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ENVIRONMENTAL STUDIES

Can restoring water and sediment fluxes across a mega-dam cascade alleviate a sinking river delta?

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Hydropower, although an attractive renewable energy source, can alter the flux of water, sediments, and biota, producing detrimental impacts in downstream regions. The Mekong River illustrates the impacts of large dams and the limitations of conventional dam regulating strategies. Even under the most optimistic sluicing scenario, sediment load at the Mekong Delta could only recover to 62.3 ± 8.2 million tonnes (1 million tonnes = 10^9 kilograms), short of the (100 to 160)–million tonne historical level. Furthermore, unless retrofit to reroute sediments, the dams are doomed to continue trapping sediment for at least 170 years and thus starve downstream reaches of sediment, contributing to the impending disappearance of the Mekong Delta. Therefore, we explicitly challenge the widespread use of large dead storages—the portion of the reservoirs that cannot be emptied—in dam designs. Smaller dead storages can ease sediment starvation in downstream regions, thereby buffering against sinking deltas or relative sea level rises.

INTRODUCTION

A healthy pristine river has high connectivity: Water, sediment, and nutrients can flow freely within the basin (*1*, *2*). However, development of hydropower necessitates the construction of dams and accompanying reservoirs, which interrupt this free flow and thereby cause negative impacts on ecology and riverine communities (*3*, *4*). However, water infrastructure development worldwide is intensifying, especially in the developing economies of Asia-Pacific, South America, and Africa (*5*, *6*). Despite their high costs, large dams are proving attractive to planners (*4*, *7*–*10*), with a large proportion of them found in Asia (fig. S1). For downstream regions, this trend is worrying because large dams, without eventual operational controls and devices, can withhold massive amounts of water and sediment, preventing vital replenishment of sediment to deltas and coasts, which face the risk of submergence and accelerated erosion (*11*–*13*). However, mitigating efforts have been limited because there are no easy solutions. Unlike small dams, these larger dams cannot be readily drawn down to facilitate sediment routing, nor can they be easily removed to restore connectivity (*14*, *15*).

The downstream effects of mega dams (defined as having heights ≥100 m or storage capacity ≥1 km^3) are brought into clear focus on the Mekong River, where a cascade of at least 11 large dams, with a combined reservoir volume of at least 45.5 km^3, has been built in the Upper Mekong River Basin (UMB) in China, also known as the Lancang River (Fig. 1). The Lancang cascade has majorly altered the hydro-geomorphology of the entire Mekong Basin (*16*, *17*) and has been linked to recent hydrological droughts experienced downstream in the Lower Mekong Basin (LMB) (*18*, *19*). At the Vietnamese Mekong Delta (VMD), insufficient sediment supply from upstream sources is a key stressor threatening the continued existence of the delta landform; rendering the delta highly vulnerable to erosion, subsidence, and salt intrusion; and threatening the livelihoods of the 17 million people there (*13*, *20*–*24*).

The problems experienced in the Mekong Basin, water and sediment conflict between upstream and downstream users, are emblematic of many transboundary rivers. What makes the Mekong River case pressing is that the siting of multiple mega dams in a cascade with little possibility of removal is unprecedented worldwide, making it a bellwether for future mega-dam developments. While past research has demonstrated that reoperation of dams (*16*, *17*), optimization of dam building sequences (*25*, *26*), or reservoir regulation strategies (*12*, *27*) can help restore water and sediment connectivity, these approaches may not be directly applicable to the existing cascade dams in the Mekong River basin. The scale of operation for the current cascade dams is considerably larger than that of the dams examined in those studies. Only under alternative hypothetical scenarios, such as where the Mekong dams were constructed differently, would these approaches potentially be effective.

We asked the question: Can these mega dams of the Lancang cascade be retrofitted or operated such that sediment and water flows to downstream can be restored or maintained? We first present a comprehensive snapshot of the Mekong River from source to sea to better evaluate the impacts of the Lancang cascade so that we can then better evaluate the effectiveness of possible solutions and challenges. Then, we modeled the potential effects of retrofitting the dams to pass sediment.

