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Publication Date
2015

Peer reviewed

SEDIMENT STARVATION FROM DAMS IN THE LOWER MEKONG RIVER BASIN: MAGNITUDE OF THE EFFECT AND POTENTIAL MITIGATION OPPORTUNITIES

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ABSTRACT

The Mekong River is undergoing rapid dam construction. Seven mainstem dams are completed or under construction in China and 133 completed or proposed for the Lower Mekong River basin. We developed geomorphically-based estimates of sediment yield from different geologic provinces and applied the 3W model to calculate the net sediment trapping from existing and future proposed dams, using improved methods and data over prior such estimates. Our results indicate that the 133 dams built as planned would trap 96% of the river's former sediment supply to the delta, a significantly greater trapping than prior estimates of 50-75%. The most significant downstream impacts of this sediment-starved water will be accelerated erosion and subsidence of the delta in response to the virtual elimination of its sediment supply. Upstream, the mostly bedrock channel upstream of Kratie will have its thin sediment deposits stripped away (with consequences for aquatic organisms dependent on the alluvium) and the bedrock reach of Vientiane will likely incise. The impacts of dam-induced sediment starvation can be partially mitigated by implementing strategies to pass sediment through or around dams (e.g., sediment sluicing, flushing, density current venting, and bypasses), and our team is currently working with staff of Laotian and Cambodian ministries to identify opportunities to relocate/redesign dams to make such sustainable sediment management feasible.

Keywords: Sediment starvation, reservoir sedimentation, Mekong River, sediment management, impacts of dams

1. INTRODUCTION

The Mekong River basin is undergoing rapid and widespread dam construction, with seven mainstem dams on its upper reaches in China (the Lancang), and another 38 dams on the lower Mekong River and tributaries in Laos, Thailand, Cambodia, and Vietnam (Grumbine and Xu, 2011). How will these dams alter the sediment load of the Mekong and thereby alter nutrient dynamics and the morphology of the downstream channel and delta? Our recent work has attempted to address this question (Kondolf et al. 2014b; Rubin et al., 2014), and ongoing work with a team of colleagues working through the Natural Heritage Institute is focused on understanding potential changes in sediment yield due to land-use change, and exploring alternate designs and operation strategies to increase fish and sediment passage through proposed dams.

The Mekong River drains about 800,000 km^2 and has an average discharge (at its mouth) of about 15,000 m^3s^{-1}, with predictable 20-fold seasonal fluctuation from dry season (November-June) to wet (July-October) (Gupta, 2002; Adamson et al., 2009). The Mekong Delta is one of the world's largest at 94,000 km^2, having built out over the past 8,000 years by deposition of river sediments (Statteger et al., 2013). The Mekong is a remarkable human-natural system, with 60 million people dependent on fish from the river system, and the Delta alone supporting 16 million, whose lives and economy are at risk from loss of nutrients and reduced fish populations, subsidence, increased flood risk, and other changes in the delta.

Prior to the ongoing dam construction, the average annual suspended load of the entire Mekong was estimated at about 160 million tonnes per year (Mt y^{-1}), half of which from the upper 20% of the basin, the Lancang drainage in China (Gupta and Liew, 2007; Walling, 2005). An estimated 83% of the Lancang basin sediment will be trapped by the dams now under construction (Kondolf et al., 2014b), eliminating almost half of the total natural sediment load of the Mekong. Thus, the sediment load of the Lower Mekong River will consist largely of sediment derived from sources within the Lower Mekong River Basin itself. The hotspot of the river's extraordinary fish production is the Tonle Sap system, a Mekong tributary that receives seasonal backwater flooding from the Mekong River mainstem. Seasonally flooded, 'flood pulse' ecosystems are among the world's richest ecosystems (Junk, 1989). During the flood pulse, fine-grained sediments and their associated nutrients deposit across the Ton Sap basin, making the Tonle Sap tributary basin net depositional (Tsukawaki, 1997, Kummu et al., 2008). With reductions in sediment supply, the productivity of the Tonle Sap ecosystem will likely be reduced (Baran and Guerin, 2012).

