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Key Points:

- The Mekong River basin is being rapidly developed, with 140 dams built, under construction or planned
- We estimated sediment starvation with the 3W model for three scenarios of future dam building
- Full build-out of proposed dams would trap 96% of the river's predam sediment load

Supporting Information:

- Readme
- Figure S1
- Table S1

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Dams on the Mekong: Cumulative sediment starvation

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Abstract The Mekong River, largely undeveloped prior to 1990, is undergoing rapid dam construction. Seven dams are under construction on the mainstem in China and 133 proposed for the Lower Mekong River and tributaries. We delineated nine distinct geomorphic regions, for which we estimated sediment yields based on geomorphic characteristics, tectonic history, and the limited sediment transport data available. We then applied the 3W model to calculate cumulative sediment trapping by these dams, accounting for changing trap efficiency over time and multiple dams on a single river system. Under a "definite future" scenario of 38 dams (built or under construction), cumulative sediment reduction to the Delta would be 51%. Under full build-out of all planned dams, cumulative sediment trapping will be 96%. That is, once in-channel stored sediment is exhausted, only 4% of the predam sediment load would be expected to reach the Delta. This scenario would have profound consequences on productivity of the river and persistence of the Delta landform itself, and suggests that strategies to pass sediment through/around dams should be explored to prevent the consequences of downstream sediment starvation.

1. Introduction

1.1. Dam Impacts

Dams have multiple environmental impacts, including transient impacts of construction and reservoir filling (including noise, dust, social disruption of construction boomtowns, and displacing affected populations), and the longer-term hydrologic, water quality, and ecological changes resulting from converting flowing (lotic) to still (lentic) water environments, changes in sediment load and channel form, reservoir-induced seismicity, short and long-term, economic and social effects of displacing riparian populations, and alterations of river ecology [*Petts*, 1984; *Williams and Wolman*, 1984; *World Commission on Dams* (*WCD*), 2000]. By blocking migration of fish, dams have led to extinction (or large population reductions) of migratory fish species in many rivers [*Dudgeon*, 2000], and waters released from reservoirs often suffer water quality problems resulting from the interaction of nutrients, chemicals, and sunlight in standing water [*WCD*, 2000].

Reservoirs trap all the bedload (the coarse sand and gravel moved along the river bed) and a percentage of the suspended load (the sand and finer sediment carried in the water column, held aloft by turbulence). The percentage of the suspended sediment trapped by a reservoir can be estimated as a function of the ratio of reservoir storage capacity to annual inflow of water [*Brune*, 1953]. The supply of sediment to the river downstream is thereby reduced. Either sediment surplus or sediment deficit are possible below dams, depending on the relative change in sediment supply and transport capacity [*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 to regain some of its former sediment load [*Kondolf*, 1997]. These erosive flows commonly induce incision, undermine bridges and other infrastructure, and coarsen the bed [*Kondolf*, 1997], and fundamentally alter aquatic food webs [*Power et al*., 1996].

1.2. The Mekong River

Draining a narrow catchment originating on the Tibetan Plateau, the Mekong flows through bedrock canyons in Yunnan Province of southwest China and along the border with Burma. Downstream of the Chinese border, the lower Mekong flows through Laos, Thailand, Cambodia, and Vietnam, debouching in the Mekong Delta (Figure 1). The basin drained by the Mekong River has a complex geologic history 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 River drains a total of about 800,000 km^2 and has an average discharge (at its mouth) of about 15,000 m^{3}s^{-1}, with predictable 20-fold seasonal fluctuation from dry season (November-June) to wet (July-October)