The findings of this study may be relevant to other river basins with multiple mega dams either built or planned, such as the Brahmaputra or the Indus. These large transboundary rivers are expected to undergo construction of large hydropower dams (*28*, *29*), and their delta regions are under threat of sinking due to lack of water and sediment from upstream, similar to the Mekong. Our results may therefore provide insights that can improve future dam designs and operating practices.

RESULTS

Problems in the Upper Mekong Basin: Trapped sediments within reservoirs

Despite historically high sediment loads in the Upper Mekong Basin (*20*, *30*) and anthropogenically increased erosion rates (*31*), the mega dams in the Lancang cascade were built with neither sediment

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bypass tunnels nor low sluicing gates, features that would allow for sediment to be routed around or through dams (*32*). Thus, sediment that could have been transported downstream ended up accumulating in the massive reservoirs behind the dams (Fig. 2 and table S1).

We estimated sediment trapping volumes for the four bottom-most dams of the Lancang cascade: Manwan, Dachaoshan, Nuozhadu, and Jinghong (Fig. 2 and table S2). Of these, the trapping problem was the most severe at Manwan and Dachaoshan, with 64 to 90% and 52 to 100% of their total reservoir capacities, respectively, already filled. Loss of reservoir capacity decreases energy production by reducing available storage (*33*, *34*). In the future, climate change may increase sediment delivery to the headwaters region (*35*), notably due to heightened risks of landslides along the steep river valleys (*36*), eventually resulting in the likelihood of more sediment being trapped within the dams of the Lancang Cascade. Without sediment removal strategies, dams can quickly lose their operating capacity and in the worst-case situation, become a safety hazard by increasing the risk of overtopping or dam failure (*32*, *37*). Therefore, it would seem to be in the interest of the dam operators here to manage sediments to pass through or around the dams of this cascade, especially those with smaller capacities, which would be most at risk of filling.

Problems in the LMB: Water and sediment reduction

To quantify hydrological changes across the entire Mekong Basin, our study amassed an unprecedented dataset of river discharge and suspended sediment load (SSL) from multiple stations from China to Vietnam, as compared to previous studies that only considered specific sections of the Mekong basin or shorter periods of record (*18*, *21*, *38*, *39*). Following the construction of the first dam across the Mekong mainstream, Manwan Dam, in 1992, alteration in river hydrology and sediment load was documented in various studies (*18*, *21*, *38*). We compared the hydrological data collected during the mega-dam era (2010 to 2019) with pre-dam reference values before 1992. To maintain power output throughout the year, these reservoirs retain water during the wet season for release during the dry season. Expectedly, dry-season discharge during the mega-dam era increased over its pre-dam values in most of the stations downstream of the Lancang cascade (Fig. 1, fig. S3A, and table S3).

For the LMB, the annual flood pulse is essential for fisheries, river and floodplain ecology, and the agricultural calendar (*40*, *41*). Therefore, the reduction of the wet-season discharge that we observed (Fig. 1, fig. S3B, and table S3) will directly affect the livelihoods of the riparian communities (*18*, *42*). As more dams would be

