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Changing sediment budget of the Mekong: Cumulative threats and management strategies for a large river basin

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Abstract

Two decades after the construction of the first major dam, the Mekong basin and its six riparian countries have seen rapid economic growth and development of the river system. Hydropower dams, aggregate mines, flood-control dykes, and groundwater-irrigated agriculture have all provided short-term economic benefits throughout the basin. However, it is becoming evident that anthropic changes are significantly affecting the natural functioning of the river and its floodplains. We now ask if these changes are risking major adverse impacts for the 70 million people living in the Mekong Basin. Many livelihoods in the basin depend on ecosystem services that will be strongly impacted by alterations of the sediment transport processes that drive river and delta morpho-dynamics, which underpin a sustainable future for the Mekong basin and Delta.

Drawing upon ongoing and recently published research, we provide an overview of key drivers of change (hydropower development, sand mining, dyking and water infrastructures, climate change, and accelerated subsidence from pumping) for the Mekong's sediment budget, and their likely individual and cumulative impacts on the river system. Our results quantify the degree to which the Mekong delta, which receives the impacts from the entire connected river basin, is increasingly vulnerable in the face of declining sediment loads, rising seas and subsiding land. Without concerted action, it is likely that nearly half of the Delta's land surface will be below sea level by 2100, with the remaining areas impacted by salinization and frequent flooding. The threat to the Delta can be understood only in the context of processes in the entire river basin. The Mekong River case can serve to raise awareness of how the connected functions of river systems in general depend on undisturbed sediment transport, thereby informing planning for other large river basins currently embarking on rapid economic development.

1. Introduction

The Mekong is amongst the world's ten largest rivers, both in terms of its flow discharge and its sediment load (Gupta and Liew, 2007). The diverse geographic settings of its 795,000 km^2 drainage area range from the Tibetan highlands to the vast floodplains that dominate in Cambodia and Vietnam, while its pronounced flood-pulse hydrology makes it a hotspot for biodiversity (Gupta and Liew, 2007; Kummu and Sarkkula, 2008; Campbell, 2009a; Hortle, 2009). What sets the Mekong apart from many other large rivers is the very high number of livelihoods that it supports through a wide array of ecosystem services. Many of the basin's 70 million inhabitants live close to the river and depend on complex and still poorly understood interactions among river hydrology, sediment transport, and river morpho-dynamics (Hortle, 2009; MRC, 2010). The Mekong Delta is not only amongst the world's largest river deltas, but also supports a population of more than 17 million people and produces agriculture and aquaculture of regional importance (Guong and Hoa, 2012; Renaud and Künzer, 2012; Szabo et al., 2016). Its population vulnerable to global climatic change and sea level rise is nearly unparalleled, as nearly half of the delta land surface (20,000 km^2) is less than 2 m above sea level (Syvitski, 2009).

The Mekong River Basin is shared among six riparian nations (China, Myanmar, Laos, Thailand, Cambodia, and Vietnam). Political struggles and wars delayed the basin's economic development until the 1990s, when the Manwan hydroelectric dam was built on the Lancang River, China (Xue et al., 2011). The Mekong Basin has since experienced rapid economic development, manifested through a substantial expansion of dams and hydropower, intensification of aggregate mining, expansion of dykes and irrigated agriculture, urbanization and exploitation of groundwater resources, all intended to promote development and extract economic value for the six nations through which the Mekong flows.

For example, Laos aims to become the "battery" of south-east Asia through a massive expansion of its dam infrastructure and hydropower production. Vietnam has invested in the construction of higher dykes to increase crop production in the Delta (Chapman et al., 2016), along with increasing ground-water pumping rates (Erban et al., 2014; Minderhoud et al., 2017). China is developing a dense cascade of dams along the upper Mekong for both hydropower and improved navigation (Räsänen et al., 2017). In Cambodia, aggregate from floodplains and channels provides a valued commodity for export, and some mega-dam sites along the mainstem Mekong offer significant hydropower production potential (Bravard et al., 2013; Wild et al., 2016).

Each of these actions might create some immediate economic benefits for the developer. However, alone and in accumulation, these projects also create negative environmental externalities that do not stop at dam or mining sites, but extend beyond country boundaries and accumulate and amplify over the entire Mekong Basin. Most developments will impact various aspects of the ecologic and geomorphic functioning of the river, ranging from obstructed fish migration and altered hydrologic regimes, to reduced sediment transport and connectivity. The impact of these disturbances within the basin might be amplified by global climate change and higher sea levels.

As the Mekong basin supports such a large number of human livelihoods and highly diverse ecosystems, understanding the cumulative impacts of the anticipated disturbances is essential for identifying the most detrimental practices, planning for early adaptation, and minimizing future impacts on human livelihoods. Many of the Mekong’s ecosystem services, and the livelihoods they support, are driven by a continuous flux of sediment from the upstream catchment to the downstream floodplains and the delta. Sediment provides the building material for floodplains and in-channel habitat. An annual flood-pulse distributes fine sediment and sediment-bound nutrients to the Mekong floodplains and the Tonle Sap Lake, supporting one of the most diverse and highest yielding inland fisheries anywhere in the world (Lamberts 2006). The sediment delivery from the Mekong River built the entire Mekong Delta landform during the Holocene.

Now in the third decade since the onset of accelerated development in the Mekong Basin, significant changes are manifest in the river basin's sediment budget and geomorphic processes. A substantial scientific effort over the last decade has yielded a significant body of knowledge about human impacts on the Mekong's sediment budget and observations of geomorphic processes. However, there is still a lack of a high-level overview regarding the ecosystem services provided by geomorphic and sediment transfer processes in the Mekong, and the cumulative impacts of resource use and development in the basin on these processes.

We base this paper on the concept that sediment dynamics in the Mekong River provide the geomorphic template upon which both human livelihoods and ecosystems are built in the Mekong basin and its delta, and that understanding human impacts on geomorphic processes is key to protecting river and delta ecosystems. In this paper, we identify resource-use practices with the greatest impacts, the cumulative impacts of disturbance, and areas where changes in geomorphic processes will have the greatest impact. We also outline potential opportunities for more sustainable management. Such a high-level assessment of potential synergies in both threats and management responses may be informative for other basins where extensive development has begun, such as the Amazon or the Congo (Winemiller et al., 2016).

We first provide an overview of the geography and natural sediment transport dynamics of the Mekong River basin and discuss the value of ecosystem services extracted from the river, its floodplains, and delta. We then analyze four major drivers behind changing sediment transport and morpho-dynamics, namely damming, sand mining, dyking of floodplains, and groundwater pumping. The delta, which hosts the largest population and largest agricultural production in the basin, will accumulate impacts of upstream disturbance and suffer additionally from global climatic changes and sea level rise. Hence, we conclude with an overview regarding potential futures of the delta landform as a whole, and potential management responses.

2. Geographic setting and socio-economic importance of the Mekong River Basin and its delta

The Mekong River Basin

The Mekong River (its upper reach in China is known as the Lancang) drains 795,000 km^2, dropping around 4000 m from its narrow headwater catchment on the Tibetan Plateau through bedrock canyons in Yunnan Province of southwest China and along the border with Burma. Then the Mekong drops around 500 m as it flows through Laos, Thailand, Cambodia, and Vietnam *en-route* to its delta in the South China Sea. The lower Mekong displays a complex sequence of morphologic units of bedrock-controlled and alluvial reaches (Gupta and Liew, 2007; Carling, 2009). Finally, the Mekong debouches via nine distributaries within the Mekong Delta (Figure 1) into the South China Sea.

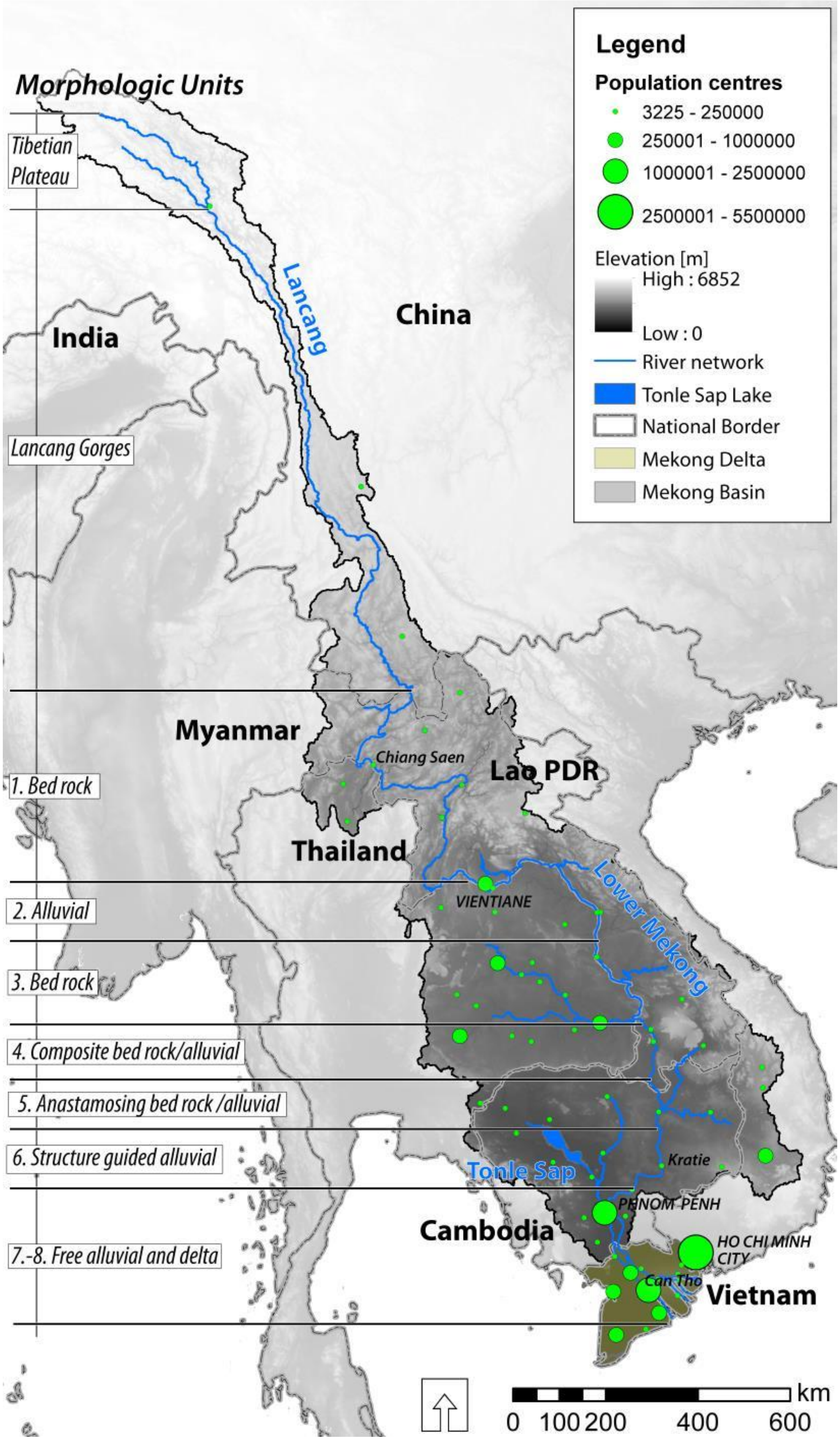
Morphologic Units
Tibetian Plateau
Lancang Gorges
1. Bed rock
2. Alluvial
3. Bed rock
4. Composite bed rock/alluvial
5. Anastamosing bed rock /alluvial
6. Structure guided alluvial
7.-8. Free alluvial and delta
Lancang
China
India
Myanmar
Chiang Saen
Lao PDR
Thailand
VIENTIANE
Lower Mekong
Tonle Sap
Kratie
PHNOM PENH
Cambodia
HO CHI MINH CITY
Can Tho
Vietnam
Legend
Population centres
3225 - 250000
250001 - 1000000
1000001 - 2500000
2500001 - 5500000
Elevation [m]
High : 6852
Low : 0
River network
Tonle Sap Lake
National Border
Mekong Delta
Mekong Basin
km
0
100
200
400
600

Figure 1: Overview of the Mekong Delta and the Mekong basin. Morphologic units of the mainstem of the Mekong are from Gupta and Liew (2007). Population centers in the basin are clustered along major rivers, especially in the Delta.