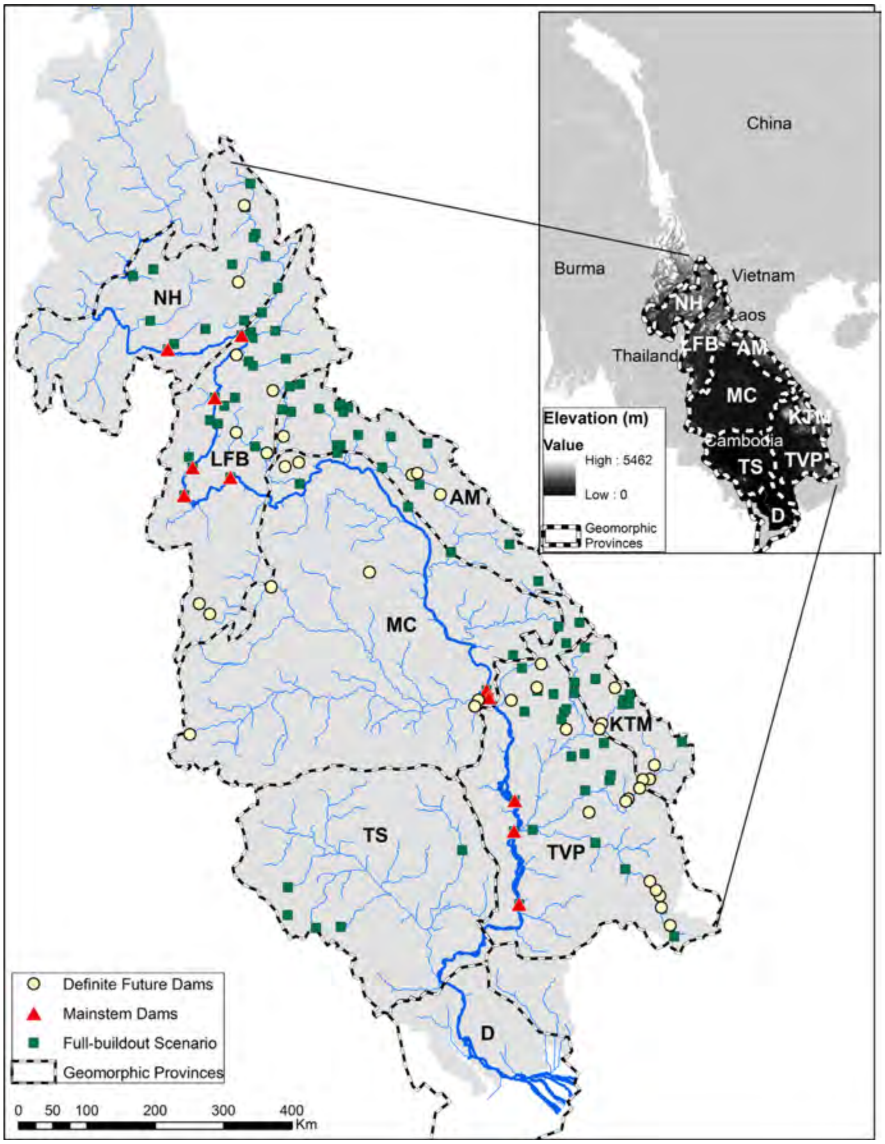

Figure 1. Lower Mekong River Basin. Based on rock type, uplift, land-use, and available sediment transport data, we delineated nine geomorphic provinces: NH (Northern Highlands,) LFB (Loei Fold Belt,) MC (Mun-Chi Basin,) AM (Annamite Mountains,) KTM (Kon Tum Massif,) TVP (Tertiary Volcanic Plateau,) TS (Tonle Sap,) D (Delta). Dam locations are indicated for three scenarios: definite future, full-buildout, and full buildout without the mainstem dams. Inset: Entire Mekong River basin, with generalized elevations indicated in black-gray-white shading.

[*Gupta et al*., 2002; *Adamson et al*., 2009]. The predam sediment flux of the Mekong River into the South China Sea has been estimated at approximately 160 million tonnes per year (Mt yr^{-1}), of which about half was produced by the upper 20% of the basin area, the Lancang drainage in China [*Milliman and Meade*, 1992; *Milliman and Syvitski*, 1992; *Gupta and Liew*, 2007; *Walling*, 2008]. However, it is worth noting that this widely used estimate has been challenged as too high based on calculated sediment flux at Khong Chiam [*Wang et al*., 2011; *Liu et al*., 2006], and as too low based on detailed studies of the sand fraction, which suggest that sand has been systematically undersampled and imply that the true transport rate is larger [*Bravard et al*., 2013a, 2013b]. In part, this may reflect the fact that sediment sampling has, until 2012, been focused almost exclusively on suspended sediment, so the values discussed here are values for suspended sediment, neglecting bedload [*Walling*, 2009], which would be preferentially trapped by dams.

The Mekong River is unique among the world's great rivers in the size of the human population supported by its ecosystem. Approximately 60 million people (mostly in Cambodia and Vietnam) use fish from the Mekong as the primary source of protein in their diet [*Hortle*, 2009; *Baran and Myschowoda*, 2009].

The river remained largely unregulated through most of the 20th century because of wars in Indochina and lack of development in remote provinces of China. With peace in the Lower Mekong River Basin (LMRB) countries and economic development in China, this is rapidly changing, and the Mekong River system is undergoing extensive dam construction throughout the basin for hydroelectric generation [*Grumbine et al*., 2012]. While there are numerous diversions for irrigated agriculture throughout the basin, and some of these involve storage impoundments that would trap sediment, we found no comprehensive inventory of irrigation impoundments. However, most are small diversions directly from river channels, and most are concentrated in the relatively-low-relief Khorat Plateau of Thailand [*Hoanh et al*. 2009]. In any event, the impact on the Mekong River system of the projected hydroelectric dams will vastly exceed that of the existing irrigation infrastructure. In the upper Mekong in China (where it is known as the Lancang), seven hydroelectric dams have been built or are under construction on the mainstem. In the Lower Mekong and its tributaries, 133 hydroelectric dams are built, under construction, or planned, including 11 on the Lower Mekong mainstem, based on data compiled by the Mekong River Commission (MRC).

1.3. Assessing Cumulative Sediment Starvation

How will the many dams planned and being constructed alter the sediment load of the Mekong? What will be the likely cumulative reduction in sediment load? Using 160 Mt yr^{-1} as the average annual suspended load of the entire Mekong and assuming that about half of this load is derived from the Lancang basin [*Walling*, 2008], the ongoing construction of seven dams on the Lancang (with cumulative trap efficiencies of about 83%) means that over 40% of the natural sediment load of the Mekong will be lost in the reservoirs of the Lancang [*Walling*, 2011]. Thus, the sediment load of the Lower Mekong River will consist of mostly of sediment derived from sources within the LMRB itself. To predict how dams in the LMRB will likely affect sediment loads requires an understanding of the relative contributions of sediment from individual subbasins and how these contributions will be affected by future dams.

We build on previous work by using information on reservoir storage and location that was not previously available, by supplementing the sparse sediment transport data with information on local factors that can influence sediment supply and transport, and by applying a model that accounts for temporal effects and spatial interactions in reservoir storage. Our study provides more accurate estimates than prior studies because (1) we utilized an updated database for locations of the planned reservoirs, (2) we used total storage estimates for the reservoirs (data not previously available), (3) we treated every dam in the network individually and calculated the sediment deficit for each channel segment, (4) we used the limited sediment transport data as only one factor in estimating sediment yields, relying also on the geologic and topographic characteristics of the regions to derive geomorphically based estimates of sediment yield, and (5) we estimated reservoir trapping under multiple dam building scenarios and accounted for changes in trap efficiency over time as reservoirs accumulate sediment.