2. SEDIMENT TRAPPING BY RESERVOIRS

Reservoirs trap all the bedload and a percentage of the suspended load carried by a river. The most obvious effect of this is loss of reservoir capacity, as the reservoir fills with sediment (Annandale, 2013). However, the equally serious "other side of the coin" is the reduced supply of sediment to the river downstream of the dam. Depending on the relative changes in sediment supply and transport capacity, erosion or deposition can occur (Schmidt and Wilcock, 2008), but most commonly the reach downstream of the dam is characterized by sediment-starved, or 'hungry' water, which can erode the bed and banks, threaten infrastructure, and coarsen bed material (Kondolf, 1997), 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. Deltas naturally subside as their freshly-deposited sediments compact, but subsidence rates in many deltas have been artificially increased by extraction of water, oil and gas. When subsidence is combined with dam-induced alterations in flow, sediment-load reduction, and channelization, the result can be 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).

3. SEDIMENT STARVATION FROM PLANNED DAMS ON THE MEKONG

Building upon prior estimates of sediment reduction from planned dams (e.g., Kummu et al., 2010) we developed sediment yield estimates for each of nine geomorphic provinces in the Lower Mekong basin, calculated trap efficiencies for individual reservoirs, and compiled total storage capacity data for more accurate trap efficiency calculations (Kondolf et al., 2014b). We 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 Mekong River Commission '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 (Figure 1). However, with full build of dams in the Lower Mekong River basin, including mainstem dams, the cumulative sediment trapping by dams will be ~96% of its pre-1990 load (Figure 2) (Kondolf et al., 2014b). Sediment starvation would actually be more severe owing to the mining of about 35 Mt y^{-1} of sand and gravel directly from the river channel, mostly in Cambodia (Bravard et al., 2013).

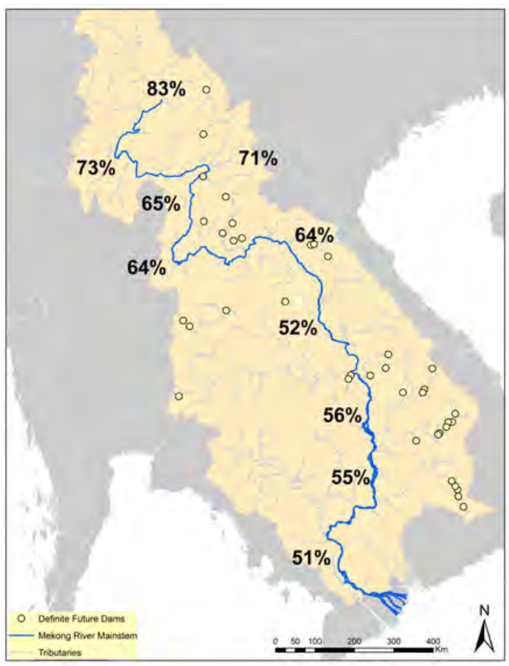

Figure 1. Cumulative sediment starvation effects of the definite-future dams. 51% of the total sediment load of the river would be trapped before reaching the delta. (from Kondolf et al., 2014b)

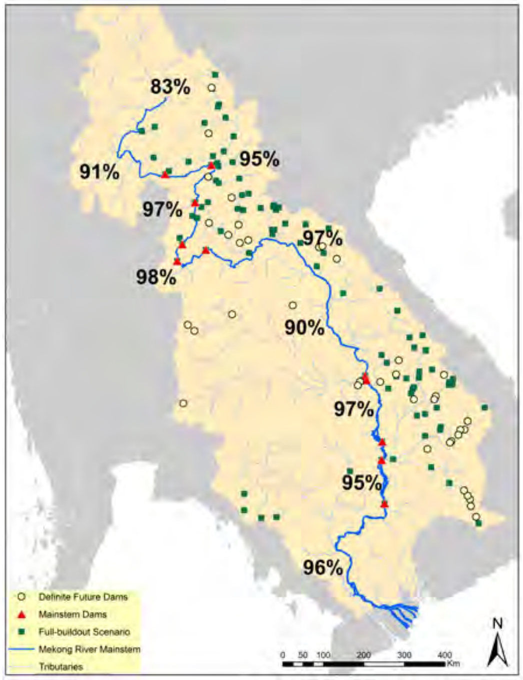

Figure 2. Cumulative sediment starvation effects of full buildout of all proposed dams. 96% of the total sediment load of the river would be trapped before reaching the delta. (from Kondolf et al., 2014b)