The Mekong River Basin has a complex geology resulting from the Tertiary collision of the Indian and Eurasian plates, consequent deformation and opening of large strike-slip fault-controlled basins, and subsequent volcanism (Carling, 2009; Gupta, 2009). The Mekong's average discharge to the sea is about 15,000 m^3s^{-1}, with predictable 20-fold seasonal fluctuation from dry season (November-June) to wet (July-October) (Gupta et al., 2002; Adamson et al., 2009).

The sediment load of the Mekong has been much debated in the literature because of the incompleteness and methodological bias of available sediment gauge data (Walling, 2008, 2009), and the range of reported values likely reflects different sampling points, methods, and different temporal ranges used, as well as a natural spatio-temporal variability in the suspended sediment transport. The depositional record in the Mekong Delta indicates a long-term average sediment flux (over the past 3 ka) of 144 ± 34 Mt/yr (Ta et al. 2002), which is in accord with Liu et al.'s (2013) value of 145 Mt/yr based on gauge data. Prior estimates of the pre-dam sediment flux of the Mekong River into the South China Sea ranged up to approximately 160 Mt y^{-1}, of which about half was attributed to the upper 20% of the basin area, the Lancang drainage in China (Milliman and Meade, 1983; Milliman and Syvitski, 1992; Gupta and Liew, 2007; Walling, 2008). Other authors have proposed lower sediment loads. Manh et al. (2014) proposed 106 Mt/yr for Kratie, around 400 km upstream of the Delta (Figure 1), for 2010-2011, based on recalculation of sediment loads; they proposed that another third of that load was deposited on floodplains downstream, with the remaining two thirds reaching the Delta. At Kratie, Darby et al. (2016) applied a correction based on recent hydroacoustic measurements of sediment transport to 25 years (1981-2005) of suspended sediment load measurements to calculate a suspended sediment load of 87.4 ± 28.7 Mt/yr. Farther downstream, upstream of the confluence of the

Mekong with the Tonle Sap river, Lu et al. (2014) calculated a suspended sediment load of 50-91 Mt/yr from 2008-2010 measurements. Recent sediment transport measurements are more reliable, but may not be comparable to older measurements, as sediment transport is already reduced due to sediment trapping in reservoirs, and sand mining directly from the channel. We discuss the possible causes of the variability in the estimates of the Mekong's sediment load further below, but it is noteworthy that the apparent general downstream decrease in sediment load can likely be attributed, at least partially, to deposition of sediment in the Cambodian floodplains (Lu et al., 2014).

While all the above studies focused mostly on suspended sediment, which may contain considerable fine sand (Bravard et al., 2014), there is uncertainty regarding the flux of sand and fine gravel as bedload (Koehnken, 2012a; Bravard et al., 2013, 2014).

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The Mekong Delta

Like any delta, the Mekong Delta is the result of sediment load transported down the river system and deposited where the river meets the sea. The subaerial Mekong Delta is a relatively recent landform of Holocene origin (Figure 2). During the mid-Holocene sea level maximum around 8000 ka ago, the upper end of the Mekong estuary system reached north as far as Phnom

Penh (Figure 2). Then, over the past 7000 years the Mekong Delta prograded from roughly the Cambodia-Vietnam border southeastward at a rate of around 10 to 16 km^2 per year (Nguyen et al., 2000; Tanabe et al., 2010). Thus, the 40,000 km^2 of subaerial delta surface, which provides space for people, agriculture and aquaculture, and a wide range of ecological services, is very young and was still expanding under the natural river flooding regimen until recent decades. Its thin sediment surface (< 1m thick) is a 'critical zone' that involves complex interactions of soil, water, air and organisms, which regulate the human and natural habitat and largely determine the availability of life-sustaining resources (Giardino and Houser, 2015).

A broader definition of an ecologically, socio-economically, and hydrologically connected Greater Mekong Delta also includes the delta of the Saigon River (where Ho Chi Minh City is located), the Mekong floodplains in Cambodia, and the Tonle Sap Lake basin. Tonle Sap Lake (Figure 1) drains, via the Tonle Sap River, to join the Mekong at Phnom Penh. When the Mekong is in flood, the level of the mainstem Mekong River is higher than the lake, driving river waters over floodplains and up the Tonle Sap River, supplying sediment and sediment-bound nutrients to the lake, and facilitating fish migration between the lower Mekong and the Tonle Sap Lake s(Kummu and Sarkkula, 2008; Hortle, 2009). The diversion of the Mekong's floodwaters to the Tonle Sap Lake attenuates extreme flood levels downstream in the delta, while the gradual release of water stored in the lake during the dry season augments low flows, sustaining agriculture in the delta during the dry season.

The many ecosystem services that the lower Mekong River and Delta provide to support human livelihoods and provide rich economic opportunities are based on an interplay between hydrologic variability, sediment and nutrient transport, and river and delta morphology. Hence, livelihoods in the lower Mekong Basin and its Delta are particularly vulnerable to any human-induced changes in the river's hydrology and sediment transport regime, and in the delta's sediment budget.

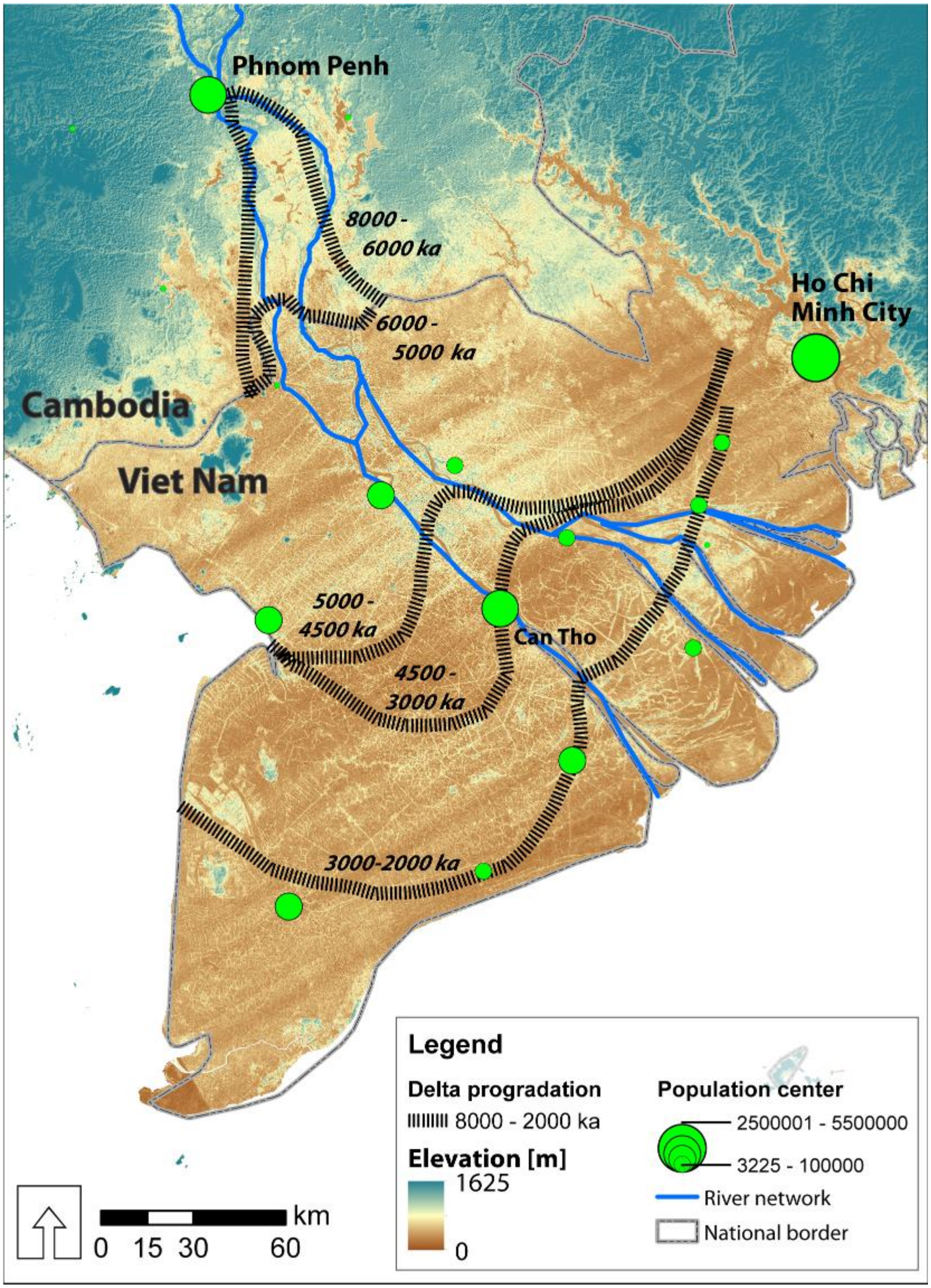


Figure 2: Holocene progradation of the Mekong Delta. During the postglacial sea-level maximum 8000 ka, an estuary system reached up to today's location of Phnom Penh. Today's Delta, that harbors many important population centers was hence prograded only over the last 5 – 6 ka from the Vietnamese-Cambodian border to its current extent (progradation data derived from Nguyen et al., (2000))

The Regional and Global Socio-economic importance of the Mekong River and its delta

Both the Mekong Delta and the entire Mekong River Basin are exceptional among the world's great rivers in the size of the human population supported by their ecosystems. The Mekong basin's population is approximately 70 million, for most of whom fish and rice derived from the rivers and floodplains are the central staple (Hortle, 2009). For people living in the Mekong Basin, fish accounts for an estimated 47 % to 80 % of protein consumption (Hortle 2007). With an annual production of around 23 Mt/yr, the Mekong Delta constitutes more than half of the 46 Mt of paddy rice harvested in Vietnam per year (as per 2014) (Thuy and Anh, 2007, Kontgis et al., 2015, FAOstat, 2017). The Vietnamese Mekong delta hence produces 2,4 % of the global paddy rice harvest of 950 Mt/yr (FAOstat, 2017). Rice constitutes 20 % of the globally consumed calories (Kontgis et al., 2015). Hence, the Mekong Delta which covers a minute fraction of global crop land produces around 0.5 % of the global calorie supply.