2. Methods

To develop a detailed depiction of reservoir sedimentation over time, we applied the 3W model [*Minear and Kondolf*, 2009], a network model that accounts for multiple reservoirs on a given river and changing trap efficiencies as reservoirs fill, to estimate the sediment trapping by various combinations of dams. To do this first required estimates of sediment yields from various tributary drainages in the LMRB, then application of the 3W model for dams within the context of these estimated sediment yields. To assess potential effects of dams in the LMRB, whose tributaries historically contributed about 80 Mt yr^{-1} (i.e., the downstream half of the 160 Mt yr^{-1} total basin load), we first sought to allocate the 80 Mt yr^{-1} to different parts of the LMRB. We conducted our analysis in three stages: (1) delineation of geomorphic regions in the Mekong basin, (2) determination of sediment yield by geomorphic region, (3) application of the 3W model with estimated sediment trapping for reservoirs based on *Brune*'s [1953] empirical relationship.

2.1. Delineating Geomorphic Regions and Estimating Sediment Yields

As a basis for estimating sediment contributions, we delineated distinct geomorphic regions based on geologic history and geomorphic characteristics. Sediment yields are fundamentally controlled by tectonic

Table 1. Lower Mekong River Sediment Yields by Geomorphic Province

Geomorphic Province	Description	Estimated Sediment Yield (t km^{-2} y^{-1})
Lancang	Active tectonics, and complex geology. Mekong River follows the fault between Sibumasu Block and older block and older block from South China-Indochina merge. High altitude, steep topography	450
Northern Highlands (NH)	Hard sandstones and limestones (Paleozoic), granites and metamorphic rocks. Late Miocene uplift	250
Loei Fold Belt (LFB)	Hard sandstones and limestones (Paleozoic), granites and metamorphic rocks. Late Miocene uplift	160
Mun-Chi Basin (MC)	Sandstones of early Cretaceous Khorat Group: almost exclusively quartz sandstones. This has the lowest relief and appears to be the oldest landscape, may be a relict of older, pre-Miocene drainage system, with little recent uplift. This area has been extensively modified for agriculture and other development, so erosion and sediment yields may have been anthropically increased in recent years, but these sediments would probably be dominantly fine grained	40
Annamite Mountains (AM)	Hard sandstones and limestones (Paleozoic), granites and metamorphic rocks. Late Miocene uplift	200
Kon Tum Massif (KTM)	Heterogeneous geology of Paleozoic sedimentary rocks and igneous intrusive rocks, along with Khorat Group and younger Cenozoic basalts. Significant late Miocene uplift as reflected in deeply incised channels	280
Tertiary Volcanic Plateau (TVP)	Heterogeneous geology of igneous intrusive rocks, younger Cenozoic basalts, and underlying Paleozoic sedimentary rocks. Significant late Miocene uplift as reflected in deeply incised channels	290
Tonle Sap (TS)	The Tonle Sap basin consists mostly of lowland floodplain and small, short tributary drainage basins in the surrounding mountains. Net deposition (from Mekong River backwater) exceeds net sediment export	0
Delta (D)	Net deposition	0

uplift, climate, lithology, and land use [*Syvitski and Milliman*, 2007]. The underlying structural fabric of the basin controls the landscape of the Mekong Basin and the elevation of the highlands that form major sediment provenances can be related to distinct episodes of "plate-scale" tectonic activity that occurred from the late Triassic (~200 million years BP) onwards. In addition to the Lancang basin upstream, we delineated eight distinct geomorphic regions in the Lower Mekong River Basin, for nine regions in total (Table 1, Figure 1).

Existing sediment transport data (compiled by the MRC) are insufficient in and of themselves as a basis for estimating sediment yields, because the number of data points and measuring period are insufficient and/or there are significant questions with data reliability for many stations [*Walling*, 2008]. Moreover, some important regions (such as the basins of the Sre Pok, Se San, and Se Kong, the so-called "3-S" basins) have had no sediment data available. Thus, we used the geomorphic-region approach, as it offered a consistent, scientifically based framework. We first assessed likely relative sediment yield of each geomorphic region based strictly on geologic and geomorphic characteristics, such as uplift history [*Clift et al*., 2004] and landform relief, as well as precipitation. We also reviewed previous studies of Mekong River channel geomorphology and sediment transport [including *Gupta et al*., 2002; *Carling*, 2005; *Gupta and Liew*, 2007; *Walling*, 2008; and *Sarkkula et al*., 2010], along with sediment data available from the MRC, to provide further insights into likely sediment yields from distinct geomorphic regions. We then assigned relative sediment yields to each geomorphic region, such that the predam sediment yields would sum to 80 Mt yr^{-1}, the total annual average sediment yield produced by the LMRB predam.

This method of predicting sediment yield has some underlying sources of uncertainty. First, because a single estimate of sediment yield is applied to an entire geomorphic region, local variability is missed. Second, without detailed sediment transport data, estimates of sediment yield are, at best, rough estimates only, based on an assumed total sediment contribution from the LMRB of 80 Mt yr^{-1}. Third, this approach ignores potential conveyance losses as sediment is transported down the drainage network, a disadvantage partially offset by the fact that the sediment load apportioned to the contributing catchment is based on the downstream sediment load, so it already reflects conveyance losses.