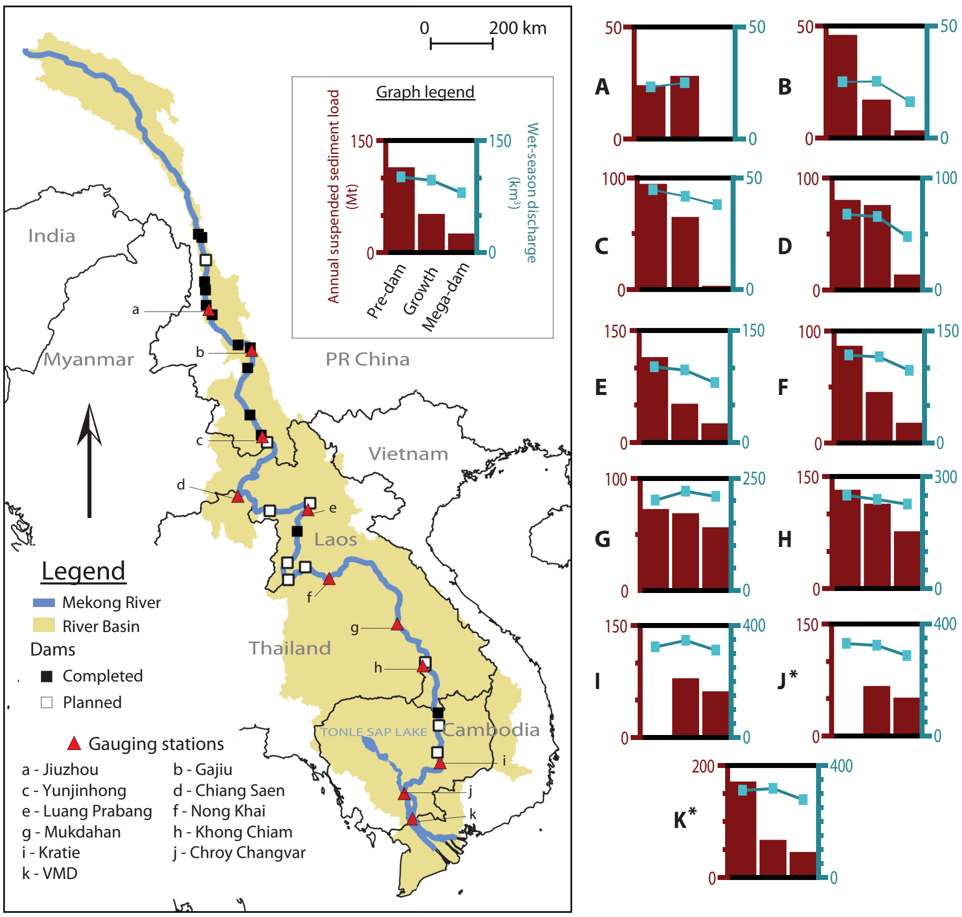

Fig. 1. Map of the Mekong River Basin and the completed/planned dams on the mainstream. Graphs (**A** to **K**) indicate the discharge and suspended sediment load (SSL) trends across the entire basin from the Chinese headwaters to the VMD. Data were divided into the pre-dam (before 1992), growth (1992 to 2009), and mega-dam (after 2009) periods, corresponding to water infrastructure development rates on the mainstream. Compared to the pre-dam levels, discharge and SSL during the mega-dam period showed a declining trend that was observed in almost all stations. *See Supplementary Text B for more details on pre-dam SSL at Chroy Changvar and VMD.