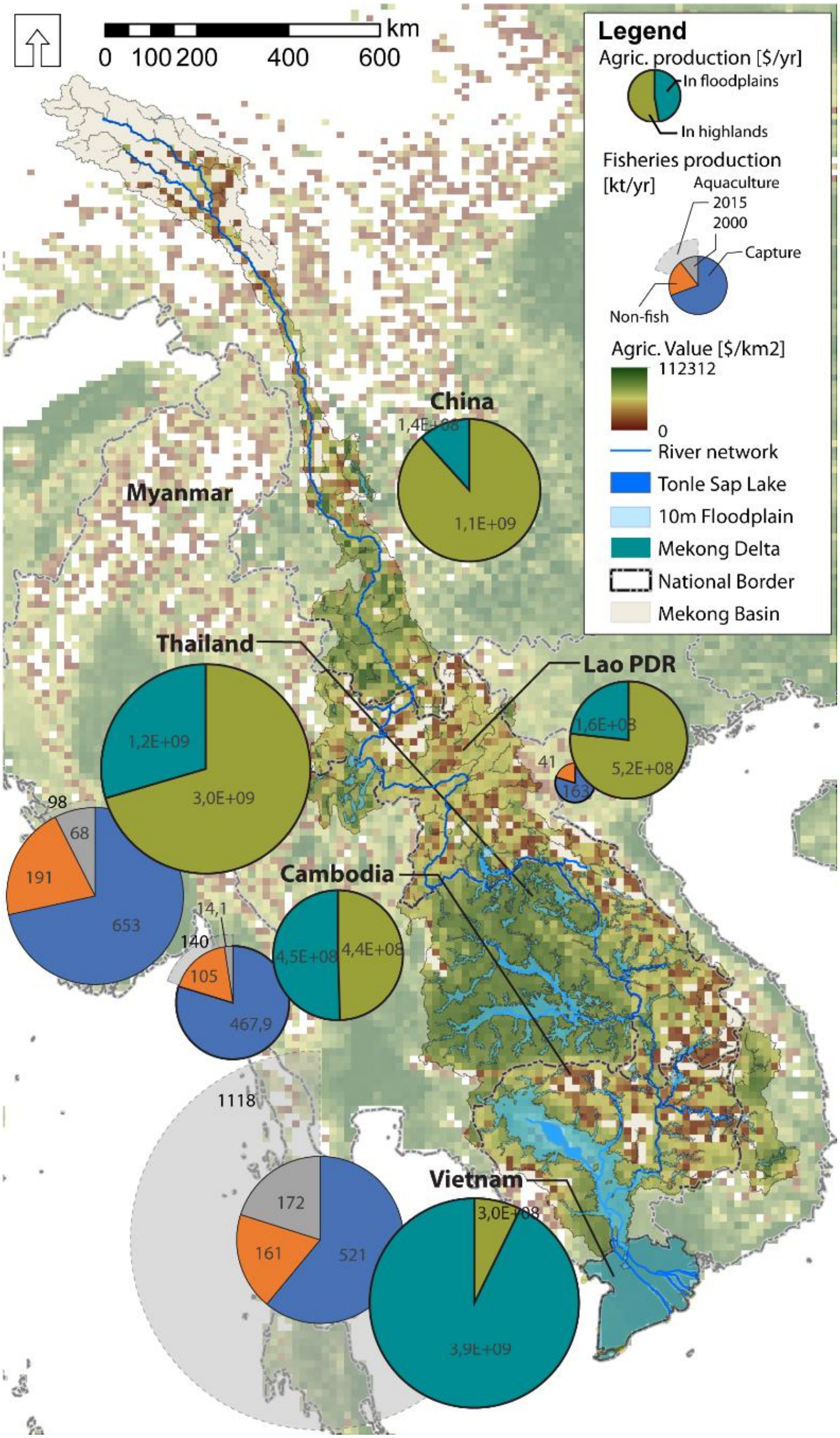
Protein is extracted from a variety of aquatic sources, namely capture fisheries, capture of non-fish aquatic organisms (crustaceans, shrimps and crabs, amphibians, etc.), and aquaculture (in freshwater and brackish water) (Hortle, 2009). While the outstanding importance of the protein derived from these sources is widely acknowledged and up to 3.2 million households are engaged in fishing, there is a considerable uncertainty regarding the yield of Mekong fisheries (Hortle, 2009; Orr et al., 2012). Hortle (2009) estimated that total production of all fisheries was 2561 Mkg/yr (around the year 2000), of which around 2063 Mkg/yr were from fish (farmed and captured) and the remainder, hence around 25 % of the total, from non-fish organisms. Phillips (2002) estimated the aquaculture production based on 1998 – 2000 data to be 259 Mkg/yr. Hence the fresh-water capture fishery would amount to 1804 Mkg/yr (2063 Mkg/yr total fish production minus 259 Mkg/yr from aquaculture, see Figure 3 and Table 1). However, ICEM (2010) estimated a much lower value (755 Mkg/yr) for fresh-water fisheries based on FAO data. According to

Hortle (2009) and Phillips (2002), total fisheries were highest in Thailand (853 Mkg/yr) and Vietnam (912 Mkg/yr) (Figure 3), followed by Cambodia (587 Mkg/yr), and Laos (204 Mkg/yr). Aquaculture was highest in Vietnam and absent in Laos. Although fish harvests are lowest in Laos, Laotian rivers are essential spawning habitats and thus contribute to productivity in the more downstream countries (Poulsen and Valbo-Jørgensen, 2000).

Aquaculture has increased over the last 15 years, ten-fold in Cambodia (from 14 to 140 Mkg/yr), nearly six-fold in Vietnam (from 172 to 1118 Mkg/yr), and more modestly in Thailand (from 68 to 92 Mkg/yr) (Figure 3 and Table 1) (Phillips 2002, FAO FishStat, 2017a, 2017b, 2017c).

Agriculture in the basin is an important part of the economy of each of the Lower Basin countries (MRC, 2016). However, there is little information regarding which part of the agricultural production is directly related to the Mekong (in the form of water or sediment-bound nutrients). As an approximation of the area of floodplain, we mapped the area 10 m or less above river channels and determined the value of agriculture falling into that floodplain from global gridded values of agricultural production (IIASA/FAO, 2012). Based on these data, Vietnam and Thailand extract the highest total agricultural value from their parts of the Mekong River Basin (Figure 3). However, it should be noted that for Thailand most of that production is outside of floodplains. For Vietnam and Cambodia, instead, the floodplains and the delta constitute hotspots of agricultural productivity where around 50 % (Cambodia) and 90 % (Vietnam) of the countries' total agricultural production in the basin originates. It should, however be considered that values are likely even higher, 1) because aquaculture is not considered, and 2) because the global gridded data provided by IIASA/FAO (2012) are derived from a relatively simple up-scaling of global data that likely underestimate the value of complex agro-economic systems along the floodplains.

The socio-economic importance of the delta is also manifest from the population patterns in the Mekong basin. The basin's three largest cities are located in the Delta, and thus on land that did not yet exist 8,000 years ago: Ho Chi Minh City (with 7.5 million inhabitants, accounts for 17 % of Vietnam’s GDP and 25 % of Vietnam’s industrial output (World Bank 2004)), Phnom Penh (with 1.6 million inhabitants), and Can Tho (with 1.1 million inhabitants) (Figure 1, 2).



km
0 100 200 400 600
Legend
Agric. production [$/yr]
In floodplains
In highlands
Fisheries production [kt/yr]
Aquaculture
2015
2000
Capture
Non-fish
Agric. Value [$/km2]
112312
0
River network
Tonle Sap Lake
10m Floodplain
Mekong Delta
National Border
Mekong Basin
China
1,4E+08
1,1E+09
Myanmar
Thailand
1,2E+09
3,0E+09
Lao PDR
1,6E+08
5,2E+08
41
163
98
68
191
653
Cambodia
14,1
140
105
467,9
4,5E+08
4,4E+08
1118
172
161
521
Vietnam
3,0E+08
3,9E+09

Figure 3: Agro-economic and fisheries value of the Mekong Basin, its rivers and floodplains (blue shade, defined as area < 10 m above stream channels). Pie charts visualize the total agricultural value extracted by each abutting country, divided by the agricultural value within the floodplain and in more upland areas (chart area proportional to total values). Data on fisheries as per 2000 are derived from Hortle (2009), Phillips (2002), and FAO FishStat (2017a, 2017b, 2017c). Values on aquaculture expansion are derived from FAO FishStat (2017a, 2017b, 2017c) for 2015.

3. Drivers and threats of changing sediment dynamics processes for the Mekong River and its Delta

In this section, we review anthropogenic pressures on the Mekong's hydrologic and sediment transport regimen, including damming, sand mining, construction of delta-based water infrastructure, excessive groundwater extraction, and global climatic changes; and we also assess the likely impacts of these drivers on river and delta morpho-dynamics, ecosystems, and livelihoods in the basin.

Dams

Hydroelectric development in the past and future

Economic development of the nations of the Mekong basin brought a relatively recent surge in the development of dams. Figure 4 shows sites where dams are built, under construction, or planned in the Lancang (International Rivers, 2014), hydroelectric dams planned in the lower Mekong and its tributaries (MRC, 2012), and around 490 smaller dams in the lower Mekong that are not part of the MRC data-base (Open Development Mekong, 2014).

As noted above, the Mekong Basin remained pristine until relatively recently. Some dams were built in the 1960s in Thailand and Lao PDR, but regional conflicts prevented most development until the mid-1990s (Hirsch, 2010). From the mid-1990s to early 2000s dam development accelerated in China and Vietnam with the construction of mainstem dams on the lower Lancang and tributary dams in the Vietnamese highlands (Figure 4). Eleven mainstem dams are built or planned, including the controversial Xayaburi project in Laos (Grumbine and Xu, 2011; Grumbine et al., 2012). In China, the existing hydropower cascade will be expanded upstream with at least 17 additional dams (Räsänen et al., 2017). However, while large dams on the mainstem receive substantial attention, there are also many dams planned or under construction in important tributary rivers, notably in Laos and Cambodia.

In addition to large hydropower dams, there are numerous diversions for irrigated agriculture and small hydropower throughout the basin, some of which involve storage impoundments that trap sediment, but most are small diversions directly from river channels, and most are concentrated in the relatively low relief Khorat Plateau of Thailand (Figure 4). While little is known about these dams, it should be noted that small dams may cumulatively impact fish migration or sediment dynamics, especially on local scales (Fencl et al., 2015). However, the principal impact of dams on the Mekong River system will be controlled by the major hydroelectric projects, on whose impacts we focus herein.

Hydrological impact

The operation of hydropower dams in the Mekong has already altered the monsoon-driven hydrological cycle, by reducing the flood peaks and increasing dry season flow and water-level fluctuations (Lu et al., 2014; Cochrane et al. 2014; Räsänen et al., 2017). Various basin-wide models have simulated the potential impacts of reservoir operation on the downstream hydrological regime. The hydrological models agree on the direction and magnitude of changes. At Kratie (the most downstream station before the river enters the Cambodian floodplains) dry season flows are predicted to be approximately 25–160 % higher and flood peaks 5–24% lower if most mainstem and tributary dams are realized (Lauri et al., 2012). The validation of modelling studies in the Yunnan part of the Mekong by Räsänen et al (2017) found that the observed impacts in 2010-2014 were very close to the simulated ones, in some months even higher than predicted by models.

While these changes to flow regime provide more water during the dry season (increasing the supply for irrigation and potentially decreasing salt water intrusion in the delta), and may reduce the extent of floods, they would likely decrease the flood-magnitude and hence the area of highly productive, seasonally inundated floodplain agriculture and fisheries (Arias et al., 2014) that supports the economy of the basin countries (see section 2.3).

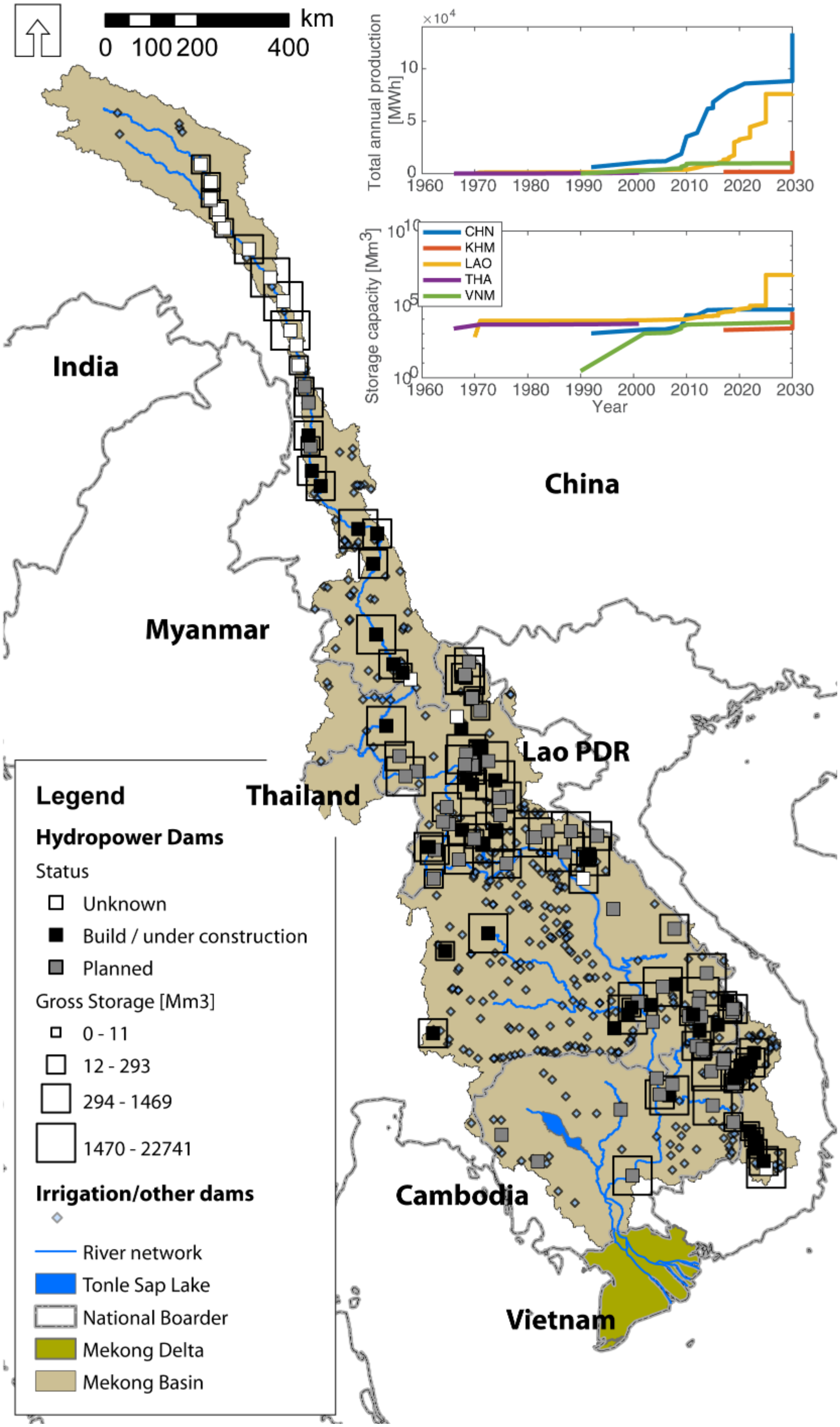

km
0 100 200 400
India
China
Myanmar
Lao PDR
Thailand
Cambodia
Vietnam
Total annual production [MWh]
×10^4
0
5
10
1960 1970 1980 1990 2000 2010 2020 2030
Storage capacity [Mm³]
10^0
10^5
10^10
CHN
KHM
LAO
THA
VNM
Year
Legend
Hydropower Dams
Status
Unknown
Build / under construction
Planned
Gross Storage [Mm3]
0 - 11
12 - 293
294 - 1469
1470 - 22741
Irrigation/other dams
River network
Tonle Sap Lake
National Boarder
Mekong Delta
Mekong Basin