2.2. Estimating Sediment Trapping in Existing and Proposed Reservoirs

We applied the 3W model of *Minear and Kondolf* [2009] to calculate how sediment trapping in individual reservoirs will change the sediment transport along tributaries and the mainstem Mekong throughout the entire LMRB. This allowed us to assess how sediment loads in different reaches of the LMRB will change from predam conditions under different reservoir development scenarios.

We used a spatial database of existing and proposed dam sites provided by the MRC to locate each project and query data detailing mean annual discharge, contributing watershed area, full supply level and bottom elevation, and expected dam completion date. We identified and, in collaboration with MRC staff, corrected seven problematic entries in the table, such as incorrect coordinates for Nam Kong 2 and Xe Kong 3d. For projects without data on the year constructed/planned, we assumed the projects would be completed in year 2020 (see online supporting information Table S1 and Figure S1).

The *Brune* [1953] curve predicts trap efficiency from the ratio of total reservoir storage to annual average inflow. While actual trap efficiency is influenced by reservoir geometry, seasonal patterns of runoff and reservoir storage, dam design and operation, and other factors, information on these factors may be difficult to obtain for many reservoirs. Thus, the Brune curve is widely used to provide first-cut trap efficiency estimates from the more readily available reservoir storage capacity and annual runoff data [*Morris and Fan*, 1998]. However, it is important to use total storage instead of active storage, because it is total storage that influences the processes of sediment deposition within the reservoir. In fact, "dead storage," the portion of the reservoir volume below the active storage layer, is commonly used in the design context as a "buffer" against reservoir sedimentation affecting dam operations. The difference between total and active storage can be significant, especially in dams with high-level intakes.

To quantify the total storage capacity of each reservoir, we used project reports when available [e.g., *Mekong River Commission* (*MRC*), 2011], drew upon MRC staff estimates of total storage calculated from overlaying the inundated areas (at the full reservoir level) onto topography, and consulted extensively with current and former MRC staff. Ultimately, we could not obtain total storage estimates for nine small reservoirs. For these, we used our data set of reservoirs with both active and total storage estimates, calculated a best-fit line relating total storage as a function of active storage, and used this relation to estimate total storage for the missing nine reservoirs. The nine reservoirs for which we used the best-fit method were all smaller than 0.5 km^3 in capacity, so they would have a limited impact on total basin sediment transport in any event.

Using ESRI ArcMap 10.1 software, a geographic information system (GIS), we overlaid dam coordinates on a stream channel layer obtained from the International Water Management Institute website (http://www.iwmi.cgiar.org/) and the U.S. Geological Survey's 1 km resolution GTOPO30 Global Digital Elevation Model (DEM). With these GIS layers, we constructed a dendritic network diagram to identify, for each reservoir, which other reservoirs were planned or constructed upstream. We calculated predam sediment load (Qs) for each reservoir based on the contributing watershed area for each project and apportioning that area among geomorphic units with defined sediment yields.

The 3W model [*Minear and Kondolf*, 2009] is an iterative tool that simultaneously calculates reservoir sedimentation, trap efficiency, and reservoir storage volume, for each individual reservoir for each year. The trap efficiency will decrease as the reservoirs fill with sediment. Moreover, as additional reservoirs are built in a drainage basin, upstream reservoirs will trap sediment that otherwise would have been delivered to downstream reservoirs, so in multiple-reservoir systems, the upstream reservoirs slow the rate at which downstream reservoirs fill. We conducted three runs of the 3W model to estimate reservoir sedimentation for: (1) the entire set of 133 existing and planned reservoirs, (2) for a set of 38 high-likelihood reservoirs designated by the Mekong River Commission as the 'Definite-Future' scenario, and (3) for the entire set of 133 dams without the eleven mainstem dams proposed for the Lower Mekong River (Figure 1).

Following *Brune* [1953], we estimated theoretical trap efficiencies for suspended load from total storage capacity and mean annual runoff. We used the following algebraic approximation to the equation based on Brune's median curve of trap efficiency for each reservoir.

$$TE=1-\frac{0.05}{\sqrt{CI}}$$

where *TE* is trap efficiency (expressed as a decimal percent) of a reservoir; and *CI* is the capacity-inflow ratio change calculated as:

$$CI=\frac{Vr}{Q}$$

where Vr is the total storage volume of the reservoir (km^3) and Q is the mean annual discharge at the reservoir site ($km^3\ y^{-1}$).

Following *Minear and Kondolf* [2009], we constructed a coupled worksheet model to calculate annual values for trap efficiency, reservoir sediment deposition, and reservoir volume. Each year, the trap efficiency decreases as the volume of deposited sediment reduces the storage volume of the reservoir. To account for sediment trapping in upstream reservoirs, the inflowing sediment load S was calculated based on upstream reservoir trapping, if upstream reservoirs were present

$$S=Qs-\sum Vs$$

where Qs is the predam annual sediment discharge (km^3), and $\sum Vs$ is the sum of sediment trapped in all upstream reservoirs calculated as

$$Vs=TE\times S$$

The model then calculated a new reservoir storage volume Vr, and used that to calculate a new trap efficiency TE for the following year. This procedure was done through the year 2420 (i.e., about 400 years). To convert estimates of sediment yield ($Mt\ yr^{-1}$) into volumes ($km^3\ yr^{-1}$) of reservoir sedimentation, we assumed a reservoir sediment density of 960 $kg\ m^{-3}$, the average value from *Dendy and Bolton* [1976]. In addition to calculating trap efficiency, we conducted a sensitivity analysis to determine the effect of the Brune curve selected on the results. We used the same alpha values assumed by *Kummu et al.* [2010], i.e., alpha = 0.76 for the upper curve and alpha = 1.24 for the lower curve. (The middle curve, reflected in the model's results already reported, reflects an alpha = 1.0.).