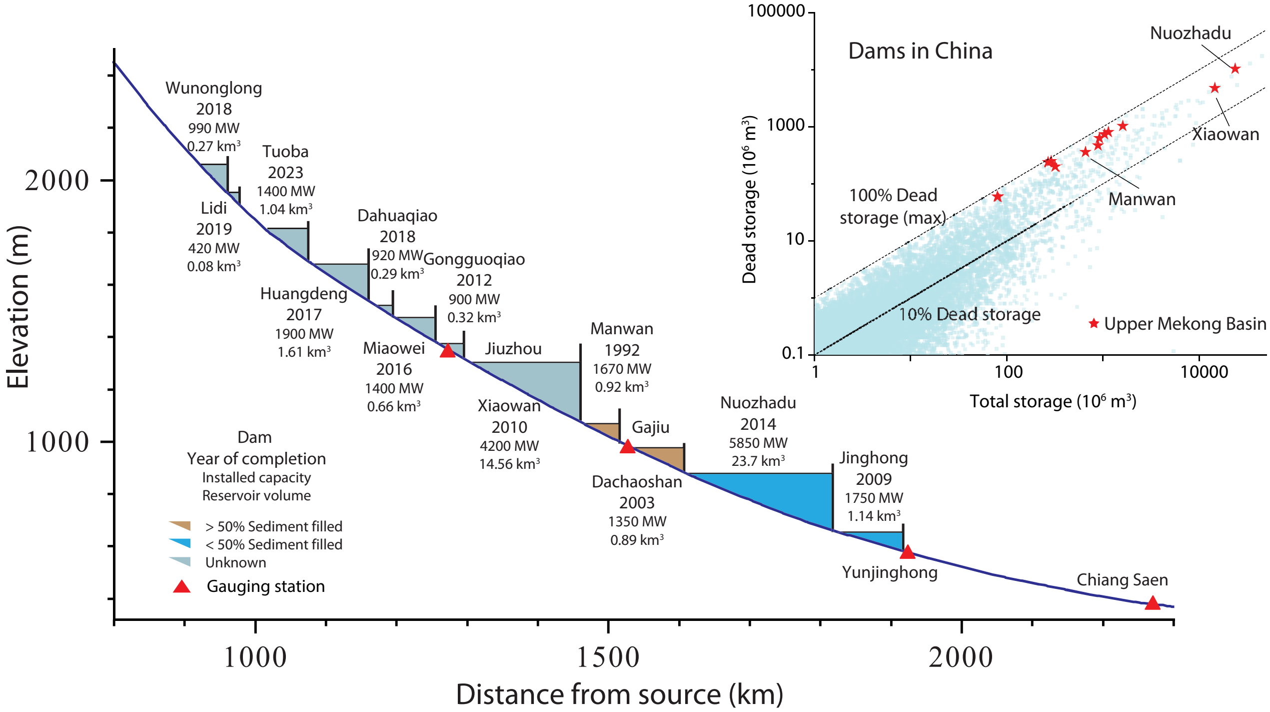

Fig. 2. Lancang cascade in the Upper Mekong Basin. Together, the dams will impound 45.6 km^3 of water, of which about 44% is locked within dead storages that cannot be released. The inset showed how the mega dams in the Mekong have dead storage capacity close to 100% of their total storages, a high percentage even when compared to other dams in China. These massive reservoirs of the Lancang cascade result in high sediment trapping rates. Already, Manwan Dam and Dachaoshan Dam have experienced more the 50% loss of reservoir capacity because of sediment accumulation.

operationalized, more water would have to be sequestered during the wet season (*25*). In years with reduced monsoonal rains, a situation that is expected to be more frequent in the coming decades (*43*), the already lowered wet-season flows will increase the risk of serious droughts in the region. These shifts in hydrological variability were most evident at Chiang Saen, Thailand, a station just downstream of the mega dams. There, total dry season flows in the mega-dam era were 54% greater than in the pre-dam era, while wet-season flows decreased by 29% over the same period (data for other stations available in table S3).

The annual flood pulse also carried almost 90% of the yearly sediment load in the Mekong. We observed that annual SSL levels had declined across all stations from the pre-dam to mega-dam era (Fig. 1, fig. S2, and table S1). Taking Chiang Saen for reference, sediment declined markedly by 84%, from 79.2 ± 6.2 million tonnes (Mt)/year in the pre-dam era to 12.5 ± 1.4 Mt/year during the mega-dam period. While natural drivers such as typhoon activity (*44*) or El Niño–Southern Oscillation variability (*45*) could reduce sediment supply, anthropogenic activities were major contributors too. Land-use changes (*46*), sand mining (*24*, *47*, *48*), and upstream dams (*20*, *21*) had all been shown to contribute to the sediment reduction. When sediment loads decrease but flows are still geomorphically competent, the river has excess energy with which to erode and degrade the riverbanks (*49*). Therefore, riverbank collapses along the Mekong Basin will become more frequent (*47*). Perhaps the most critical situation would be in the VMD, where 90% of the landform is likely to be inundated by 2100 due to the combined effects of sea-level rise and water extraction (*13*, *25*, *50*). With the current sediment load being too low for the Delta to replenish itself, the sinking and ultimate submergence of the VMD seems inevitable (*13*, *51*).