Figure 4: Distribution of major hydropower dams and other smaller dams built or planned in the basin (MRC, 2012; International Rivers, 2014). The upper insert figures show total annual energy production of existing, under construction and planned dams over time by country in Megawatt-hours (top inset figure) and the total storage capacity in millions of m^3 *of the reservoirs impounded by those dams (bottom inset figure).*

Sediment and Nutrient Trapping

As dams impound rivers and induce deposition within reservoirs, they reduce the supply of sediment to the channels downstream. Dams along the Lancang have large storage capacities relative to their inflow, resulting in long residence times, sufficient for most incoming sediment to settle out (Kummu et al., 2010). Because the Lancang basin is estimated to contribute about 50 % of the Mekong's total sediment load (Walling, 2009), dams on the Lancang alone would reduce the Mekong's sediment load by around 50 %. The ultimate reduction of sediment delivery to the delta will however strongly depend upon which dam portfolio is developed in the mainstem and tributaries of the lower Mekong. The construction of all dams as planned would greatly reduce the sediment delivery to the delta, with estimated reductions ranging from 60% (Kummu et al., 2010) to 96% (Kondolf et al., 2014b), once temporary sediment storage in the channel is exhausted.

Globally, sediment trapping in reservoirs is not necessarily equal (on the short term) to the downstream reduction in sediment transport (Walling and Fang, 2003). For one thing, sediment-starved, "hungry water" released from dams scours out sediment stored in river channels and floodplains, and can thus partially compensate for reduced sediment supply, an effect that lasts only until the stored sediment is depleted, usually on a time scale of years to decades (Kondolf, 1997). Additionally, large storage reservoirs can reduce high flows so much that the downstream channel cannot transport even a much-reduced sediment load (Schmidt and Wilcock 2008). Finally, land use changes coinciding with reservoir construction can increase sediment yields from downstream tributaries, which could serve to partially compensate for reduced sediment supply from upstream. However, grain size characteristics of the newly-eroded sediment can be quite different from those of sediment trapped by the dams, so the sediment eroded from freshly disturbed areas may only poorly compensate for sediment trapped by the dams.

In the Mekong, the effect of these compensatory mechanisms is likely limited. Because most of the lower Mekong is bedrock controlled (Figure 1), there are very limited stocks of easily eroded sediments available to the river. A reduction in sediment transport is already evident at Chian Seng (Figure 1), the upstream-most measurement station on the lower Mekong, since construction of Manwan Dam in 1993. Kummu and Varis (2007) computed a 57% sediment reduction in the total suspended solids concentration (measured in water quality sampling campaigns, not depth-integrated samples) after 1993. Darby et al. (2016) also reported substantial reductions at downstream gages from 1995-2000, attributing more than half of these reductions to reduced tropical cyclone activity. However, analyses of suspended sediment concentrations (Walling, 2008, 2009; Wang et al, 2011; Fu et al, 2006, Lu and Siew, 2006), did not generally detect significant reductions between pre-dam data and the measures from 1993-2003, following the closure of Manwan. Walling and others hypothesized that Mekong morphology (which stores most of the sediment within the channel) buffered sediment deficits and that compensatory mechanisms (increased sediment supply from deforestation and dam construction and dam induced bed scour and bank failure) could temporarily offset reservoir sediment deposition at downstream gages (Walling 2005, Wang et al. 2011, Kummu and Varis 2007). Koehnken's (2014) analysis suggests that these buffering and compensatory mechanisms were temporary, showing that the sediment load entering the LMB from China has decreased from an average of 84.7Mt/yr (1960-2002) to 10.8 Mt/yr at Chiang Saen. Downstream, the measured load at Pakse has decreased from an average of 147 Mt/yr to about 66 Mt/yr. . Hence, Koehnken's (2014) data indicate that sediment loads in the Mekong are more than halved, compared to historical base levels.

Additionally, these analyses focus on total sediment load, but the dams are more likely to retain coarser material, disproportionately passing the finer sediments. Therefore a 50% total sediment reduction will likely translate into more than a 50% reduction in delta deposition, because the remaining sediment will be finer, and more easily transported to the sea (even under historic delta distributary configurations) than baseline loads. Since completion of Nuozhadu, the largest dam in the cascade in 2014, greater reductions are likely to manifest.

Compounding effects of dams on connectivity, morpho-dynamics, and ecosystem services

Connectivity in fluvial systems refers to the magnitude and timing of transport and exchange processes across different components in the system in longitudinal, lateral, and vertical dimensions (Kondolf et al., 2006). Longitudinal connectivity can refer to the routing of discharge (Rinaldo et al., 2006a, 2006b) or sediment (Czuba and Foufoula-Georgiou, 2014; Bracken et al., 2015; Schmitt et al., 2016), or to the travel of aquatic species (Gatto et al., 2013). Lateral connectivity describes connections between floodplains and channels, and vertical connectivity to the exchange between the river and groundwater bodies (Kondolf et al., 2006). Hence, connectivity is a key determinant behind all domains of river processes and ecosystem services (Grill et al., 2015). In the case of the Mekong, conceptualizing multi-dimensional connectivity and its alteration through various compounding mechanisms can help anticipate dam impacts on various ecosystem services.

As the largest anthropogenic barriers to longitudinal connectivity, dams alter river processes in significant ways, including release of sediment-starved water, described above, which causes adjustments in bed-level (incision) and planform of alluvial channels directly downstream of dams, with effects commonly propagating for long distances downstream (Grant et al., 2003; Petts and Gurnell, 2005; Schmidt and Wilcock, 2008; Petts and Gurnell, 2013). In the Mekong, the alluvial and delta reaches are most vulnerable to the effects of sediment starvation

(Figure 1). These are the 300-km alluvial reach from Vientiane to Savannakhet, and the alluvial and deltaic reaches downstream of Kratie (Figure 1). Reduced sediment connectivity between the Mekong River and its delta (Loisel et al., 2014) deprives the delta of its building material (Syvitski et al., 2009; Anthony et al., 2015; Rubin et al., 2015).

Dams also reduce the lateral connectivity of rivers. Channel incision decreases the river bed elevation and hence reduces the water level for a given discharge and the probability that floodplains are connected to the river during higher flow stages (Bravard et al., 1999). On the Mekong, incision will be compounded with lower flood stages because of dam operations (see "hydrological impacts" sub-section) potentially leading to strongly decreased connectivity between the Mekong River and its floodplains, affecting the highly productive floodplain agriculture currently practiced in the Mekong Delta and the Cambodian floodplains (see Figure 3 for floodplain extent). The delivery of nutrients from their upstream sources to downstream floodplains is hence impacted by dam-induced changes in both longitudinal and lateral connectivity. Hydrological alterations and trapping by upstream dams of 50% of the natural sediment load (approximately the status quo) will likely decrease the lower Mekong floodplain ecosystem's primary productivity by 34% (±4%) (Arias et al., 2014).

Sand mining

Mining of sand and gravel from river channels for construction or land reclamation is widespread globally (Torres et al., 2017). River sediments tend to be clean, well-sorted, and suitably sized for direct use in construction (for fill and aggregate), and river deposits extracted from navigable rivers allow easy transportation. In-stream extraction of sediment directly lowers the bed elevation within the footprint of the mining, but more significantly, bed incision (downcutting) can propagate upstream and downstream from the extraction site for many kilometers, endangering river ecosystems and infrastructure in the river and on its banks through changes in channel longitudinal profiles and planform (Kondolf, 1994; Mossa and McLean, 1997; Rinaldi et al., 2005; Padmalal et al., 2008). The over-steepened part of the channel flowing into the pit migrates upstream as a head-cut, extending incision upstream. The voids created by the mining (the pits themselves and the incised channels) trap sediment transported into the reach from upstream, reducing sediment loads downstream of the pit, thereby inducing incision from hungry water.

Instream mining has been intensive in the lower Mekong River. Bravard et al. (2013) estimated a minimum of 34 Mm^3 (approximately 54 MT/yr for an aggregate density of 1.6 t/m^3) extraction annually, mostly (90 %) sand, and to a smaller degree gravel (8 %) and pebble (1%). Most of the aggregate is mined in Cambodia (21 Mt/yr) and Vietnam (8 Mt/yr), and less in Thailand (5 Mt/yr) and Laos (1 Mt/yr) (Bravard et al., 2013) (Figure 5). This aggregate has been used nearby to raise elevations of low-lying lands (known locally as 'beng') in the floodplains of Cambodia and Vietnam. Aggregate from the Mekong is also an internationally commodity despite recent efforts to control the export of river sand. Cambodia, for example, banned exporting dredged sand in 2009 (Bravard et al., 2013; Pnomh Phen Post, 2016). Nonetheless, according to the United Nations Comtrade Database (UN Comtrade, 2016) for the 2000-2016 period, Singapore, as the largest sand buyer in the region, bought 80 Mt of sand from Cambodia at a reported value of 778 $ million (USD) and 74 Mt from Vietnam at a reported value of $878 million. However, it is unknown what percentage of these total amounts were derived from river vs coastal sources, and in the case of river sand from Vietnam, what part was derived from the Mekong vs the Red/Hong River (Figure 6 a). Sand and other aggregates from the Mekong are still available from online wholesale platforms, fetching similar prices to those reported by UN-Comtrade (ca. 5 – 10 $ per tonne for sand, and up to 90 $/tonne for gravel and pebbles) (Figure 6 b and c).

It is difficult to determine the exact contribution of sand mining amongst the many compounding drivers that contribute to the changing sediment budget of the Mekong. However, if we assume a natural sediment transport rate of 160 Mt/yr (Walling, 2009), the estimated total extraction (54 MT/yr, Bravard et al. (2013) is around one third of the natural flux of all sediment. If we assume that around 3 % (i.e., 4.8 Mt/yr) (Koehnken, 2012a, 2012b) was sand or coarser, then extraction is about ten times the river's annual sand load. The geomorphic effects of extracting sand deposits from bedrock-controlled reaches would be more limited than effects in alluvial reaches, but the sand deposits in bedrock reaches likely play an important ecological role in terms of habitat and food webs, which would be lost. Moreover, sand deposits over the bedrock riverbed can serve to temporarily buffer the impact of sediment trapping by upstream dams, but this buffering will be lost if the sand is removed by mining. Effects on the river's morpho-dynamics and bio-physical functioning will be more severe in the downstream alluvial parts of the river system (Bravard et al., 2013), where sand mining contributes to the retreat of delta coastlines (Anthony et al., 2015) and bank erosion in delta distributary channels (Hung et al., 2006; Pilarczyk, 2003, p. 11).