3. Results

3.1. Sediment Yields by Geomorphic Region in the Mekong River Basin

As noted by *Clift et al.* [2004, p. 20], competing controls on erosion rates include "topography, modern tectonic rock uplift rates and climate, especially precipitation." They found "a relatively good correlation between rates of tectonic deformation and erosion, but no strong link with seismicity," with the highest erosion rates in the "steep margins of the Tibetan Plateau in regions of active tectonic strain" [*Clift et al.*, 2004, p. 22].

Yields from the upper Mekong River Basin (Lancang) are clearly the highest in the basin, with predam sediment yields of about 450 $t\ km^{-2}\ yr^{-1}$, based on long-term suspended sediment records at Chiang Sean. Within the LMRB, heavy precipitation in the Kontum Massif and Central Highlands of Vietnam, combined with the region's recent and ongoing uplift documented by apatite fission track analysis [*Carter et al.*, 2000] results in the next-highest erosion rates, which we estimated to be 280 and 290 $t\ km^{-2}\ yr^{-1}$ for the Kon Tum Massif and the Tertiary Volcanic Plateau, respectively (Table 1), and as reflected in the active incision of river channels. These two regions are drained primarily by the Sre Pok, Se San, and Se Kong rivers, which are known informally within the Basin as the "3-S" rivers, and which have been identified as important sediment contributors to the mainstem [e.g., P. T. Adamson, An exploratory assessment of the potential rates of reservoir sediment in five Mekong mainstream reservoirs proposed in Lao PDR, Unpublished report, Mekong River Commission, Vientiane, 2009], although no sediment data for them have been available. The Tonle Sap basin receives substantial sediment in backwater flooding upstream from the Mekong River mainstem at flood stage and is actually net depositional [*Tsukawaki*, 1997; *Kummu et al.*, 2005], so we assigned a zero sediment yield. The Delta is also (by its nature as a delta) a sediment sink, so also has a zero sediment yield.

Recall that these sediment yields are based on apportioning a total of 80 $Mt\ yr^{-1}$ contributed to the river from the Lower Mekong River Basin among geomorphic provinces, and they do not account for the well-known inverse relationship between drainage area and sediment yield [*Walling*, 1983], nor conveyance losses downstream. Thus, actual sediment yields by subbasin may have been higher than implied by the exercise of apportioning 80 $Mt\ yr^{-1}$ amongst the potential source areas. The model could be viewed as overcoming the need to incorporate conveyance losses because the sediment load apportioned to the contributing catchment is based on downstream sediment load, which already reflects conveyance losses. However, because conveyance losses are not taken into account, the sediment loads estimated for upstream stations will underestimate the true loads passing these points. An important corollary is that amount of sediment deposited in the various reservoirs will likely be underestimated, reservoir life overestimated, and trap efficiencies decreased more rapidly than predicted.

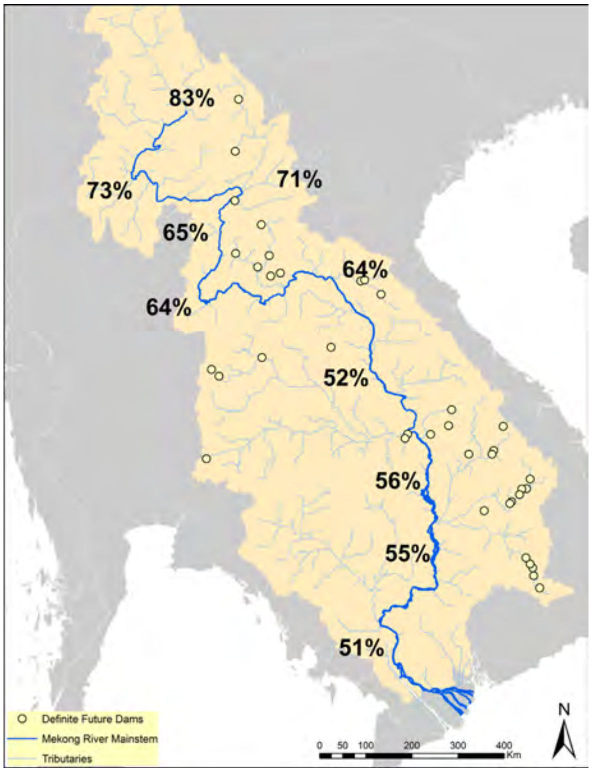

Figure 2. Cumulative sediment starvation effects of the definite-future dams. 51% of the total sediment load of the river would be trapped before reaching the delta.

