrawaddy delta region since 1850. *The Geographical Journal*, 176: 138–149.
Hori, K. and Y. Saito. 2008. Classification, Architecture, and Evolution of Large-River Deltas, in Large Rivers: Geomorphology and Management (ed A. Gupta), John Wiley & Sons, Ltd, Chichester, UK.
Ibàñez, C., N. Prat, and A. Canicio, 1996. Changes in the hydrology and sediment transport produced by large dams on the lower Ebro River and its estuary. *Regulated Rivers: Research & Management* 12:51–62.
Jimenez, J. A., and A. Sanchez-arcilla, 1997. Physical impacts of climatic change on deltaic coastal systems (II): driving terms, Climatic Change, 35(1), 95-118.
Kondolf, G. M. 1997. Hungry water: effects of dams and gravel mining on river channels, *Envionmental Management* 21, 533-552.
Kondolf, G.M., Z.K. Rubin, J.T. Minear, *submitted.* Dams on the Mekong: Cumulative sediment starvation.
Kummu, M. J. Koponen, and J. Sarkkula. 2005. Modeling sediment and ecosystem in Tonle Sap Lake for impact assessment. *RMZ -Materials and Geoenvironment* 52(1):87-89.
Kundzewicz, Z. W., D. Nohara, et al. 2009. Discharge of large Asian rivers-Observations and projections. *Quaternary International* 208(1-2): 4-10.

Lamberts, D., and J. Koponen, 2008, Flood pulse alterations and productivity of the Tonle Sap ecosystem: a model for impact assessment, *AMBIO: A Journal of the Human Environment*, 37(3), 178-184.

Lane, E. W. 1955. The importance of fluvial morphology in hydraulic engineering, paper presented at American Society of Civil Engineers.

Leopold, A., 1921, A plea for recognition of artificial works in forest erosion control policy, *Journal of Forestry*, 19(3), 267-273.

Leopold, A., 1923, Watershed handbook. Rep., 28 pp, U.S Forest Service SW District.

Lóczy, D. 2007. The Danube: morphology, evolution and environmental issues, in Large Rivers: Geomorphology and Management (ed A. Gupta), John Wiley & Sons, Ltd, Chichester, UK. p. 235-260.

Luecke, D. F., Pitt, J., Congdon, C., Glenn, E., Valdes-Casillan, C., and M. Briggs, 1999. A Delta Once More: Restoring Riparain and Wetland Habitat in the Colorado River Delta, Environmental Defense Fund.

Malini, B. H., and K. N. Rao, 2004. Coastal erosion and habitat loss along the Godavari delta front- a fallout of dam construction (?), *Current Science*, 87(9), 1232-1236.

McManus, J. 2002. Deltaic responses to changes in river regimes, *Marine Chemistry*, *79*(3), 155-170.

Mekong River Commission, 2010. Assessment of basin-wide development scenarios: Main report. Basin Development Plan Programme, Phase 2 Report.

Mertes, L. A. K. and Magadzire, T. T., 2008. Large Rivers from Space, in Large Rivers: Geomorphology and Management (ed A. Gupta), John Wiley & Sons, Ltd, Chichester, UK.

Meshkova, L.V. and P.A. Carling. 2012. The geomorphological characteristics of the Mekong River in northern Cambodia: a mixed bedrock–alluvial multi-channel network. *Geomorphology* 147-148: 2–17. doi:10.1016/j.geomorph.2011.06.041

Milliman, J. D., and J. P. M. Syvitski, 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers, *The Journal of Geology*, 525-544.

Minear, J. T., and G. M. Kondolf, 2009. Estimating reservoir sedimentation rates at large spatial and temporal scales: A case study of California, *Water Resources Research*, 45(12).

Nilsson, C., C.A. Reidy, et al. 2005. Fragmentation and Flow Regulation of the World's Large River Systems. *Science* 308(5720): 405-408.

Oczkowski, A. J., S. W. Nixon, S. L. Granger, A.-F. M. El-Sayed, and R. A. McKinney, 2009. Anthropogenic enhancement of Egypt's Mediterranean fishery, *Proceedings of the National Academy of Sciences*, 106(5), 1364-1367.

Panin, N. 1999. Global Changes, Sea Level Rising and the Danube Delta: Risks and Responses, 4. Geo-Eco-Marina, Bucharest, Romania, pp. 19-29.