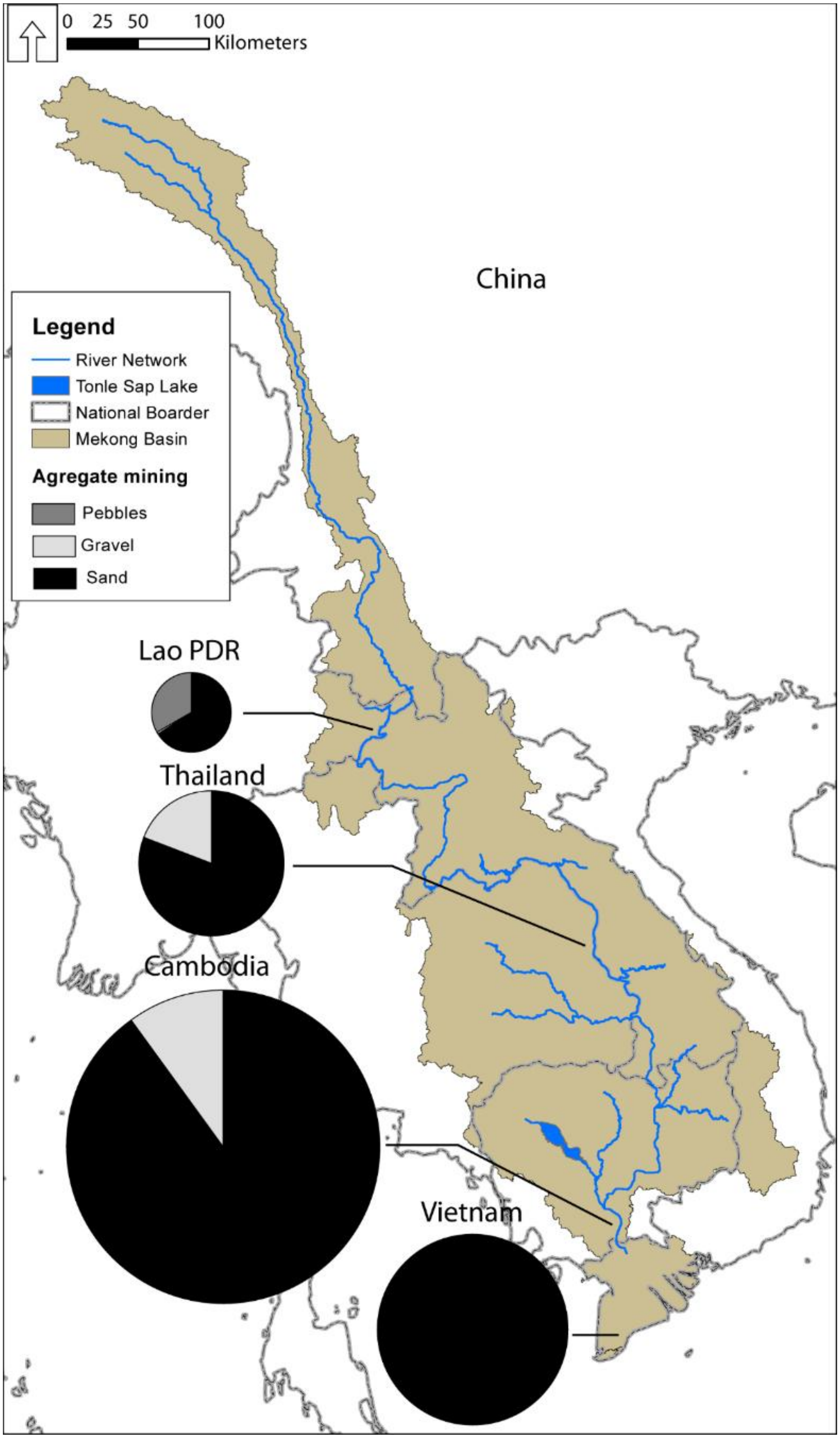
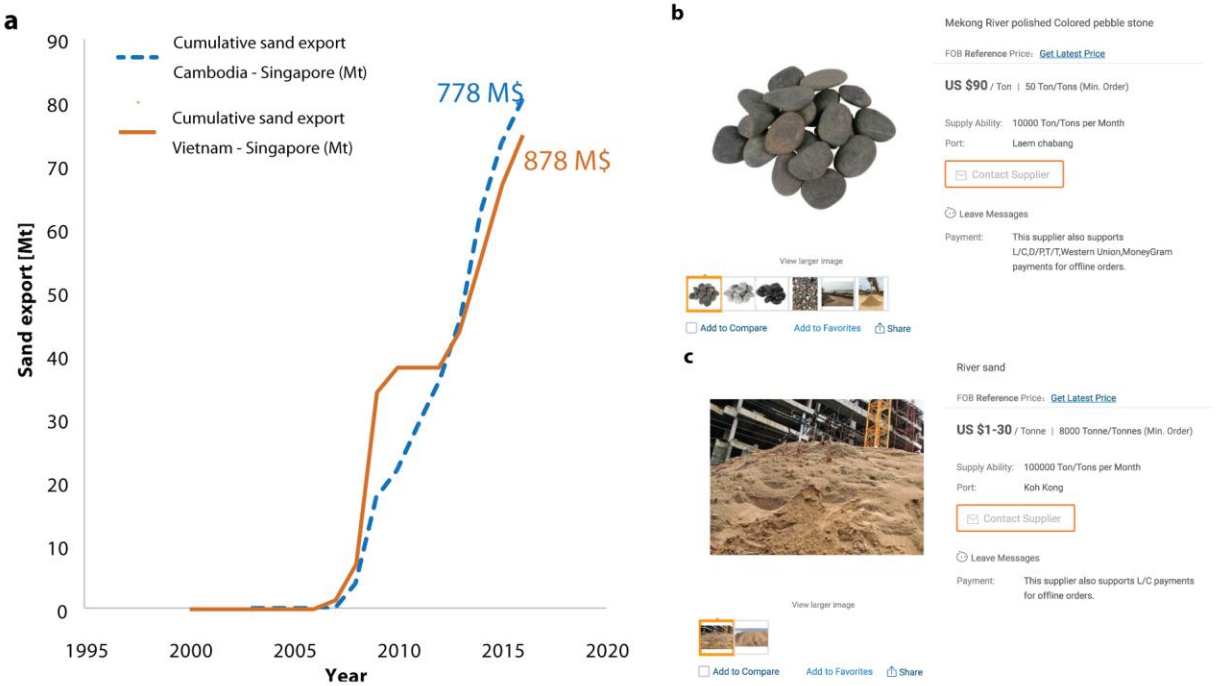
495 
0 25 50 100
Kilometers
China
Legend
River Network
Tonle Sap Lake
National Boarder
Mekong Basin
Agregate mining
Pebbles
Gravel
Sand
Lao PDR
Thailand
Cambodia
Vietnam

Figure 5: Spatial distribution of aggregate mining in the Mekong basin (visualizing data by Bravard et al. (2013)). The size of each pie chart reflects the magnitude of total mining in each country.



Mekong River polished Colored pebble stone

FOB Reference Price: Get Latest Price

US $90 / Ton | 50 Ton/Tons (Min. Order)

Supply Ability: 10000 Ton/Tons per Month

Port: Laem chabang

Payment: This supplier also supports L/C,D/P,T/T,Western Union,MoneyGram payments for offline orders.

River sand

FOB Reference Price: Get Latest Price

US $1-30 / Tonne | 8000 Tonne/Tonnes (Min. Order)

Supply Ability: 100000 Ton/Tons per Month

Port: Koh Kong

Payment: This supplier also supports L/C payments for offline orders.

Figure 6: Regional aggregate trade from the Mekong basin. (a): total sand export to Singapore from Vietnam (VN) and Cambodia (KH) The cumulative value of sand exports was 778 million dollar for Cambodia and 878 million dollar for Vietnam 2000 to 2014. (data: UN-Comstat) (note that this sand can also originate from other rivers or maritime sources). While there are no data for the post-2014 period, postings from wholesale websites (b and c) indicate that aggregate from the Mekong in Laos and Cambodia can still be ordered for global delivery.

Water infrastructure and floodplain dykes

Extensive networks of irrigation and drainage channels and flood protection infrastructure dominate the landscape of the Vietnamese Mekong Delta, the Cambodian Floodplains, and the Tonle Sap basin (Figure 7a). This complex network of canals, irrigation channels, dykes gates, and pumping stations allow for the production of a third rice crop annually and help to control flooding (Hung et al., 2012; Dang et al., 2016, Chapman et al., 2016; Chapman and Darby, 2016). However, high dykes and the irrigation network also change the spatio-temporal pattern of flows and sediment transport. Extensive levees decouple the main channel from the floodplains, restrict high flows to the channel and locally prevent overbank flooding, but consequently increase flood stage and flooding in downstream coastal areas (Alexander et al., 2012). Studies by Le et al. (2007) and Triet et al. (2017) indicate that high dykes along the Mekong and Bassac distributaries close to the Vietnam-Cambodia boarder, which were constructed in response to major floods in 2000, decreased local flood risk, but increased flood stage downstream in coastal areas.

Backwater effects from the dyked reaches may also increase the flood risk upstream of the dyked reaches (MRC, 2008) (i.e., on the Cambodian Floodplains), especially as there is a strong asymmetry between downstream Vietnamese reaches that are heavily dyked, and upstream reaches in the Cambodian floodplains with much less flood protection infrastructure (MRC, 2006). In Vietnam, dykes might be useful to fight off medium to large floods, but subsequent encroachment of residential and economic development of floodplains can greatly increase the risk in case of inevitable higher floods that overtop the dykes, an example of the “levee effect”, inducing more development behind the levees (Tobin 1995). In addition to these impacts on regional river hydraulics, dykes also have a major impact on local channels and the delta’s nutrient balance. Channel narrowing due to levees, local dykes and other hard points increase local flow velocity, scour and general bed degradation (May et al., 2002) which lowers water levels, leading to impacts on infrastructure, such as stranding of gravity-fed water supply and irrigation intakes. By separating the river from its floodplain, levees prevent the natural application of sediment and nutrient-rich flood-water fluxes, resulting in decreased crop productivity. For the Mekong Delta, Chapman et al. (2016) and Chapman and Darby (2016) provided evidence that the construction of high dykes opened the opportunity for a third paddy cropping season, but also cut-off farmers from sediment-bound nutrients delivered by the floodwaters. This effect increases farmers’ dependence on chemical fertilizer, penalizing small-holder farmers who cannot afford the chemicals (Chapman and Darby, 2016). The natural sediment deposition in the Vietnamese delta is estimated to provide 20-30% of the total N, P, and K required for growing rice (Manh et al., 2014). Chapman et al (2016) estimated the economic value of this sediment deposition to be US$ 26M (+/- US$9M) annually in the An Giang province (located in the Long Xuyen Quadrangle), alone.

While the development of flood protection has increased agricultural production locally, flood prevention has greatly altered the natural hydrological regime of the Mekong floodplains by changing the spatial distribution of flooding, resulting in increased flooding to unprotected regions within the delta (Dang et al., 2015). The currently uncoordinated development increases risk of conflicts between people in different regions and social sectors in the delta as people are displaced and economic interests threatened. To date, an integrated cost-benefit analysis accounting for the value of river sediment as natural fertilizer, effects of displacing flooding longitudinally along the river, etc., has not been undertaken, and thus it is not possible to contextualize the economic benefits of natural fertilization (Chapman et al. 2016) within a complex mosaic of other tradeoffs. Such integrated cost benefit analysis would need to consider many factors, and scaling the analysis across the delta as a whole will involve spatial trade-offs between upstream and downstream communities. For example, promoting flooding in upstream communities could attenuate flooding further downstream, such that the local economic impacts of additional flooding in one area could be offset elsewhere by the economic benefit of flood wave attenuation.

Increased flow velocities in dyked reaches (Le et al., 2007) are likely to exacerbate erosion caused by sediment-starvation from sand mining and upstream dams, and resulting bed incision and falling water levels will increase energy demand for pumped irrigation in the upper delta and create water scarcity in the lower delta that is irrigated mainly by gravity-fed irrigation (Nhan et al., 2007).

While less documented than developments within the delta, large irrigation schemes and related water infrastructure in the Tonle Sap basin and the Cambodian floodplains are also increasingly being developed (Figure 7 b). Changes in land use and uncoordinated development of water infrastructure (levees, dykes, small dams and reservoirs) change the timing and reduce the duration and magnitude of flood water and nutrients arriving in the Tonle Sap Lake and its floodplains, with likely impacts on the complex and vulnerable foodweb and the agricultural and fishery resources it provides (Baran et al., 2007).