3.2. Sediment Trapping in Reservoirs

As trap efficiency is a function of the capacity/inflow ratio, the largest trap efficiencies were found for tributaries with relatively large reservoirs. Twenty four reservoirs had initial trap efficiencies greater than 95%, with many more above 90%. At the other extreme, reservoirs that are small relative to the annual inflow will have negligible trapping. Our algebraic approximation of the Brune curve has an *x*-intercept for the capacity/inflow ratio of around 0.0025, which means that we account for no sediment trapping when $CI < 0.0025$. In our data set, ten of the dams fall below this cutoff, with negligible trap efficiency and thus were ignored in our model. Even dams with trap efficiencies far less than 90% can have a significant effect on basin sediment yield depending on the location within the channel network. Sambor Dam would have an initial trap efficiency of 48%. Under the "Definite Future" scenario, about 77 Mt yr^{-1} of sediment would be delivered to Sambor from upstream of which it would trap about 38 Mt yr^{-1}, significantly affecting sediment delivery to downstream reaches. We modeled the cascade of dams in the upper Mekong (Lancang) in a separate 3W model, resulting in a collective trap efficiency of 83% (of the upper Mekong's 80 Mt yr^{-1}). Because the cascade of reservoirs has such a large storage volume, the trap efficiency of the Lancang cascade will remain at 83% for many decades and thus we treated it as a constant. As upstream reservoirs fill and then trap less sediment, the downstream reservoirs of the Lancang cascade will simply capture that sediment.

3.3. 3W Model of Basin-Wide Reservoir Trapping

Under the 38 dam "Definite-Future" scenario, the cumulative sediment trapping by reservoirs will be 51%, implying that sediment load reaching the Delta will be 49% of its pre-1990 level, after sediment stored in-channel is exhausted (Figure 2). This result indicates surprisingly modest impacts given that this scenario includes the Lancang cascade and some dams on high-sediment-yield tributaries, such as the "3-S" basins. Eight of the "Definite-Future" dams are small reservoirs and with limited trap efficiencies (less then 25%) and many are high in the catchments, offering the tributary rivers some opportunity to partially recover their sediment loads downstream.

However, with full build-out of dams in the Lower Mekong River basin, including mainstem dams, about 96% the sediment load will be trapped (as of year 2020, the year by which we assume all dams are to be completed) (Figure 3). This is not to say that the sediment load reaching the Delta will immediately drop to only 4% of its pre-1990 load, because the model does not account for the potential of sediment-starved

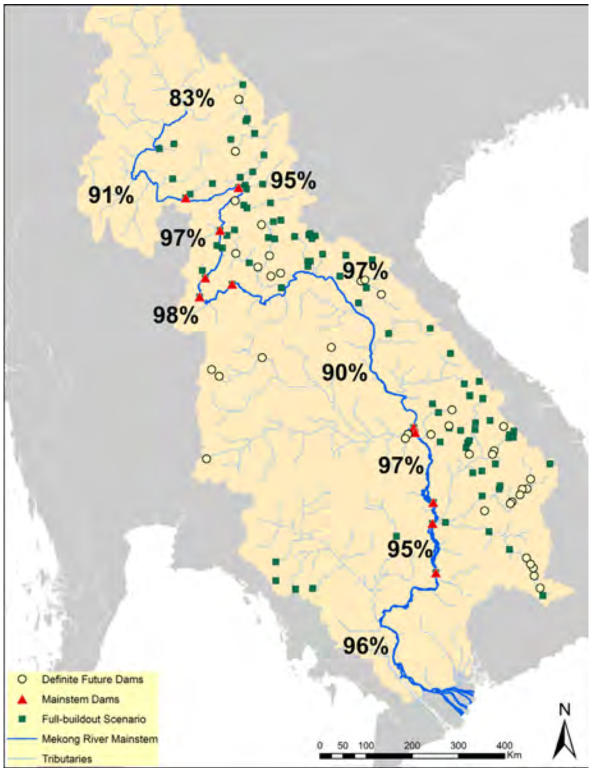

Figure 3. Cumulative sediment starvation effects of full buildout of all proposed dams. 96% of the total sediment load of the river would be trapped before reaching the delta.

flows downstream of dams to erode sediment from the bed and banks to compensate for lack of sediment supply. The 3W model simply assumes that decreased supply from trapping sediment in reservoirs results in a comparable decrease in downstream sediment loads. Given that most of the Mekong River is bedrock controlled with very limited sediment storage [*Carling*, 2009; *Gupta*, 2009], this assumption could be expected to hold for bedrock-controlled reaches, at least once sediment deposits are stripped out.

A number of studies have examined sediment loads after closure of Manwan Dam with various results, in part because of a data gap in the records at Chiang Saen from the mid-1970s to early 1990s [*Lu and Siew*, 2006; *Kummu and Varis*, 2007; *Fu et al*., 2008; *Walling*, 2011; *Liu et al*., 2013]. *Walling*'s [2011] analysis of suspended sediment data for the Lancang River at Jinghong from 1963 to 2003 provided clear evidence for increased sediment loads from the 1970s to early 1990s attributable to human disturbance (nicely shown on a double-mass curve), followed by a reduction in sediment loads (since 1993, post-Manwan Dam).

Because of the importance of the mainstem dams to sediment trapping, as well as their profound impacts as barriers to fish migration and conversion of formerly lotic habitats to lentic water bodies, we also modeled a scenario for full buildout in tributaries (by year 2020) but *without building the mainstem dams*. Under this scenario, the cumulative sediment trapped would be 68%, so that once in-channel sediment deposits had been stripped out (and not accounting for other factors such as sand mining), about 32% of the historical sediment load would reach the Delta (Figure 4).

Our sensitivity analysis showed relatively little effect on results through using the upper or lower Brune curves. For the Full Buildout scenario, cumulative sediment trapping below Sambor Dam (the lowest in the system) was 93% using the lower curve and 98% using the upper curve, compared to the 96% calculated using the middle curve. For the Definite Future scenario, cumulative trapping was 50.1% using the lower curve and 51% using the upper curve, compared to 51% calculated using the middle curve.