Peng, J., S. Chen, and P. Dong, 2010. Temporal variation of sediment load in the Yellow River basin, China, and its impacts on the lower reaches and the river delta, *Catena*, 83(2), 135-147.

Piman, T., T. Lennaerts, et al. 2013. Assessment of hydrological changes in the lower Mekong Basin from Basin-Wide development scenarios. *Hydrological Processes* 27(15): 2115-2125

Poulsen, A. and J. Valbo-Jorgensen, 2001. Deep pools in the Mekong River. Mekong

Fish Catch and Culture 7(1-Sep. 2001).
Power, M. E., W. E. Dietrich, and J. C. Finlay, 1996. Dams and downstream aquatic biodiversity: potential food web consequences of hydrologic and geomorphic change, *Environmental management*, 20(6), 887-895.
Rovira, A., and C. Ibàñez, 2007. Sediment management options for the lower Ebro River and its delta, *Journal of Soils and Sediments*, 7(5), 285-295.
Sabatier, F., O. Samat, et al., 2009. Connecting large-scale coastal behaviour with coastal management of the Rhone delta. *Geomorphology* 107(1-22): 79-89.
Saito, Y., N. Chaimanee, T. Jarupongsakul, and J. P. M. Syvitski, 2007. Shrinking megadeltas in Asia: Sea-level rise and sediment reduction impacts from case study of the Chao Phraya Delta, *Inprint Newsletter of the IGBP/IHDP Land Ocean Interaction in the Coastal Zone*, 2, 3-9.
Sarwar, M.G.M.S. and C. D. Woodroffe, 2013. Rates of shoreline change along the coast of Bangladesh. *Journal of Coastal Conservation* 17(3): 515-526.
Schmidt, J. C. 2008 The Colorado River, in Large Rivers: Geomorphology and Management (ed A. Gupta), John Wiley & Sons, Ltd, Chichester, UK.
Schmidt, J. C., and P. R. Wilcock, 2008. Metrics for assessing the downstream effects of dams, *Water Resources Research*, 44(4).
Shearman, P., Bryan, J., and J.P. Walsh, 2013. Trends in Deltaic Change over Three Decades in the Asia-Pacific Region. *Journal of Coastal Research*: Volume 29, Issue 5: pp. 1169 – 1183.
Syvitski, J. P. M., and Y. Saito. 2007. Morphodynamics of deltas under the influence of humans. *Global and Planetary Change* 57:261–282.
Syvitski, J. P. M. 2008. Deltas at risk, *Sustainability Science*, 3(1), 23-32.
Syvitski, J. P. M., and J. D. Milliman, 2007. Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean, *The Journal of Geology*, 115(1), 1-19.
Syvitski, J. P. M., Kettner, A.J., Overeem, I., E. Hutton, E.W., et al. 2009. Sinking deltas due to human activities, *Nature Geosci*, *2*(10), 681-686.
Ta, T. K. O., V. L. Nguyen, M. Tateishi, I. Kobayashi, S. Tanabe, and Y. Saito, 2002. Holocene delta evolution and sediment discharge of the Mekong River, southern Vietnam, *Quaternary Science Reviews*, 21(16), 1807-1819.
Thampanya, U., J.E. Vermaat, et al. 2006. Coastal erosion and mangrove progradation of Southern Thailand, *Estuarine, Coastal and Shelf Science* 68(1-2): 75-85.
Tsukawaki, S. 1997. Lithological features of cored sediments from the northern part of The Tonle Sap Lake, Cambodia. Proceedings of the International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific, Bangkok Thailand, August 1997.
Van Maren, D. 2004. Morphodynamics of a cyclic prograding delta: the Red River, Vietnam, Utrecht: Royal Dutch Geographical Society.
Walling, D. 2005. Analysis and evaluation of sediment data from the Lower Mekong River. Report submitted to the Mekong River Commission *Rep.*, Department of Geography, University of Exeter.
Wang, H., N. Bi, Y. Saito, Y. Wang, X. Sun, J. Zhang, and Z. Yang, 2010. Recent changes in sediment delivery by the Huanghe (Yellow River) to the sea: Causes and environmental implications in its estuary, *Journal of Hydrology*, 391(3), 302-313.