The marked shifts in discharge and sediment fluxes during the mega-dam era as compared to the pre-dam era illustrate how large dams can profoundly influence a river system (*18*, *21*, *52*), even a river as large as the Mekong. Furthermore, the rapidity of the hydrological changes challenges downstream communities to adapt, putting the densely populated floodplains and delta at risk. Thus, there is an urgent need for authorities to consider retrofits or adopt reoperation strategies for dams to arrest or reverse the damage downstream, so that the rich Mekong River floodplain and delta can be sustained.

Can dam (re)operation restore water and sediment flows?

The steep terrain and the cascade arrangement of the mega dams complicate efforts to restore water and sediment flows. Water flow can be restored by retiming releases to align with the natural flood cycle; however, restoring sediment flow is more complex. Aside from the outright removal of the mega dams, several potential mechanisms can be considered. These options include routing sediment through the reservoirs (sluicing), flushing sediment after it has accumulated in the reservoirs, creating bypass tunnels, or dredging sediment and disposing of them downstream of the dams (*53*, *54*).

As the dams are in a cascade, engineering efforts such as installing tunnels would be required for the entire length of cascade, spanning a distance of at least 500 km, a technically challenging and costly endeavor. Similarly, the lack of low-level gates in the mega dams will not allow the reservoir to drawdown, thereby impeding any flushing operations. Thus, the remaining option would be sluicing, which involve opening the dam gates at a coordinated time so that water can pass freely through each reservoir sequentially. We modeled the effectiveness of this approach for the Lancang cascade.

Because the exact operational strategy of the mega dams was not publicly available, we estimated the amount of water drawn by mega dams during the wet season from discharge records at Chiang Saen. According to the operating pattern set during 2015 to 2019, the dam began impounding waters on 1 June and continued to store water over the course of the wet season (fig. S4).

The implementation of sluicing operations must consider the needs of both upstream and downstream users. Long sluicing durations will benefit downstream communities, which will receive more water and sediment, at the cost of upstream dam operators filling less water for the upcoming dry season (Fig. 3). Therefore, we considered three sluicing scenarios: (i) maximum sluicing (MaxS), (ii) compromise sluicing (CompS), and (iii) single-month sluicing (SinMonS) (see Materials and Methods).

Under MaxS, the cascade will be sluiced for almost the entire wet season with four months of operations; in other words, the sediment and water released during MaxS will be at their upper limits. However, this strategy will not allow the active storages of the reservoirs to be filled, resulting in the dams not being ready for hydropower production in the upcoming dry season. During CompS, the cascade gates will be kept open for about 2.5 months starting from mid-July, an arrangement derived from our sluice index (SI) that attempted to maximize water and sediment released, without jeopardizing too much the ability of the cascade to replenish its active storage. Here, we estimated that 29 ± 3% of the active storage can be replenished by the end of the wet season. These 2.5 months of operations with CompS might be deemed too long for dam operators, so we developed a further option that limits sluicing operations to 1 month, the SinMonS scenario. Under this 1 month of flushing scenario, about 45 ± 7% of the active capacity can potentially be maintained. This result may be more acceptable to dam operators and closer to the 77 ± 9% of the active capacity that can be maintained under the business-as-usual scenario.