4. Discussion

4.1. Original Methodological Contribution

We build on previous work, using data not previously available, accounting for differences among geomorphic provinces, and accounting for time and space effects in sediment trapping, to develop the best possible estimate of cumulative sediment trapping. Our compilation of total storage values for the Mekong reservoirs allowed our analysis to avoid systematic underestimates of trap efficiencies that could result from using the more widely available active storage values as input to the Brune curve. For example, for the proposed Xayaburi Dam in Laos, the active storage listed in the MRC database is 0.225 km^3, but the total storage is 1.3 km^3 [*MRC*, 2011]. Using these different values in the Brune curve yield very different trap efficiencies: negligible versus 51%, respectively. Thus, although Xayaburi has been called a "run of the river" dam because it will not significantly alter the flow regime, the Brune curve suggests it has the potential to trap half the river's sediment.

The 3W model allows the calculation of each reservoir individually, rather than lumped calculations by basin as done in an earlier study. Consider a simple case: a basin with three principal tributaries. If three reservoirs are built, one each on the three tributaries, then the reservoir storage could be combined and used to estimate trap efficiency with the Brune curve, probably without introducing great errors. However, if the reservoirs are built all on one tributary in series (a cascade of reservoirs), the theoretical trap efficiency of the lower dam is meaningless because there may not be any sediment left to trap in that reach, although it may be abundant in other tributaries.

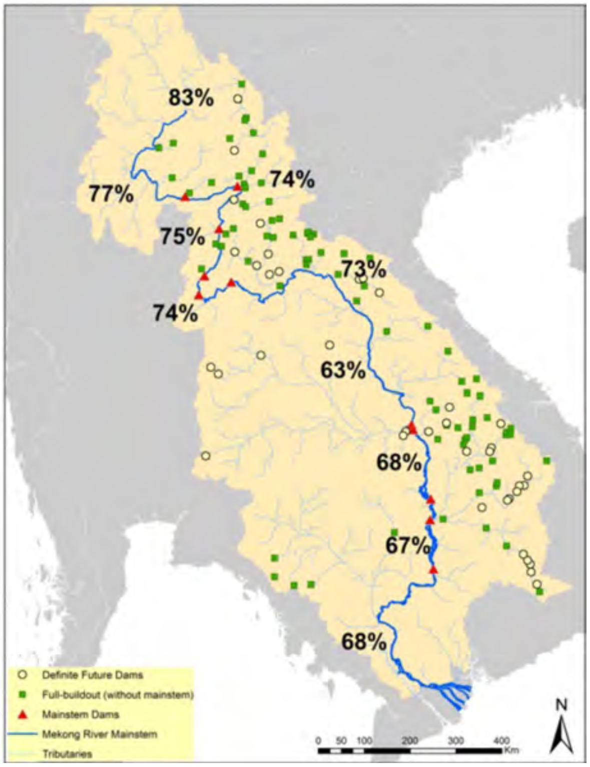

Figure 4. Cumulative sediment starvation for full buildout without the mainstem dams. 68% of the total sediment load of the river would be trapped before reaching the delta.

The 3W model is clearly a simplification of real river processes, as it ignores conveyance losses downstream, scaling effects of reduced sediment yield with increasing drainage area, and potential "buffering" effects of sediment stored in and adjacent to the channel, the erosion of which can partially compensate for sediment sequestering behind dams. The general problem is illustrated by the fact that worldwide, the amount of sediment impounded behind dams is estimated to be nearly an order of magnitude greater than the amount by which downstream sediment loads have been reduced [*Walling*, 2012].

4.2. Effect of Dams on Sediment Supply

Unlike many river basins with high sediment loads, the LMRB does not contain large areas of weak, easily-eroded rocks. Most rock types are relatively hard, so the range of sediment yields (and the high yields from some regions) reflect very active tectonic setting and differences in geologically-recent tectonic shearing and uplift history. Besides the rapidly-eroding catchment of the Lancang, which includes the Tibetan Plateau and deeply incised valleys downstream, the highest sediment producing regions in the basin are the Northern Highlands, Kon Tum Massif, and Tertiary Volcanic Plateau, which we estimated to produce 200–290 t yr^{-1} km^{-2}.

The already built and certain future dams in the MRC's "Definite-Future" scenario are distributed in such a way that their impact of sediment loads is relatively modest, leaving nearly half of the natural sediment load in the river when it passes into the downstream alluvial reach and Delta. This result is somewhat surprising, but encouraging, as it implies that some rethinking of dam-building plans, along with incorporation of sediment management strategies such as sediment pass-through or sediment bypass, could mitigate the magnitude of the sediment starvation from dams in the LMRB.

The full build-out scenario without reservoir sediment management measures would trap 96% of the river's sediment load, and eventually result in nearly complete sediment starvation, with only 4% of the natural load reaching the Delta. This predicted sediment starvation is significantly greater than previous estimates [*Kummu et al*., 2010], and implies that the downstream impacts of full build-out of all dams would be greater than previously recognized.

Figure 5. Mekong River bedrock channel with surficial sand deposits, near Xayaburi. (photo by Kondolf, January 2012)

Our results indicate that if all planned dams except the mainstem dams were built, the cumulative sediment trapping would be 68%, i.e., allowing 32% of the sediment load to pass downstream to the Delta. While still a large impact, a 68% reduction in sediment load is not as severe as a 96% reduction in sediment load, suggesting that some combinations of tributary-only dams might be worth evaluating, especially because the mainstem dams have other profound ecosystem effects, especially on migratory fish [*Baran and Myschowoda*, 2009].