Unregulated floodplain encroachment can drive a self-reinforcing process of unsustainable floodplain management. Concentration of economic activity and livelihoods on the floodplain creates pressure for protective measures such as dykes or operation of dams to reduce flood pulses. The resulting perception of reduced flood hazard and availability of inexpensive land can then result in further encroachment, and land reclamation to generate additional construction sites. For example, Phnom Penh expanded rapidly over the past decade. Inspection of sequential satellite imagery shows that much of this development is focused on the floodplains (Figure 8:Floodplain encroachment in Phnom Penh between 2004 (a) and 2016 (b). Arrows i and ii in a and b indicate locations where major floodplains were still largely undeveloped in 2004 and encroached in 2016. Panel c shows the closeup up such a major urban development. Arrow iii and iv show the use of sand for land reclamation, likely derived from the surrounding rivers.

a and b) potentially making use of river sand for land reclamation (Figure 8:Floodplain encroachment in Phnom Penh between 2004 (a) and 2016 (b). Arrows i and ii in a and b indicate locations where major floodplains were still largely undeveloped in 2004 and encroached in 2016. Panel c shows the closeup up such a major urban development. Arrow iii and iv show the use of sand for land reclamation, likely derived from the surrounding rivers.

c).

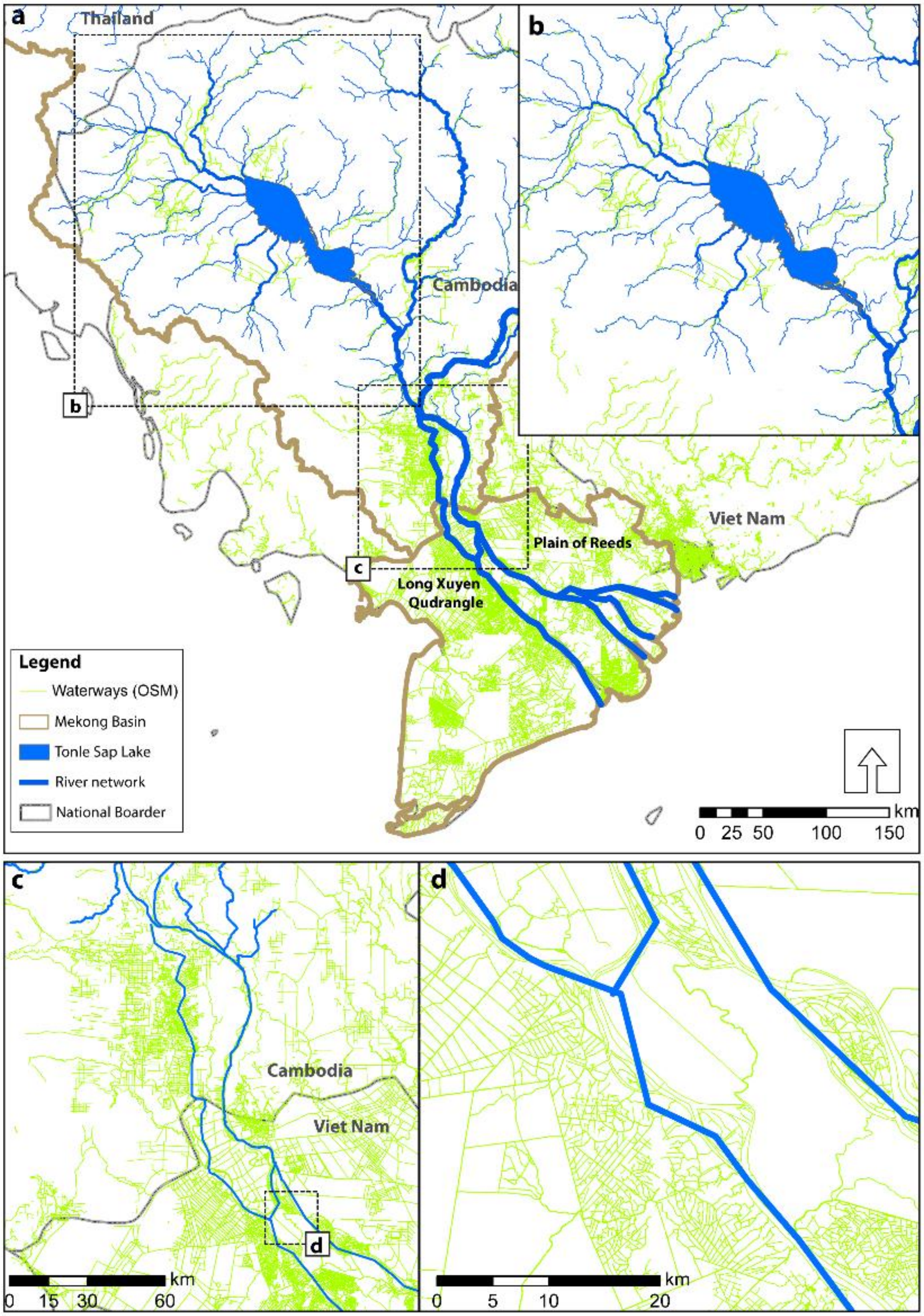


Figure 7: Irrigation infrastructure in the lower Mekong Basin. (a) Overview over irrigation infrastructure in the Mekong Delta, floodplains, and the Tonle Sap basin. The extremely dense network of irrigation infrastructure over

multiple scales (b and c) contributes to changing sediment dynamics in the delta and is at the same time valuable infrastructure that is threatened by hydrologic and geomorphic changes in the delta (data derived from Open Street Map, 2017).

Figure 8:Floodplain encroachment in Phnom Penh between 2004 (a) and 2016 (b). Arrows i and ii in a and b indicate locations where major floodplains were still largely undeveloped in 2004 and encroached in 2016. Panel c shows the closeup up such a major urban development. Arrow iii and iv show the use of sand for land reclamation, likely derived from the surrounding rivers.

Regional climate change and globally rising sea levels

Climate change is expected to alter temperature and rainfall patterns, and thus the basin's hydrology. Compounded with the effects of dams and infrastructure development, climate change threatens to change the Tonle Sap and other floodplains of the Mekong. Much of the Mekong's sediment load is mobilized during the wet season's extreme events, and almost a third of the Mekong's suspended sediment load at Kratie is forced by runoff generated by tropical cyclones (Darby et al. 2016). Thus, changes in extreme events and peak discharges are likely to impact sediment loads most in terms of the magnitude and spatial pattern of sediment mobilization and transport.

An ensemble prediction of changing peak flows (Q_{95}) from multiple global circulation models (GCMs) by Thompson et al. (2014) showed that 1) that the probability of changing peak flows is spatially heterogeneous and 2) there is no general agreement among GCMs simulations as to whether global climatic change will increase or decrease peak flows. Regarding 1), the Lancang seems in general to have a lower risk of changes in Q_{95}, while tributary catchments in the Lower Mekong are potentially most impacted. Broadly, the range of Thompson et al's. (2014) ensemble prediction for Q_{95} vary from a 15% decrease to a 20% increase. A study based on more recent CMIP5 projections suggested instead an increased magnitude and frequency of high flows and a reduced frequency of extreme low flows throughout the basin (Hoang et al., 2015). The different trends predicted by global circulation models agree with findings by Shrestha et al. (2016) pointing out that causes for uncertainty in sediment yield over the next century vary highly over time (e.g. uncertainty for the next few decades is dominated by model uncertainty, while uncertainty after the mid of the next century is dominated by the climate scenarios) and in function of the considered spatial scales. Impacts of dam operations on river discharges will likely exceed the impact of climate change in most reaches (Lauri et al. 2012, see section 3.1).

However, the spatial complexity of drivers of sediment supply processes beyond regional climatic changes must merit further attention. For example, Darby et al. (2016) showed that localized extreme weather events like tropical cyclones play a key role in the basin's sediment dynamics. Changes in such extreme events might change without correlation to regional climate change and create additional complexity.

The low-lying Mekong delta is vulnerable to sea-level rise. Estimates for global sea level rise from the most recent IPCC report show a consistent upward trend with variation in magnitude between different representative concentration pathways (RCPs). Eustatic sea level is predicted to rise between 0.28 m (minimum for RCP2.6) to 0.98m (maximum for RCP8.5) by 2100 on current less than above sea level (Church et al., 2013). However, the upper 95 % confidence interval for projected sea-level rise under RCP8.5 might reach 1.8 m (Jevrejeva et al., 2014). Such a rise would have dramatic effects on a landform with nearly 50 % of its current surface less than 2 m above sea level. To maintain the current delta surface in the face of rising seas, additional sediment deposition would be required, and thus rising sea levels can be viewed as acting like a sediment sink (Schmitt et al., 2017).

Accelerated subsidence from groundwater pumping

Although sea-level rise associated with global warming has received much focus and interest, pumping-induced land subsidence in unconsolidated deltas around the world can occur at rates greatly exceeding sea-level rise. Pumping-induced subsidence of up to 4 cm yr^{-1} has occurred in parts of Tokyo (Hayashi et al., 2009), 12 cm yr^{-1} in Bangkok (Phien-wej et al., 2006). The impact of subsidence is effectively the same as sea-level rise: extended duration of flooding, ultimately leading to permanently inundated land. Because groundwater pumping (for domestic, industrial, and agricultural uses) is typically more intensive in areas with higher population density, the impacts of pumping-induced subsidence may be expected to disproportionately impact population centers. Analysis of subsidence in the Mekong delta (Erban et al., 2014) found a delta-averaged rate of 1.6 cm yr^{-1} with higher subsidence rates around the population centers of Ca Mau (3 cm yr^{-1}) and Can Tho (2.5 cm yr^{-1}). Minderhoud et al. (2017) used a hydro-geologic model to translate remotely sensed rates of subsidence into rates of groundwater abstraction, finding an abstraction rate of 2.5 Mm^3 per day (or around 900 Mm^3 per year), with an increasing trend. While there is no clear evidence for how that water is split between domestic and agricultural uses, it should be noted that this groundwater abstraction nearly matches the domestic water demand in the delta of around 1240 Mm^3 per year, assuming a per capita demand of 0.17 m^3 per day (Cheesman et al., 2008) and 20 million inhabitants, but is small compared with the agricultural water demand of around 13.4 km^3 (13,400 Mm^3) per year (Haddeland et al., 2006), and the total flow of the river of 475,000 Mm^3 per year (Adamson et al., 2009).

However, it is unlikely that such pumping rates can be sustained far into the future, as salt water intrusion into the aquifers and loss of delta land would begin to limit agricultural and other economic activities. As environmental hazards increase in the delta, many delta residents will seek opportunities elsewhere in Vietnam, hastening the outmigration already underway (Kim Anh et al., 2012; Szabo et al., 2016). However, in the immediate future, pumping of groundwater might increase as a short-term response to pollution and salt intrusion into delta surface water resources (Wagner et al., 2012).

4. Cumulative impacts of basin-scale drivers on the Mekong Delta

Located at the downstream end of the Mekong drainage system, the Mekong Delta is impacted cumulatively by all disturbances in the basin upstream, from dam construction to climatic changes. Even though the Mekong Delta accreted rapidly (up to +16km^2/yr) over the past 8,000 years (Figure 2) adding new land for human habitation and agriculture, in the last few decades changing sediment budgets have turned the Mekong Delta from a growing to a shrinking landform, with a reported rate of current land loss of up to 2.3 km^2/yr (Anthony et al., 2015).

However, given the wide range of uncertainty in drivers of the Delta's sediment budget (e.g., dam construction, climate change impacts on sediment yield), global changes (sea level rise), management responses (from stopping ground water extraction to dyking and poldering most of the Delta) and the hydraulic complexity of the system (see section 3.4) it is difficult to predict the future of the land form.

To overcome these limitations, Schmitt et al. (2017) conceptualized the subaerial Delta (around 40,000 km^2) as a planar, sloped surface (delta plane) over which sediment is spread evenly leading to the accretion of the landform. The delta plane model allowed for a rapid assessment of how different drivers and management approaches might compound and cumulatively result in various levels of relative 'drowning' (i.e., a reduction in delta elevation compared to rising sea levels). By compiling ranges of magnitudes for various drivers of the delta's mass balance (sediment input from the Mekong, organic accumulation in the delta, dam sediment trapping, sand mining, ground water pumping), they created scenarios for relative subsidence (rSUBS) change through to the year 2100. Their resulting estimates range from rSUB change of less than 0.5 m (by stopping groundwater pumping, main-stem dam construction, and sand mining) to close to 2 m (only modest reductions in pumping and sand mining, construction of the full dam portfolio). The difference between these scenarios would result in vastly different futures for the Delta landform as a whole, because of its very low topography (Figure 9). For less than 0.5 m rSUB change, only coastal parts of the Delta, and some low lying inland areas would become submerged. For 1 m of rSUB change, substantial inland areas of the Delta would be inundated (19,100 km^2, 48 % of total). For 2 m rSUB change, 29,400 km^2 (73 % of total) would be drowned. Even based on the current topography, areas with the most significant population centers would be amongst the most impacted (i.e., the areas around Ho Chi Minh City and Can Tho). However, this potential land loss will be exacerbated by a changing topography, as ground water pumping in and around urban centers leads to a more rapid subsidence compared with the rest of the delta (Erban et al., 2014).