At Chiang Saen, we estimated that 55.7 ± 0.6 km^3 of water will be discharged following the SinMonS plan (Fig. 4, fig. S5, and table S5). Even under CompS, wet-season discharge at Chiang Saen (59.8 ± 1.4 km^3) was still short of its pre-dam levels of 67.4 km^3, although better than its current mega-dam levels of 47.7km^3. Recovery to pre-dam water amounts was only possible under MaxS, which was not a practical option. More sobering, the sediment loads released during SinMonS (18.0 ± 0.6 Mt) and CompS (23.8 ± 1.3 Mt) fall far short of the pre-dam SSL levels of 79.2 Mt at Chiang Saen, although slightly improved over current mega-dam levels of 12.5 Mt. Under the MaxS scenario, sediment loads could reach 29.2 ± 1.9 Mt, still far below pre-dam levels. This inadequacy of the full sluicing scenario is attributable to sediment trapping by the large dead storage in the reservoirs.

Looking at the potential increases in discharge and sediment loads from sluicing the Lancang cascade dams downstream at Khong Chiam, in the middle reach of the LMB, we found more subtle effects (Fig. 4). While 30 days of sluicing operation (SinMonS) would increase wet-season discharge from the current, mega-dam levels of 227 km^3 to 235 ± 2.4 km^3, (contrast with its pre-dam era 250 km^3), the effect on sediment loads was modest. Even with 4 months of sluicing under MaxS, SSL was only expected to increase to 94.3 ± 12.4 Mt, far short of its pre-dam baseline of 131 Mt. While released sediment amounts might be higher than modeled in the initial years of sluicing due to remobilization sediments from other parts of the LMB, the additional influx will decline following exhaustion of erodible sediments.

In the future, the sluicing operations must account for mainstem dams in the LMB such as the newly operationalized Xayaburi Dam. Although the mainstream dams in the LMB were described as run-of-the-river by their proponents (*55*, *56*), they still hold reservoirs

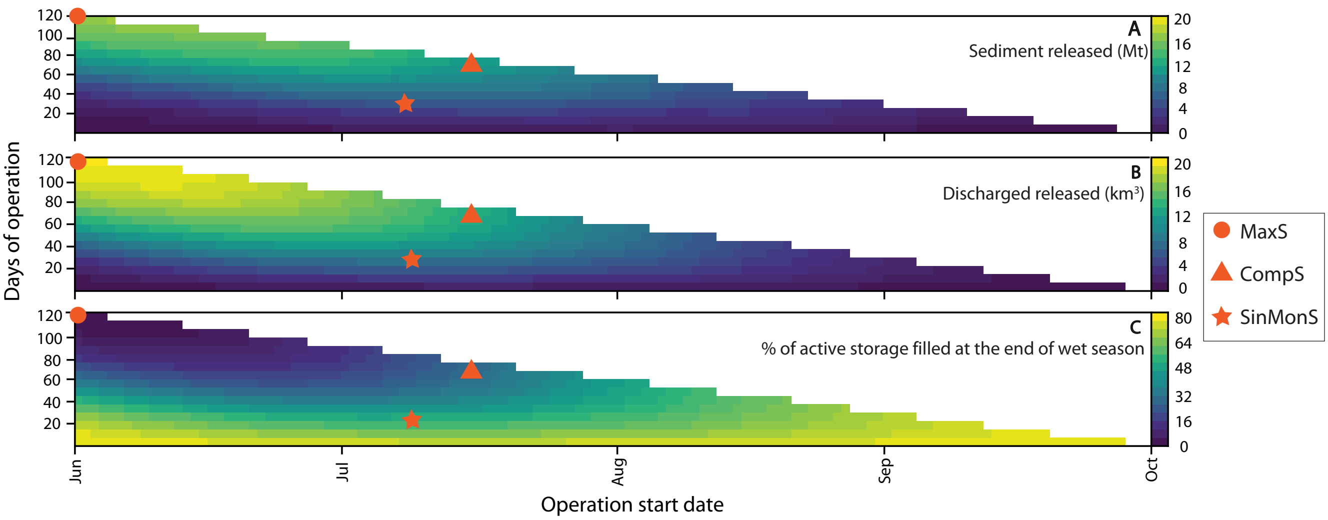

Fig. 3. Sediment, discharge released, and the percentage of the active storage of the reservoirs that can be filled at the end of the wet season after various sluicing operations. Under the maximum sluicing (MaxS) scenario (red circle), the amount of sediment (**A**) and water released (**B**) will be maximized, but minimal water will be available for the reservoirs (**C**). The compromise sluicing (CompS) scenario (red triangle) provides a compromise between the three factors but its 2 months of sluicing might still be too unattractive for dam operators. Thus, the single-month sluicing (SinMonS) scenario (red star) presents a case with only 30 days of sluicing.