Wells, J. T., and J. M. Coleman, 1984. Deltaic morphology and sedimentology, with special reference to the Indus River delta, edited, pp. 85-100, Van Nostrand Reinhold, New York

Wells, J. T., and J. M. Coleman, 1984. Deltaic Morphology and Sedimentology, with Special Reference to the Indus River Delta. B.U. Haq, J.D. Milliman (Eds.), Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan, Van Nostrand Reinhold Co., New York, pp. 85–100

Wolman, M., and A. P. Schick, 1967, Effects of construction on fluvial sediment, urban and suburban areas of Maryland, *Water Resour. Res*., 3(2), 451-464.

Yang, S. L., Belkin, I., Belkina, A., Zhao, Q., Zhu, J., and P. Ding, 2003. Delta response to decline in sediment supply from the Yangtze River: evidence of the recent four decades and expectations for the next half-century, *Estuarine, Coastal and Shelf Science*, 57(4), 689-699.

Yang, S. L., J. Zhang, J. Zhu, J. P. Smith, S. B. Dai, A. Gao, and P. Li, 2005. Impact of dams on Yangtze River sediment supply to the sea and delta intertidal wetland response, *Journal of Geophysical Research: Earth Surface*, 110(F3), F03006.

Yang, S. L., Zhang, J. and X. J. Xu, 2007. Influence of the Three Gorges Dam on downstream delivery of sediment and its environmental implications, Yangtze River. *Geophysical Research Letters* 34, L10401.

Yang, S. L., J. Milliman, P. Li, and K. Xu, 2011. 50,000 dams later: Erosion of the Yangtze River and its delta, *Global and Planetary Change*, *i*(1), 14-20.

Yang, Z., H.-j. Wang, Y. Saito, J. Milliman, K. Xu, S. Qiao, and G. Shi, 2006. Dam impacts on the Changjiang (Yangtze) River sediment discharge to the sea: The past 55 years and after the Three Gorges Dam, *Water Resources Research*, 42(4), W04407.

Zhang, W., X. Ruan, J. Zheng, Y. Zhu, and H. Wu, 2010. Long-term change in tidal dynamics and its cause in the Pearl River Delta, China, *Geomorphology*, 120(3-4), 209-223.

Table 1. Deltas of the World

River	Drain-age Area [qq] (1000's km^2)	Relief (km) [qq]	Total Delta Area [b] (1000's km^2)	Delta Area <2m above sea level [a] (1000's km^2)	Flow Reg. [k] (%)	Early 20th Century Aggradat-ion Rate [a] (Mm y^{-1})	Recent Aggra-dation Rate [a] (Mm y^{-1})	Relative Sea Level Rise [a] (Mm y^{-1})	Reduction in Sediment Delivery (%)	Wave Energy [r] w_a : max monthly wave height (m)	Notes
Amur, Russia	1,755	2.51		1.2	9%	2	1.1	1	0% [a]		
Chao Phraya, Thailand	142	1.9	11	1.8	76%	0.2	0	13-150	~ 85%[a,l]	1.5	~50% reduction in average annual maximum flow after flow regulation [s]
Colorado, Mexico	638	3.7	0.6 [c]	0.7	280%	34	0	2-5	100% [a]	0.5	Total annual flow reduced ~90% [t]. Since 1930, ~90 km^2 y^{-1} of delta area lost [u].
Danube River, Romania	779	4.1	4 [f]	3.7 [jj]	5%	3	1	1.2	63% [a]	1.5	Prograding during last 2,800 years. Mean rate of coastal retreat from 3 to 5 m y^{-1} during recent decades [kk]. Eroded land includes ~ 6 km^2 y^{-1} of agricultural and industrial land and 83 km^2 y^{-1} wetlands from 1987-2001 [nn].
Ebro River, Spain	85	3.34	0.3 [d]	0.1 [i, j]	23%	5-7 [i]	0 [i]	3-4 [i]	99% [d]	1.5	Flow regulation reduced max monthly discharge and annual average discharge by ~70% [r]. 10-60 m y^{-1} coastline retreat [v] with 45% of the emerged delta expected to be submerged by 2100 [d]