Our analysis estimates sediment starvation only from hydroelectric dams, and does not address sediment starvation resulting from mining of sand and gravel from the river channel, which was estimated by *Bravard et al.* [2013a] at about 27 Mt yr^{-1} upstream of Vietnam, of which 20.7 Mt yr^{-1} was mined in Cambodia. In addition, we do not take into account sediment trapping by irrigation dams on tributaries, which are most concentrated on the Khorat Plateau of Thailand [*Hoanh et al*., 2009]; this region has low natural sediment yields, so it is unclear how significant an impact these impoundments would have on sediment load of the river. As discussed above, our analysis does not account for buffering of sediment starvation by erosion of sediment deposits, which is likely to be limited and short-term over most of the river's course over bedrock, but would be greater in the lower alluvial reach in Cambodia. Nor does our analysis address factors such as the construction of extensive dykes along the river in Cambodia, which will prevent frequent inundation of large areas of the floodplain and thereby may result in less floodplain sedimentation in the alluvial reach in Cambodia. Other land-use changes and climate change can also affect sediment load. Clearly, assessment of sediment starvation effects of planned dams must consider other factors and trends, whose effects on the sediment budget can be significant.

Our calculations of reduced sediment supply to the Mekong from reservoir trapping assume no sediment bypass or pass-through strategies are implemented in these dams, but there are many proven techniques to pass sediment through or around reservoirs [*Morris and Fan*, 1998; *Kondolf et al*., 2014], and implementing these measures on Mekong dams could significantly reduce the sediment trapping and resulting sediment starvation. Planning and modeling efforts are now underway on several proposed dams in Cambodia and Laos to assess potential benefits of implementing sediment passage to prolong reservoir life and reduce downstream sediment starvation impacts.

4.3. Effects of Sediment Starvation on Downstream Channels

The reduction in sediment supply predicted by our analysis would likely have profound implications for the productivity of agriculture and the fishery within the lower Mekong River and Delta, as well as the offshore fishery and the sustainability of the Delta landform itself. While the objective of this study was primarily to estimate the likely magnitude of sediment reduction from planned dams, some mention of the likely effects of this reservoir-induced sediment supply reductions may be in order. These impacts should depend largely on the magnitude of the reduction and the nature of the river channel affected. Except for the 300 km alluvial reach from Vientiane to Savannakhet, the river upstream of Kratie is bedrock controlled [*Gupta and Liew*, 2007]. These bedrock controlled reaches display considerable diversity in form [*Meshkova and Carling*, 2012] and contain a variety of alluvial forms within the larger bedrock channel context (Figure 5). However, the main response to reduced sediment load in bedrock reaches will be to strip out alluvial deposits, without affecting the overall structure of the channel. In alluvial reaches, however, the potential for channel change is much greater: incision from sediment starvation is likely to occur, and with it, some bank collapse and retreat [*Carling*, 2010]. Reduced suspended load in overbank flows over the floodplains of Cambodia will reduce the natural renewal of soil fertility, and reduced suspended sediment and nutrients flowing into Tonle Sap threaten the productivity of this extraordinary system [*Sarkkula et al*., 2003]. At the downstream end of the fluvial system, the delta is vulnerable to reduced sediment supply, especially in light of its relatively rapid, recent formation [*Sarkkula et al*., 2010].

4.4. Effects of Reservoir Sedimentation on Storage Capacity

Sediment trapping in reservoirs affects not only downstream reaches through sediment starvation, but also reduces storage capacity of reservoirs and can interfere with functioning of the dam and hydroelectric powerplant. With full build of all 133 dams proposed in the LMRB, our model results indicate that by 2100 (after about 80 years), seven will be more than 70% full and 13 will be more than 50% full. By 2420 (after about 400 years), 23 will be more than 70% full and 39 will be more than 50% full. In some cases, the relatively slow rates of filling result from upstream dams trapping sediment that would otherwise have deposited in the reservoir.

5. Conclusions

The unprecedented rate of dam construction in the Mekong River Basin is likely to result in greater sediment starvation than previously recognized. By developing systematic estimates of sediment yield by geomorphic province within the basin (constrained by historical measured transport rates), using total storage instead of active storage in calculating trap efficiency, calculating trapping by individual reservoirs instead of lumping by tributary basin, and accounting for trapping effects of upstream reservoirs and changes in trap efficiency over time, we developed refined estimates of sediment trapping. Our results indicate that full build-out of proposed dams would trap the equivalent of 96% of the river's historical sediment supply to the lower alluvial Mekong River and Delta. Dams already built and deemed virtually certain in the near future would reduce the sediment supply only to 49% of its pre-dam level. While our model is transparently simple (ignoring effects such as buffering of sediment starvation by bank and bar erosion), our results indicate significant sediment starvation is likely downstream, though after a lag time during which the river would "cannabilize" its limited supply of sediment stored in channel deposits and accessible bank deposits, probably much less than two decades for bedrock-dominated reaches. Predicting consequent impacts on the river and delta were outside the scope of this study, but we need only look at analogous cases [*Syvitski et al*., 2009] to recognize the potential severity of impacts on the river channel and delta landforms, floodplain fertility, and productivity of the ecosystem, including the extraordinary Mekong River fishery, which provides essential protein to 60 million people [*Hortle*, 2009]. In light of the magnitude of the potential sediment starvation on the river system, riparian countries, international agencies, and donor countries should arguably prioritize efforts to require new dams to be designed to pass sediment (and retrofit existing ones where possible), with the added benefit of more sustainable hydropower production into the future if reservoir sedimentation can be reduced.

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