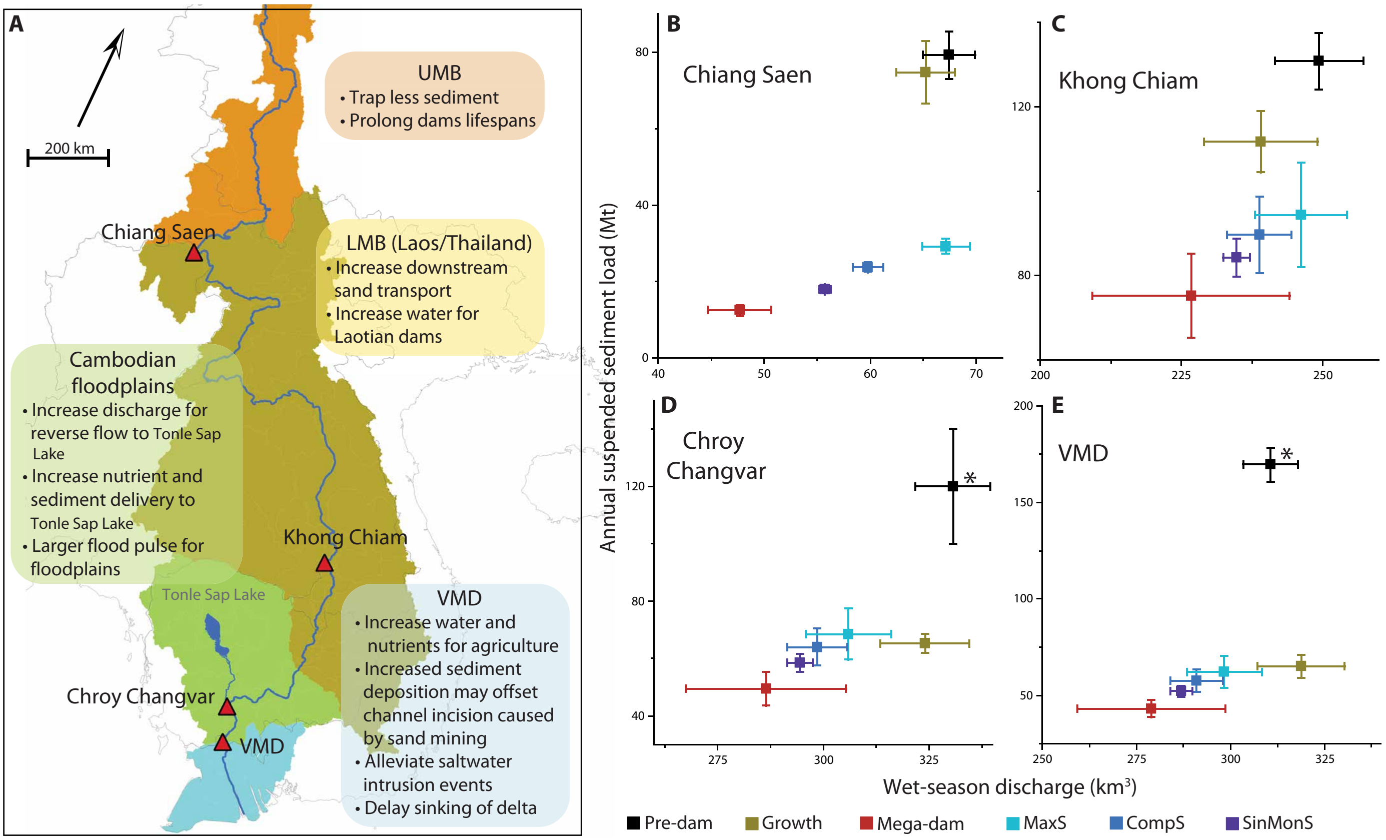

Fig. 4. Effects of sluicing operations for downstream regions. (**A**) The potential impacts on downstream regions. In greater detail, (**B** to **E**) show the estimated annual SSL and wet-season discharge after sluicing operations as compared to their historical values. Error margins represent SEs. The scenarios considered were MaxS, CompS, and SinMonS. While the sluicing operations might allow discharge to recover to pre-dam values, SSL would be unlikely to recover with sluicing alone. *Based on geomorphic considerations, pre-dam SSL at Chroy Changvar was estimated to be (100 to 140) Mt/year. Also note that the calculated pre-dam SSL at VMD (170 ± 9 Mt) could be overestimated. See Supplementary Text B for more details.

that have the capacity to trap sediment. Thus, sluicing these dams as well could increase the amount of sediment available downstream. Further analyses accounting for changes predicted by climate projection models for the near term (2020 to 2029), medium term (2030 to 2050), and long term (2050 to 2099) gave similar estimates: ~16 Mt of additional sediment can be released per year at Chiang Saen with the MaxS scenario, implying that SSL at the LMB would be unlikely to recover in the future (fig. S5).

The best-case scenario that water and sediment will be conveyed without loss from Khong Chiam to the VMD was imagined so as to consider the effects of sluicing operation there. Of course, actual values will be much lower because water and sediment would be lost via infiltration, evaporation, diversion, deposition, or anthropogenic extraction (*13*, *47*, *57*). Even with this optimistic assumption, we calculated that, while wet-season discharge could come close to 95% of pre-dam volume at the VMD, the increase in sediment was insufficient to revert to pre-dam values.