River	Drainage Area [qq] (1000's km^2)	Relief (km) [qq]	Total Delta Area [b] (1000's km^2)	Delta Area <2m above sea level [a] (1000's km^2)	Flow Reg. [k] (%)	Early 20th Century Aggradation Rate [a] (Mm y^{-1})	Recent Aggradation Rate [a] (Mm y^{-1})	Relative Sea Level Rise [a] (Mm y^{-1})	Reduction in Sediment Delivery (%)	Wave Energy [r] w_a : max monthly wave height (m)	Notes
Ganges-Brahmaputra, Bangladesh	1,628	6.09	106	6.1	8%	3	2	8-18	30% [a,l]	1.0	~20 m y^{-1} of coastal retreat in recent decades along the coast of Bangladesh [ll]. Eroded land includes ~ 292 km^2 y^{-1} of agricultural and industrial land and 358 km^2 y^{-1} wetlands from 1989-2001 [nn].
Godavari River, India	313	1.06	5 [e]	0.2	37%	7	2	3	40% [a] 74% [l]	2.0	0.74 km^2 y^{-1} loss of delta land area since the 1970's [w]. Saltwater intrusion exacerbated by surface and groundwater withdrawals [c].
Indus River, Pakistan	941	5.18	30	4.8	13%	8	1	>1.1	80% [a] 93% [l]	3.5	Flow regulation reduced max monthly discharge (~40%) and annual average discharge (~50%) [r]. Prior to dam construction, coastline prograding ~100 m y^{-1}. Recent decades average 50 m $^{y-1}$ of coastline retreat [x]. The Indus Delta has the highest wave energy of any major delta [y]. Eroded land includes ~ 79 km^2 y^{-1} of agricultural and industrial land and 199 km^2 y^{-1} wetlands from 1992-2000 [nn].
Irawaddy, Burma	406	4.8	21	1.1	1%	2	1.4	3.4-6	30% [a] 0% [l]	1.5	From 1925 to 1989 the Irawaddy delta grew 8.7 km^2 y^{-1}, then eroded at a rate of 13 km^2 y^{-1} from 1989-2006, probably a result of sediment trapping in small-medium sized tributary dams[mm].

River	Drain-age Area [qq] (1000's km^2)	Relief (km) [qq]	Total Delta Area [b] (1000's km^2)	Delta Area <2m above sea level [a] (1000's km^2)	Flow Reg. [k] (%)	Early 20th Century Aggradat-ion Rate [a] (Mm y^{-1})	Recent Aggra-dation Rate [a] (Mm y^{-1})	Relative Sea Level Rise [a] (Mm y^{-1})	Reduction in Sediment Delivery (%)	Wave Energy [r] w_a : max monthly wave height (m)	Notes
Krishna River, India	259	1.33	5 [e]	.3	37%	7	0.4	3	~90% [a,l]	2.0	Flow regulation reduced max monthly discharge (~20%) and annual average discharge (~40%) [r]. 0.78 km^2 y^{-1} loss of delta land area since the 1970's [c].
Mahanadi, India	142	1.14	11 [f]	.2	17%	2	0.3	1.3	~ 7% [a,l]	2.0	Eroded land includes ~ 7 km^2 y^{-1} of agricultural and industrial land and 31 km^2 y^{-1} wetlands from 1989-2002[nn].
Mekong, Vietnam	759	5.47	94	21	3%	0.5	0.4	6	12% [a] 0% [l]	1.5	Negligible change in annual discharge and monthly maximum discharge [r]. Delta area stable in recent decades. 4.4 m $^{y-1}$ of coastline retreat with higher rates (12.2 m $^{y-1}$) along Cau Mau Peninsula [rr]
Mississippi River, USA	3,203	4.4	29	7.1	16%	2	0.3	5-25	48% [a] >60% [m]	0.5	Negligible change in annual discharge and annual monthly maximum discharge [r]. 4,900 km^2 lost since early 20th century [m] with land-loss rates from ~ 40 km^2 y^{-1} to 100 km^2 y^{-1} from 1940's to 2000 and wetland losses of 43 km^2 y^{-1} from 1985-2010 [z].
Niger, Nigeria	1,240	2.1	19	0.4	15%	0.6	0.3	3.2	50% [a]	1.4	Eroded land includes ~ 0.5 km^2 y^{-1} of agricultural and industrial land and 6 km^2 y^{-1} wetlands from 1987-2002 [nn].