4. GEOMORPHIC EFFECTS OF REDUCED SEDIMENT SUPPLY

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. Cumulative sediment trapping by dams will be substantial (Kondolf et al., 2014b) while reductions in high flows will be minimal (Mekong River Commission, 2010; Piman et al., 2013). 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 with future hydropower development. Thus, sediment trapping by reservoirs is arguably the most important consequence of dams for the downstream channel. Channel adjustment will be limited primarily by geologic controls.

The Mekong can be divided into alternating bedrock and alluvial reaches (Figure 3). The Upper Bedrock reach extends from the Chinese border to about 5 km upstream of Vientiane, where bedrock is discontinuously overlain by a thin (ca 1-2 m) veneer of sand (Figure 4). The Middle Alluvial Reach extends downstream from Vientiane to Savannakhet, and from Savannakhet downstream to Kratie, the Middle Bedrock Reach includes a wide range of channel forms, but the key attribute is bedrock control. 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. Downstream of Phnom Penh is the Mekong delta, by definition a reach of net deposition, with flow bifurcating four main channels to the sea. In bedrock-controlled reaches, loss of sediment supply will produce only modest channel adjustment, with loose sediment deposits over bedrock likely swept away in the first competent floods post-dam. In the Middle Alluvial and Cambodian Alluvial reaches, reduced sediment supply will induce post-dam erosion and channel adjustment, including channel widening as the river seeks to recover its sediment load by eroding the channel margin, and incision (except where bed elevation is controlled by bedrock), as commonly observed in sediment-starved rivers (Kondolf, 1997).

Figure 3. Reaches of predominantly bedrock vs alluvial channel from Rubin et al. (2014). 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 4. Bedrock channel of the Mekong River with surficial sand deposits 1-2 m thick, near Xayaburi, Laos. (photo by Kondolf, January 2012)

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.

5. POTENTIAL EFFECTS ON MEKONG DELTA

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). As discussed in Rubin et al. (2014), sediment delivery to the Mekong delta remained relatively constant over most of the 20th century, but with accelerated sea level rise, more rapid compaction due to groundwater extraction, loss of sediment to offshore waters by channelization, and reduced sediment delivery resulting from in-channel mining of sand and gravel, the delta has already been submerging, its flood-prone areas expanding. Anticipated dam-induced reductions in sediment supply can only exacerbate the rate of land loss (Rubin et al., 2014).

Mekong delta data are limited and predictions are complicated by uncertainty in subsidence rates, sediment delivery, and eustatic sea-level rise. However, we can look at analogous cases to provide some guidance regarding possible responses. The Colorado, Ebro, Indus, Krishna, Nile, and Yellow River deltas have all experienced sediment reductions of 90% or more, comparable to the predictions for Mekong full-build scenario. 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 (Rubin et al., 2014). The Indus, Nile, and Yellow River deltas were all prograding prior to dam construction and subsequently were net erosional. The Indus coast changed from ~100 m y^{-1} progradation pre-dam to ~50 m y^{-1} erosion post-dam, and the Colorado, Ebro, and Krishna are actively eroding in the post-dam period, losing from 1-90 km^2 y^{-1} of area and experiencing 10 to 70 m y^{-1} of coastline retreat. Experience from around the world suggests substantial erosion is likely unless sediment starvation can be mitigated, perhaps by implementing sediment management practices into proposed Mekong dams (Rubin et al., 2014). Although there is considerable variability, Rubin et al.'s (2014) dataset of deltas worldwide (n = 24) shows a strong relationship (r^2= 0.53) between reduction in sediment supply to deltas and the subsequent reduction in aggradation rates reported in the literature (Figure 5), as might be expected from geomorphic principles. The six deltas with sediment reductions of 80% or more (Indus, Chao Phraya, Krishna, Ebro, Nile, and Colorado), all show reductions in aggradation rates of more than 88%.