The sinking of land might itself reinforce unintended feedbacks that accelerate the pace of submergence. For instance, increased flooding may drive further dyke construction, which will further limit sediment deposition on the delta’s floodplains. Sea level rise will cause salt intrusion into surface water bodies and shallow aquifers, reducing the yield from the prevalent paddy rice (Genua-Olmedo et al, 2016), incentivize groundwater pumping and thereby increase rates of subsidence. Also, changes to the current topography, primarily driven by land subsidence and sediment deprivation, could compromise the integrity of the complex water infrastructure of the delta (Figure 7), possibly leading to expensive investments in retrofitting and ultimately causing further alterations to the water and sediment cycles. More difficult access to freshwater, saltwater intrusion into surface and groundwater, and increasing natural hazards will strongly reduce the productivity of agriculture and aquaculture. As land subsides and surface and ground water resources become more saline, ongoing outmigration from the delta (as already observed, Kim Anh et al. (2012)) and losses of agricultural production will impact the socio-economic patterns of Vietnam and the entire region.

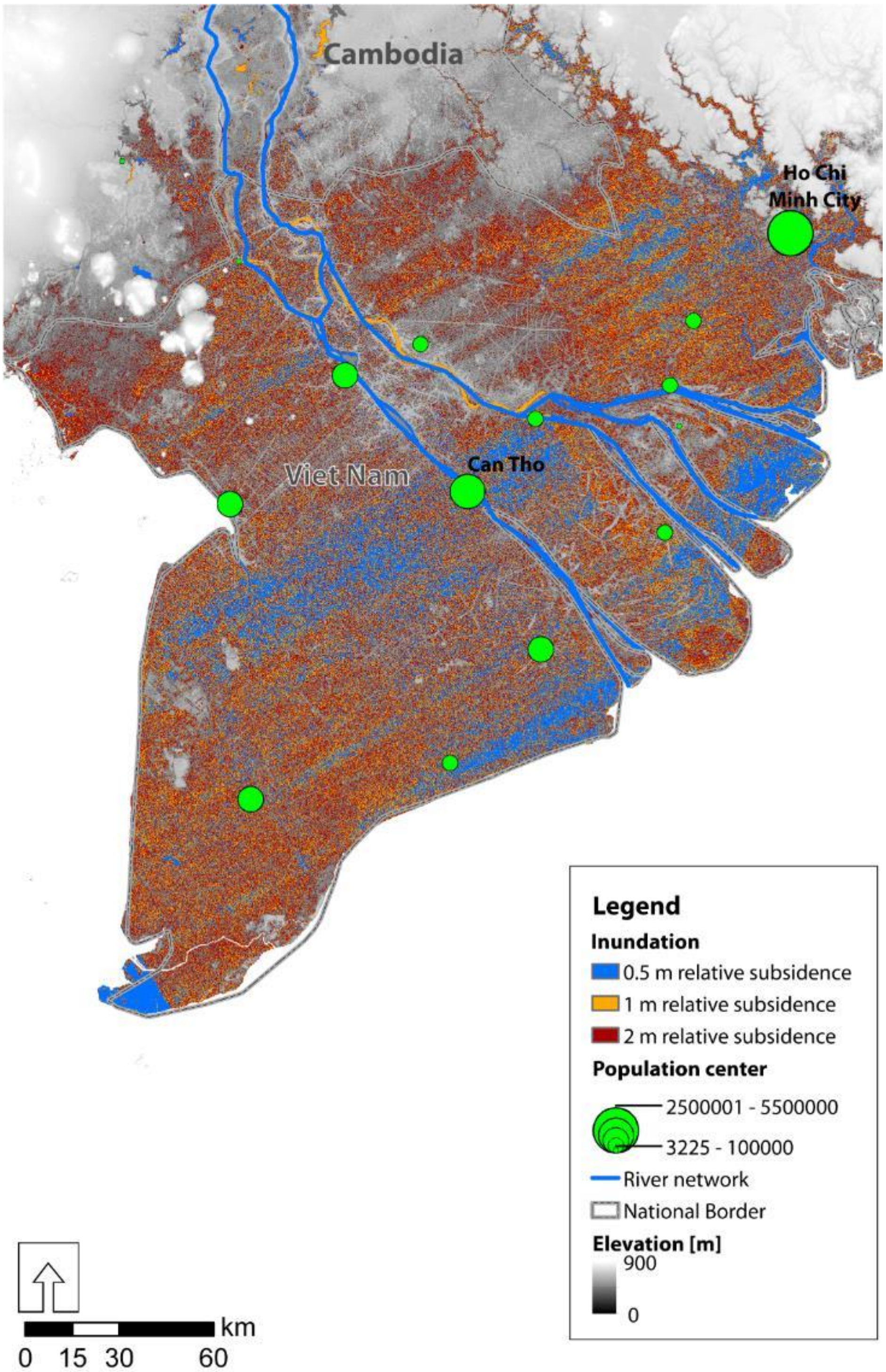


Figure 9: Relative subsidence endangers the delta landform as a whole. Even for a moderate relative subsidence of 0.5 m, most of the central coast-line and the Ca Mau Peninsula, but also a swath of land south-west of Can Tho, would fall below mean sea level (blue). Relative subsidence of 1 m would endanger land throughout the delta

and especially between Can Tho and Ho Chi Minh City. For 2 m of relative subsidence, most of the delta land would fall below sea level.

5. Discussion: Potential management responses to basin scale drivers

The threats described above affect different components of the river's water and sediment budgets, and the morphology of its channels and delta, separately as well as cumulatively. As we review the range of threats to the Mekong River and Delta, the question arises as to which of these threats are inevitable, and which can and should be mitigated through changes in management practices, adaptation, or technical solutions (which might come at different costs and might have a variable efficiency). We present potential approaches to alleviate basin-scale change in Table 2, and discuss them in the following sub-sections.

Strategic dam siting, design, and operation

At the scale of individual dams that are now in the planning stage, modifications to dam locations, designs, and operations have the potential to improve the flows of sediment, nutrients, adult fish, and fish larvae through and around dams. A dam's position within the river network and in relation to other dams and other activities affects its final impact (Kondolf et al 2014). Dams can be strategically sited in areas with smaller contributions to the basin sediment budgets, and away from critical habitats and fish migration routes. Such a strategic selection of dam sites and strategic assessments of environmental impacts could improve performance of the final dam portfolio compared to the current *ad-hoc* approach to building dams, with dam sites proposed by developers without strategic oversight (Richter et al., 2010; Ziv et al., 2012; Jager et al., 2015; Schmitt, 2016). A strategic approach is especially important in a large basin such as the Mekong, where impacts of a single dam might extend far beyond the vicinity of the dam, and thus far beyond what is typically considered in an environmental assessment.

Reservoir operational techniques such as drawdown flushing (i.e., sediment removal) and sluicing (i.e., pass-through) could improve sediment passage through Mekong dams, and tools are available to roughly assess the potential for these various techniques to improve sediment passage at dams in data-limited settings like the Mekong (Palmieri et al., 2003; Wild and Loucks, 2015b). However, large dams are generally unsuitable reservoir sediment management methods like flushing and sluicing, a limitation that would apply to several large Mekong dams now planned (Wild and Loucks 2015a; Wild et al. 2016). Furthermore, some techniques (e.g., flushing) are operationally challenging and are financially unattractive to dam owners and operators because they reduce hydropower production and associated revenue by preventing inter-annual carryover of water storage and requiring lower reservoir water levels. However, very large dams could be replaced by cascades of smaller dams through which sediment can be routed more easily (Annandale, 2013; Wild et al., 2016). Even when such modifications are not possible, simply including bottom and mid-level outlets in new dam designs would create flexibility for future reservoir re-operation for sediment passage, which can effectively mitigate downstream geomorphic impacts of dams and increase the operational lifespan of these projects (Yin et al., 2014; Bizzi et al., 2015). In large, already constructed reservoirs, operational strategies such as density current venting can improve the passage of fine sediment fractions (Kondolf et al., 2014a).

Although the technologies for passing sediment through and around dams work well in certain contexts, they are rarely implemented where they could be, and thus opportunities are lost to extend reservoir life and reduce downstream impacts (Annandale et al. 2016). The inclusion of such features and the adoption of concerted reservoir flushing in tributaries (Wild et al., 2016) could be incentivized economically in the basin. Concerted cascade reservoir operations would also require strengthened multi-national cooperation and regulation as many tributary cascades are built by individual private developers in different countries. However, convincing Mekong dam owners and operators to conduct reservoir sediment management practices will be difficult given their short-term interest. With the many dams being built across the basin, in effect sediment trapping is distributed over many reservoirs, reducing storage capacity loss in any one reservoir, and hence reducing the incentive for any one operator to implement sustainable sediment management strategies (Wild and Loucks 2014). For reservoir sediment management to become commonplace, the likely long-term owners and operators of hydropower dams (i.e., governments of LMB countries) must consider the costs of inaction, particularly with respect to intergenerational inequity. Inaction may result in enormous costs being borne by future generations to decommission dams (in the absence of dam retirement funds), manage the accumulated sediments, and resort to developing new dams in the potential dam sites that remain unbuilt, which are inevitably less advantageous that the sites already developed (and thus more expensive to construct, less efficient to operate, etc.) (Wild and Loucks 2014). However, even in the unlikely case that all dams would adopt concerted and effective sediment management, each dam would still result in some residual sediment trapping. Cumulatively, even small residual trapping rates would lead to a major reduction in sediment transport in the river basin, given the scale of planned dam development.

Enabling fish migration through the planned and existing dams will be a difficult task. The great species richness and very variable life-cycles of fish species in the Mekong will likely hinder the success of common solutions such as fish ladders that are applied in temperate rivers (Ferguson et al., 2011). Many of the species in the Mekong display complex migration patterns, in which larvae, juveniles, and adults rely on undisturbed upstream and downstream migration as well as on connectivity between floodplains and channels. Concerted dam operation would hence be imperative not only to maintain sediment connectivity buts also hydrologic and biologic connectivity between the Mekong, its floodplains, and Tonle Sap Lake.

Sand Mining

While sand constitutes a relevant commodity for international trade, its extraction from the river creates significant environmental externalities in the lower Mekong basin. For these reasons, sand export has been largely banned, notably in Cambodia, but apparently the regulations have not been effectively enforced (Vichea, 2016). Enforcement of a prohibition on sand mining could reduce immediate changes in channel morphology and disturbance of in channel habitats and reduce long-term sediment starvation attributable to sand mining. Before a prohibition on sand mining can succeed, it will be essential to identify (and incentivize) alternative sources of sand near major domestic demand for construction material in the dynamically growing population centers of the lower Mekong. Alternative sources of sand include floodplain pit mines, which have been developed along many rivers in the US and Europe as alternatives to in-channel mining with its impacts. Floodplain pits can have their own set of negative environmental impacts, but these are typically considered to be less than those of in-channel mining (Kondolf 1994). Using recycled construction rubble or some industrial by-products can accommodate part of the demand for aggregate (and reduce problems related to waste disposal) (Ghannam et al., 2016; Wagih et al., 2013), but these sources could likely replace only a small fraction of the construction related domestic demand for river sand.

Water infrastructures, floodplain dykes, and floodplain management

Given the negative effects of flood dykes on lateral connectivity between the channels and floodplain, and on maintaining the delta landform through deposition over the delta plane, the current policy of dyke building may merit reconsideration. Most distributaries of the Mekong remain relatively little dyked, so there is opportunity to correct the current trend of extending high dykes and thereby reducing lateral connectivity, which disadvantages small-holder farmers (Chapman et al., 2016; Chapman and Darby, 2016). Drainage in the Mekong Delta and Tonle Sap is heavily modified by an intricate irrigation network, which may offer opportunity to distribute floodwaters over the delta so to increase deposition (Hung et al., 2014a, 2014b), as controlled flooding during high-flow, high sediment transport conditions can greatly increase deposition and accretion (e.g., Edmonds, 2012; Pont et al., 2017).