River	Drain-age Area [qq] (1000's km^2)	Relief (km) [qq]	Total Delta Area [b] (1000's km^2)	Delta Area <2m above sea level [a] (1000's km^2)	Flow Reg. [k] (%)	Early 20th Century Aggradat-ion Rate [a] (Mm y^{-1})	Recent Aggra-dation Rate [a] (Mm y^{-1})	Relative Sea Level Rise [a] (Mm y^{-1})	Reduction in Sediment Delivery (%)	Wave Energy [r] w_a : max monthly wave height (m)	Notes
Nile River, Egypt	2,026	3.78	13	9.4	95%	1.3	0	4.8	98% [a]	1.5	Dams and diversions reduced max monthly discharge (~80%) and annual average discharge (~60%) [r]. The delta was prograding prior to construction of Aswan Dam in 1970. Coastal erosion rates of 38-71 m y^{-1} [aa] and crash of the abundant sardine fishery of the Mediterranean after Aswan. Eroded land includes ~ 0.7 km^2 y^{-1} of agricultural and industrial land and 0.8 $km^2 y^{-1}$ wetlands from 1984-2001 [nn].
Pearl (Zhu Jiang), China	370	3.5	8 [g]	3.7	31%	3	0.5	7.5	67% [a] 22% [l] >90% [n]	1.5	Dam construction began in the 1950s and expanded to reach over 9,000 dams. Rapid and widespread development obscure changes in the coastline, but river regulation, combined with incised channels (from reservoir sediment trapping and extraction of sand for construction) and sea level rise has led to saltwater intrusion and increased erosion potential due to the larger tidal prism [bb].
Po, Italy	72	4.8	13	0.6	4%	3	0	4-60	50% [a]	1.5	Flow regulation reduced max monthly discharge (~30%) and annual average discharge (~20%) [r].

River	Drain-age Area [qq] (1000's km^2)	Relief (km) [qq]	Total Delta Area [b] (1000's km^2)	Delta Area <2m above sea level [a] (1000's km^2)	Flow Reg. [k] (%)	Early 20th Century Aggradat-ion Rate [a] (Mm y^{-1})	Recent Aggra-dation Rate [a] (Mm y^{-1})	Relative Sea Level Rise [a] (Mm y^{-1})	Reduction in Sediment Delivery (%)	Wave Energy [r] w_a : max monthly wave height (m)	Notes
Red (Hong Ha), Vietnam	150	3.14	12		3%				76% [l] 50% [o]	1.5	Flow regulation reduced annual average discharge (~10%) [r]. Notorious for extreme floods, the delta of the Red River is dynamic with large and rapidly shifting zones of erosion and deposition. In recent decades, the coastline has retreated 2 km in some areas while advancing up to 5 km in others making it difficult to discern the coastal impacts of sediment trapping [cc]
Rhone, France	99	4.81	1.5 [h]	1.1	6%	7	1	2-6	30% [a]	2.0	Coastal retreat halted through hard engineering structures, though steepening of shoreline suggests chronic erosion problems in the future [oo].
Tigris-Euphrates, Iraq	1,050	2.96	18	9.7	124%	4	2	4-5	50% [a]	1.0	Close to 10,000 km^2 of marshes destroyed in last decades of 20th Century through dam construction and diversion of water away from marsh area [pp]. Though not 'eroded', this change is one of the most dramatic of any delta system.

River	Drainage Area [qq] (1000's km^2)	Relief (km) [qq]	Total Delta Area [b] (1000's km^2)	Delta Area <2m above sea level [a] (1000's km^2)	Flow Reg. [k] (%)	Early 20th Century Aggradation Rate [a] (Mm y^{-1})	Recent Aggradation Rate [a] (Mm y^{-1})	Relative Sea Level Rise [a] (Mm y^{-1})	Reduction in Sediment Delivery (%)	Wave Energy [r] w_a : max monthly wave height (m)	Notes
Yangtze (Chang Jiang), China	1,794	4.38	67	6.7	12%	11	0	3-28	~ 70% [a,l,p]	1.5	Negligible change in annual discharge and annual monthly maximum discharge [l,r]. Sediment delivery decreased since the 1950's and the delta became net erosional with the filling of Three Gorges Dam in recent years [dd,ee,ff,gg].
Yellow (Huanghe) River, China	865	5.9	36	1.4	51%	49	0	8-23	30% [a] 84% [l] 90% [q]	1.5	Flow regulation reduced max monthly discharge and annual average discharge by ~20% [r]. The delta was prograding at a rate of 20–25 km^2 y^{-1} in the early 20th century, but is now net erosional [hh,ii], grain size has coarsened, and sediment dispersal patterns and the slope of the coastline have changed [q]. Eroded land includes ~ 66 km^2 y^{-1} of agricultural and industrial land and 67 km^2 y^{-1} wetlands from 1989-2000 [nn].