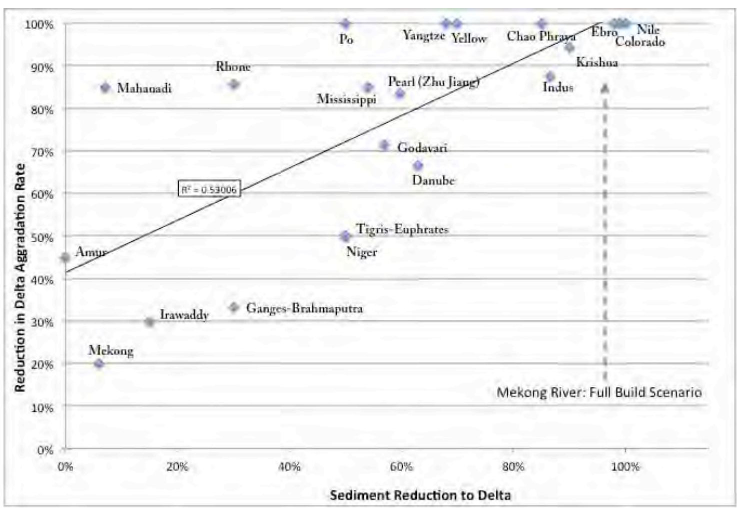

Figure 5. Published data from 24 deltas shows a relationship between degree of reduction in sediment supply to deltas and decreases in rates of aggradation. In particular, sediment reductions of more than 80% are associated with nearly complete cessation in aggradation. The full build scenario of Mekong dam building would result in 96% reduction in sediment delivery and we would then expect an almost complete cessation in sediment deposition in the delta. (source: Rubin et al., 2014)

6. SUSTAINABLE SEDIMENT MANAGEMENT STRATEGIES

The best way to manage sediments is avoid accumulation in reservoirs in the first place, either by passing sediment around or through dams. See Kantoush and Sumi (2010), Annandale (2011), and Morris and Fan (1998) for descriptions of these approaches, or Kondolf et al. (2014a) for a brief, recent treatment of the topic (from which much of the following is adapted). The latter two publications are freely available online.

A *sediment bypass* diverts part of the incoming sediment-laden waters into a tunnel around the reservoir, so they never enter the reservoir at all, but rejoin the river below the dam. The diversions normally operate only at high flows when sediment loads are high; once concentrations fall, inflowing water is allowed to enter the reservoir again. The ideal geometry for sediment bypass is one where the river makes a bend in the reservoir, such that the bypass tunnel can serve as a steeper 'shortcut'. A related approach is to build an *off-channel storage reservoir* that receives its inflow via a diversion from the main river. The diversion is operated only when flows are relatively clear, to minimize the sediment load of the diverted water. In this approach, the natural river functions as the sediment bypass. Japan and Switzerland are the leading countries for sediment bypasses, with the oldest bypass in Japan dating from 1908 (Sumi et al., 2008).

Sediment *sluicing* (or drawdown routing) involves passing high flows through the dam such that the reservoir behaves like a river and transports the sediment through the reservoir. The reservoir is drawn down before the flood flows arrive, and then large-capacity outlets in the dam are opened to allow high flows to pass through. One advantage of this approach is that deposition in the reservoir is minimized and the sediment continues to be transported downstream during the flood season when sediment is naturally discharged by the river. Finer sediments are more effectively transported through the reservoir than coarse sediments. By virtue of passing the rising limb of the flood, which generally contains higher sediment concentration than the falling limb of the flood hydrograph, sluicing is consistent with the Chinese strategy to, "release the muddy flow and store the clear water" (Wang and Hu, 2009).