In many large rivers world-wide, the aim to improve navigation motivated channel modification through dredging and infrastructure such as groins and dykes. These alterations had wide-ranging morphologic and eco-hydraulic impacts, which in some rivers now motivate extensive and costly restoration projects (Buijse et al., 2002). On the Mekong, to date, navigation has focused in reaches upstream of Chiang Saen and downstream of Phnom Penh, (MRC, 2016), but a large blast and dredge project is being prepared to make the river navigable from the planned Pak Ben reservoir to Luang Prabang, part of an ultimate ambition to make the Mekong navigable from the South China Sea up to Yunnan in the face of local opposition (Campbell, 2009b; Suksamran, 2017). Major in-channel (removal of rapids and shoals, and eventually partial canalization) works are ongoing in the upper part of the basin between Laos and China to enable passage of 500-ton vessels (Lazarus et al., 2006; Mirumachi and Nakayama, 2007). It is unclear how great the modifications would be to improve navigation through the lower Mekong , (MRC, 2016), but the current ecosystem and agricultural productivity of the Lower Mekong floodplains and Delta depend on lateral connectivity, which would be impaired by dredging and construction of hydraulic structures. Thus navigation improvements merit careful evaluation with respect to impacts.

The current urban development of floodplains will create a long-term legacy for future floodplain and basin management. While there is an obvious push for urbanization in the population centers along the banks of the Mekong strategic management of these developments will be crucial. For example, current urban development in Phnom Penh should leave enough room for the river such that flood-peaks, which are crucial to deliver water and sediment to the Mekong Delta, can pass without excessive risks for lives and infrastructure. Otherwise, urban development there could be in direct conflict with sustaining livelihoods in the delta downstream.

Within the Mekong Delta, active management of organic material holds potential to reverse subsidence, even on deeply subsided delta land (Miller et al., 2008; Wakeham and Canuel, 2016). In the Mekong Delta, the annual production of organic residues from rice production (up to 26 Mt/yr) provide potential material with which to build delta land in the most subsided parts of the delta (Diep et al., 2015; Schmitt et al., 2017). Restoration of mangrove forests, which once shielded nearly the entire coast but are now in rapid decline (Hong and Hoang, 1993; Benthem et al., 1999; Thu and Populus, 2007), would be an additional ecological engineering approach to reduce coastal erosion, increase sediment trapping, and provide potential economic benefits if combined with sustainable aquaculture (Furukawa et al., 1997; Ellison, 2000; Victor et al., 2004).

Groundwater Pumping Regime

As the impacts of groundwater abstraction are mostly deemed irreversible (Ingebritsen and Galloway, 2014), except in some specific circumstances (Chen et al., 2007), regulating groundwater pumping is an obvious management response to slow subsidence. A 2007 regulation on groundwater pumping in Ho Chi Minh City led to a decrease in subsidence measurable from space-borne instruments (Minderhoud et al., 2017). As only a third of rural Vietnamese households get their water from public sources, expanding public access to safe surface water sources could reduce dependence on groundwater abstraction (Cheesman et al., 2008). As an adaptation to increasing saline intrusion, farmers in the Mekong Delta are increasingly switching to aquaculture. While shrimp aquaculture benefits from brackish or salty water (Guong and Hoa, 2012), production of freshwater fish can be a significant consumer of fresh water resources and was shown to strongly correlate to increased groundwater abstraction and ground subsidence (Higgins et al., 2013). Yet, the rapid growth of aquaculture in Vietnam has mainly been fueled by a growth in fresh-water agriculture (FAO FishStat, 2017a). Groundwater pumping could be reduced by switching to production modes that are less demanding of freshwater, such as brackish-water aquaculture, mangrove associated aquaculture, adapting cropping cycles for paddy rice or using more salt resistant varieties, or cultivation of dry-farmed cash-crops (CCAFS-SEA, 2016).

An alternate approach would be to allow current rates of pumping and subsidence to continue, and to attempt structural solutions to maintain the Mekong Delta when it is mostly below sea level. Some societies have adapted to living below the sea level, most notably the Netherlands in the Rhine River delta. However, such a strategy requires extensive, expensive infrastructure, and is likely not feasible for the Mekong Delta given its vast extent and long shoreline (Ingebritsen and Galloway, 2014).

Potential Institutional Frameworks for Managing Threats

While some threats to the delta (such as dyking and groundwater pumping) could be managed within the delta itself, other threats result from actions throughout the basin, notably construction of dams and sand mining, and their consequent alteration of the sediment supply to the Delta. The exceptional productivity of this unique ecosystem, and the large population dependent upon it, argue for a basin-scale perspective, and international cooperation to reduce impacts, with the goal of sustaining the Mekong River and Delta system (Campbell 2009b). The Mekong River Commission (MRC), established under the auspices of the United Nations in 1995 (following on predecessor organizations since 1957, the Mekong

Committee and Interim Mekong Committee), serves as a forum for communication, data sharing, and promotion of sustainable development of the basin. However, its membership includes only the lower basin countries of Laos, Thailand, Cambodia, and Vietnam. It does not include Myanmar, nor, most importantly, China. Even within the lower basin, the MRC has principally an advisory role. When a member nation plans to build a dam on the river's mainstem, it is obliged to provide advance notification to the MRC and the other member states, and the MRC reviews studies of the potential impacts of the proposed dam. This process was illustrated in the case of Xayaburi, the first dam to be built on Lower Mekong River mainstem. Laos provided prior notification, and the MRC conducted a review of the proposed project, which identified a number of unclear aspects and substantial problems with the proposal. However, after going through this consultation, the government of Laos went forward with the project essentially unmodified (Hensengerth, 2015). Vietnam was particularly concerned about the potential impacts of Xayaburi dam and called for a 10-year moratorium on mainstem dams (Keskinen et al., 2012). However, the MRC had no authority to stop or slow the process of dam construction.

In the context of this international river basin, it would seem necessary to create incentives for basin states and other actors to take actions for the greater good of the river system and its delta, even when those actions might require a basin state to forgo a potential income-producing project. It is outside the scope of this paper (and beyond the expertise of the authors) to fully explore potential institutional frameworks within which management actions to sustain the river and delta system can be identified and incentivized, but clearly the greatest challenge at this point lies not with the scientific questions, but how the scientific information about the existential threats to the Mekong Delta's persistence as a landform can influence decisions by basin states and individual actors.

6. Conclusion

Like many deltas, the Mekong Delta is subject to threats such as accelerated sea level rise, reduced supply of sediments and nutrients, accelerated subsidence, and channelizing of sediment laden flows directly to the sea instead of depositing over the delta plain (Syvitski, 2009). Such cumulative impacts are common to many of the world’s major river deltas and the subsequent erosion is globally consistent (Bucx et al., 2010; Rubin et al., 2015). In many cases, the shift from an actively prograding delta to an eroding one can occur in as little as a few decades (Rubin et al., 2015). The consequences are accelerated shoreline erosion, threatened health and extent of mangrove swamps and wetlands, increase salinization of cultivated land, and human populations at risk of costly natural disasters (Syvitski, 2009).

In this paper, we set out the impact that cumulative changes in this large river’s sediment budget can have on the fluvial processes, landforms, ecosystems, and livelihoods it supports. Given the rate of development of the basin, the resultant cumulative impacts on the Mekong River ecosystem pose an existential threat to the Mekong Delta as a landform, and to the human and natural ecosystems that depend upon it. There are large uncertainties in estimated rates of the threats, but if current rates of relative subsidence continued through the rest of this century, as much as half of the Delta could be at or below sea level, and far more could be rendered agriculturally unproductive. Long before then, the ecosystem is likely to collapse as dams prevent fish migration to upstream tributaries essential for reproduction and access to inundated floodplains important for juvenile rearing and spawning, and because dam-reduced inputs of sediment-bound nutrients will undermine the riverine foodweb while simultaneously increasing demand for artificial fertilizer to maintain the productivity of the Mekong’s agricultural systems.

The existential threat to the Delta, the remarkably short time-scales involved, and its implications may not be fully appreciated by decision-makers. There are many internationally funded initiatives to improve livelihoods, increase agricultural productivity, preserve wildlife habitats, and empower local residents in the Delta. As worthy as these efforts are, they may be rendered irrelevant if the river ecosystem, and the delta landform itself, cannot be sustained beyond several decades.

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Table 1: Fisheries production in the Basin. Values of catch fisheries are derived from subtracting aquaculture production (Phillips, 2002) from total catch (Hortle, 2009). Production of freshwater aquaculture for 2015 is calculated by multiplying the fraction of a nation's total annual aquaculture production that is derived from within the MRB (calculated from Phillips, 2002 and FAO FishStat, (2017a, 2017b, 2017c) for 2000 with the total national aquaculture production in 2015 (from and FAO FishStat, (2017a, 2017b, 2017)).

	All Fisheries	Other aquatic animals	Catch fisheries (Phillips (2002), Hortle (2009))	Aquaculture			Fraction of national aquaculture production from MRB (2000)	National aquaculture production from MRB (2015)
	Hortle (2009)		Calculated	Phillips (2002)	Fao FishStat (year 2000)	Fao FishStat (year 2015)	Calculated	Calculated
	Mkg/yr	Mkg/yr		Mkg&yr	Mkg/yr	Mkg/yr	[%]	Mkg/yr
Cambodia	482	105	468	14	14	140	100%	140
Lao PDR	168	41	163	5				
Thailand	721	191	653	68	270	390	25%	98
Vietnam	692	161	521	172	368	2400	47%	1118
Total	2063	498	1357	259	652	2930		1357

Table 2: Cumulative threats and potential management repsonses for the Mekong river delta.

Threats	***Process/Mechanism***	***Description/Consequences***	***Potential Management Response***
Dams	Fragmentation	• Loss of food security/protein/nutrients	• National/Catchment Scale: Quantify tradeoffs between hydropower output and dam environmental impacts, identify dam sites to optimizeoptimizeyield optimal network. • Release of artificial flood and sediment pulses from upstream dams • Replace very large dams with a cascade of smaller dams. • Select dam-sites and dam-designs that effectively pass sediment and fish. Set economic incentives to incorporate these designs. • Adopt effective sediment strategies in existing dams. • Concerted sediment management for entire hydropower cascades.
	Altered Hydrology	• Loss of connectivity with the Tonle Sap and floodplains which impacts extent of natural inundation and nutrient delivery, which will reduce river and marine fish production, and potentially that of floodplain agriculture	
	Channel incision downstream of dam	• Destabilizing infrastructure • Stranding irrigation works and water intakes • Declining groundwater levels • Impacts on floodplain vegetation and ecosystem	
	Sediment Trapping	• Loss of future hydropower and water storage potential • Loss of habitable and arable land in the delta • Intercepting of sediment-bound nutrients for delta agriculture and ecosystems	
Floodplain dykes, irrigation infrastructure, and diversions	Reduced lateral connectivity between rivers and floodplains	• Loss of terrestrial nutrient subsidies • Disrupts hyporheic exchanges (ground water) • Impacts floodplain obligate fisheries • Loss of delta building material to off-shore (and consequent loss of delta land) • Incentivizes artificial fertilizers because of the loss of river sourced nutrients in the flood plains	• Levee set-backs and furthering flood resilient development of communities • Agricultural flood easements • Careful dredging, groin, and dyke construction for navigation purposes • Improved agricultural practices and ecological engineering to locally mitigate

		• Increases residual risk – incentivizes development that leads to low frequency - high consequence events	delta subsidence
Sand Mining	Local incision and bank erosion	• Damage to infrastructures, land loss through river bank failure	• Reducing in channel mining rates • Enforce export and exploitation regulations • Explore alternative sources for domestic use
	Reduction of total load	• see under dam sediment trapping	
Groundwater pumping	Accelerated land subsidence	• Accelerated delta subsidence • Land loss in the delta • Salt water intrusion in the delta	• Incentivize domestic, agricultural, and industrial water saving • Promote and enable safe use of surface water for domestic and industrial use • Change to less water intensive crops and brackish water tolerant aquacultures • Improved agricultural practices and bio-engineering to locally mitigate delta subsidence
Global climate change	Sea Level Rise	• Greater vulnerability during high tides and storm surges • Salt intrusion	
Global climate change	Basin hydrology	• Increase extreme events during the wet season • Augmented sediment loads	Better management of water and sediments through dam operations