References:

a) Syvitski et al. 2009
b) Hori and Saito 2008
c) Luecke et al. 1999
d) Rovira and Ibàñez 2007
e) Gamage and Smakhtin 2009
f) Coleman and Huh 2003

g) Encyclopedia Britannica Online 2013
h) Grillas 2013
i) Ibàñez, et al. 1996
j) Less than 0.5 m above mean sea level
k) Nilsson et al. 2005- flow regulation calculated as sum of live reservoir storage relative to virgin mean annual flow.
l) Gupta et al. 2012
m) Alexander et al. 2012
n) Dai et al. 2008
o) Dang et al. 2010
p) Yang et al. 2011
q) Wang et al. 2010
r) Syvitski and Saito 2007
s) Kundzewicz, et al. 2009
t) Schmidt 2008
u) Luecke et al. 1999
v) Jimenez and Sanchez-arcilla 1997
w) Malini and Rao 2004
x) Giosan el al. 2006
y) Wells and Coleman 1984
z) Couvillion el al. 2011
aa) Frihy el al. 1994
bb) Zhang el al. 2010
cc) Van Maren 2004
dd) Yang el al. 2003
ee) Yang el al. 2007
ff) Yang el al. 2005
gg) Yang el al. 2006
hh) Peng el al. 2010
ii) Saito el al. 2007
jj) Lóczy 2007
kk) Panin, 1999
ll) Sarwar and Woodroffe 2013
mm) Hedley et al. 2010
nn) Coleman et al. 2008
oo) Sabatier et al., 2009
pp) Mertes and Magadzire 2008
qq) Syvitski and Milliman 2007
rr) Anthony et al., 2012

Table 2. Reach characterization of the lower Mekong River

Reach Location	Adamson 2001 and Carling 2009a	Gupta 2004	Representative reach characteristics	Expected Changes
China	Zone 1: China	-	Not applicable	
Upper Bedrock Chinese border to 5km upstream of Vientiane	Zone 2: Bedrock single-thread channel - Chiang Saen to Vientiane: deep pools, bedrock benches	1a, 1b, 1c, 1d	Gradient: 0.0003 Channel width: 200m to 2000m Low flow depth: 10m Seasonal stage change: 20m	Negligible downcutting. Erosion limited to stripping of alluvial deposits overlying bedrock (bars, islands, inset floodplains, banks)
Middle Alluvial Vientiane to Savannakhet	Zone 3: Alluvial single-thread or divided channel	2a, 2b	Gradient: 0.0001 Channel width: 800m to 1300m Low flow depth: 3m Seasonal stage change: 13m	Alluvial bed and banks susceptible to erosion. Both downcutting and bank erosion likely.
Middle Bedrock Savannakhet to Kratie	Zone 3 continued (Savannakhet to Pakse). Zone 4: Bedrock anastomosed channels: Pakse to Kratie i.e. Siphandone (4000 islands reach)	3, 4, 5, 6	Gradient: 0.00006-.0005 Channel width: 750 to 5000m Reach length: 400km Low flow depth: ≤ 5 to 8 m Seasonal stage change: 9-15 m	Negligible downcutting. Erosion limited to stripping of alluvial deposits overlying bedrock (bars, islands, inset floodplains, banks)
Cambodian Alluvial Kratie to Phnom Penh	Zone 5A: Alluvial meandering/ anastomosed channels - Kratie to Phnom Penh: scroll bars, backwaters, overbank flooding, i.e. upstream of confluence with Tonlé Sap River Zone 5B: Tonlé Sap Lake and River seasonally reversing flows	6, 7	Gradient: 0.000005 Channel width: ≤4km. Floodplain width: 8 to 64km Low flow depth: 5m Seasonal stage change: 18m	Alluvial bed and banks susceptible to erosion. Both downcutting and bank erosion likely.
Vietnamese Delta Phnom Penh to ocean	Zone 6: Alluvial deltaic channels-Phnom Penh to ocean: distributaries, no marine influence in upper delta	8	Gradient: 0.000005 Channel width: ≤3km Delta inundation width: ~180km Low flow depth: 25m Seasonal stage change: 15m	Reduced rates of aggradation, shrinking delta, increasing risk of flooding from river and storm surge.