In contrast to *sluicing*, whose aim is to pass sediment without allowing it to deposit, drawdown *flushing* scours and re-suspends deposited sediment from the reservoir, and transports it downstream. It involves the complete emptying of the reservoir through low-level gates that are large enough to freely pass the flushing discharge through the dam without upstream impounding, so that the free surface of the water is at or below the gate soffit. The best scenario for flushing is to establish river-like flow conditions through the reservoir, which is favored by the following conditions: narrow valleys with steep sides; steep longitudinal slopes; river discharge maintained above the threshold to mobilize and transport sediment; and low-level gates installed in the dam (Morris and Fan, 1998). For flushing to be successful, the ratio of reservoir storage to mean annual flow should not exceed 4%, because with larger storage the reservoir cannot be easily drawn down (Sumi, 2008). Because flushing flows need to pass through the low-level outlet without appreciable backwater, it may not be feasible to use large floods that exceed low-level gate capacity as flushing events. Unlike sluicing, the timing of sediment release to the downstream channel from flushing need not correspond to the times of natural high flow, and if flushing releases large amounts of fine sediment to the downstream channel during periods of relatively low flow, the accumulation of sand and finer sediment on the bed can have substantial impacts on the river ecology.

Density current venting involves opening dam outlets when turbidity currents pass through the reservoir so that they can remain intact and exit the reservoir via the outlets, carrying most of their sediment with them. Density (or *turbidity*) currents form in many reservoirs when inflowing water with high sediment concentrations forms a distinct, higher density current that flows along the bottom of the reservoir towards the dam without mixing with the overlying, lower-density waters. This sediment management technique can be undertaken even on large reservoirs where reservoir drawdown is not feasible. Some dams have been able to pass half of the inflowing sediment load by venting density currents, but the technique is possible only in cases where the density current has sufficient velocity and turbulence to maintain particles in suspension and the current can travel all the way to the dam as a distinct flow, where it can then be passed downstream (Morris and Fan, 1998).

Mechanical removal in a drawn-down reservoir can be done with scrapers, dump trucks, and other heavy equipment, or if the reservoir is not drawn down, by dredging using hydraulic pumps on barges with intakes. However, unless the removed sediment is placed in the river downstream, the sediment removal does not help address the downstream sediment starvation issue.

7. CONCLUSION: TOWARDS SUSTAINABLE SEDIMENT MANAGEMENT FOR THE MEKONG

If all dams planned for the lower Mekong River and tributaries are built as initially proposed, without designing and operating to pass sediment, nutrient loads essential for ecosystem productivity will decrease, undermining the fishery that now supports 60 million. Morphological effects will include incision in alluvial reaches of the river, and most importantly, as 96% of the sediment supply to the Mekong delta will be trapped, we expect an almost complete cessation of sediment deposition in the Delta. (Indeed, our analysis of morphological changes in other deltas worldwide shows that sediment reductions of 80% or more were all associated with reductions in aggradation rates of more than 88%.) As such, land subsidence and eustatic sea-level rise will be essentially uncontrolled, and few options will be available to mitigate coastal retreat.

While detailed models of delta morphodynamics would no doubt be helpful in predicting the response to reduced sediment supply, for management decisions that need to be taken soon, we see no need to wait for such detailed studies. Rather, we believe the available information is sufficient to motivate urgent efforts to modify the location, design, and operational plans for new dams to incorporate sustainable sediment management, such that the dams can pass most of their incoming sediment load, reducing the severity of downstream sediment starvation and also prolonging useful reservoir life. Proven techniques exist to pass sediment through or around dams, but to date they have not been implemented in most dams in the Mekong River basin.

The severity of the potential downstream impacts of sediment starvation is motivating national and international agencies to explore possibilities to relocate, redesign, and/or reconsider operations for some planned hydroelectric dams in the Mekong River basin so that they can pass sediment and fish. Our team (with colleagues from Cornell and other institutions) is working with ministry staff of riparian nations to model alternative scenarios, to analyse tradeoffs between short-term power forgone vs longer-term benefits of reducing downstream dam impacts and extending reservoir life.

ACKNOWLEDGMENTS

This research was partially supported by the Natural Heritage Institute, and made possible by the generous support of the American people through the United States Agency for International Development (USAID). The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government. Additional support was provided by the Mekong River Commission, and by the Beatrix Farrand Endowment of the Department of Landscape Architecture at the University of California Berkeley. Greg Morris, Tetsuya Sumi, Rollin Hotchkiss, and other participants in the international workshop that led to publication of Kondolf et al. (2014a) contributed important information presented in that document, and some of which is briefly summarized here. Greg Thomas and Xuan Gao of the Natural Heritage Institute were instrumental in bringing both the workshop and publication to fruition.

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