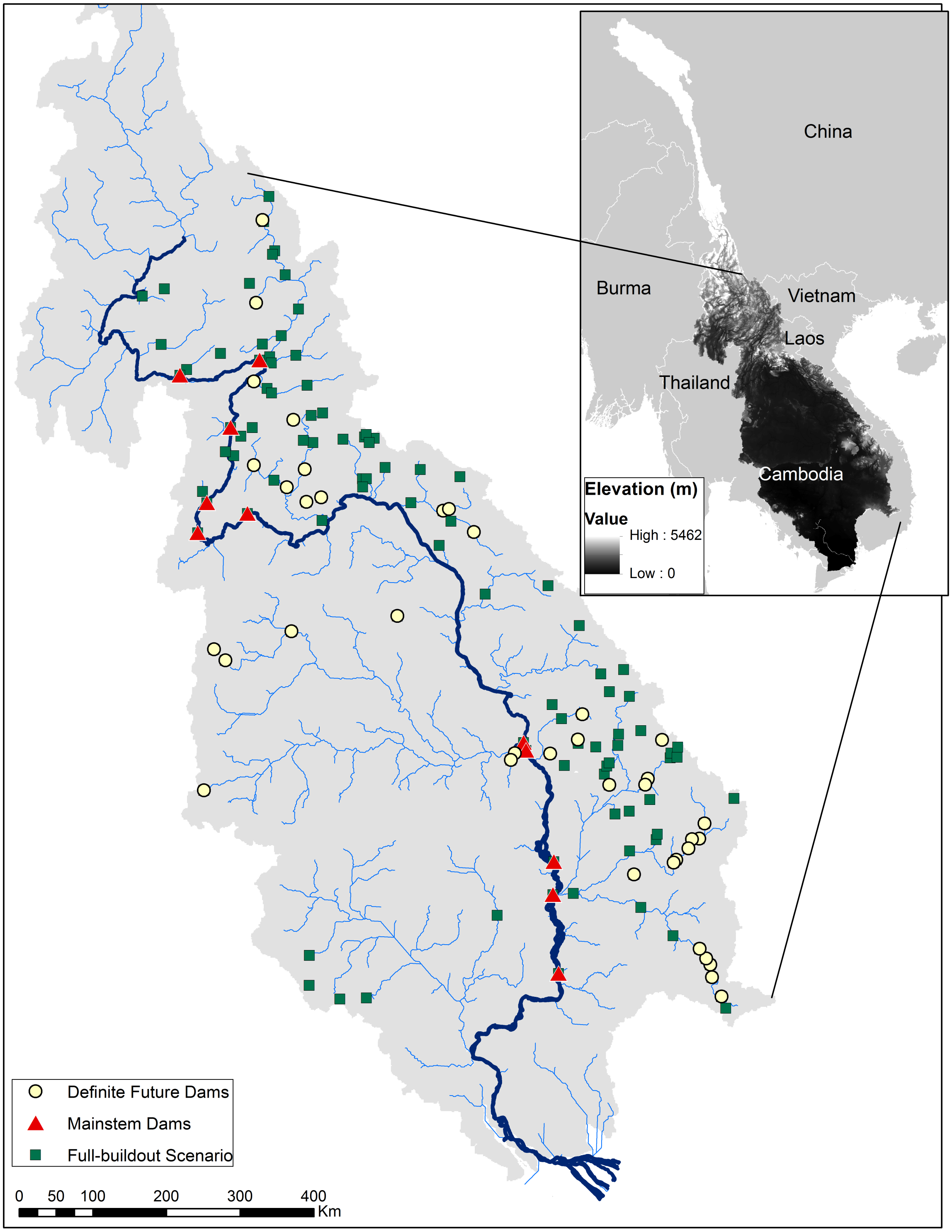

Figure 1. Dam locations are indicated for two scenarios: definite future, and full-build. Mainstem dams are included in full-build scenario, but represented separately.

Figure 2. Reaches of predominantly bedrock vs alluvial channel, as generalized from Adamson (2001) Gupta (2004) and Carling (2009 a). Bedrock-controlled channel reaches are likely to experience rapid loss of surficial sediment deposits, but will not manifest large channel changes in response to reduced sediment loads, whereas alluvial reaches will likely incise and/or widen as they erode to compensate for reduced sediment supply.


Figure 3. Bedrock channel of the Mekong River with surficial sand deposits 1-2 m thick, near Xayaburi, Laos. (photo by Kondolf, January 2012)