At Chroy Changvar, the station just upstream of the Tonle Sap River confluence, 30 days of sluicing under SinMonS can increase SSL to 58.4 ± 3.2 Mt, close to its growth-era amount of 65.2 Mt. For the Cambodian floodplains, the annual flood pulse and the corresponding reverse flow from the Mekong River to the Tonle Sap Lake largely determine the productivity of fisheries and the surrounding agricultural fields (*40*, *57*). Hypothetically, with additional water from sluicing, the volume of reverse flow would increase, simultaneously bringing in more nutrients and sediments to the Tonle Sap Lake. However, as channel degradation has been observed in this area due to sand mining and consequent channel erosion (*58*, *59*), the amount of increase might not be much because the main channel conveyance is larger. Nonetheless, there is still some potential that the problem of declining reverse flows observed during the mega-dam era (*57*) could be at least partially mitigated.

Further downstream at the VMD, annual SSL during the mega-dam era had been observed to be only 43.2 ± 4.5 Mt. With SinMonS scenario, SSL can increase to only 52.2 ± 2.8 Mt, far less than its pre-dam level of (100 to 160) Mt (see Supplementary Text B on variability of pre-dam SSL estimates). Even under the MaxS scenario, SSL would be only 62.3 ± 8.2 Mt, roughly a 50% increase over current levels but still falling short of restoring historical sediment loads that sustained and prograded the VMD. Moreover, the potential for sluiced sediment to restore or maintained the VMD must be assessed in the context of massive sand mining that has occurred in the Lower Mekong and the VMD (and which continues to this day) (*13*, *58*). When this sand mining and groundwater-pumping–induced subsidence are taken into account (*50*, *60*), the low sediment load challenges the ability of the delta to maintain its elevation above sea level. Sluicing sediment from the Lancang cascade dams alone will not prevent the Delta from inundation because the released sediment is too little. Instead, saving the VMD would require a much greater sediment supply as well as local measures that help to conserve sediment connectivity within the floodplains (*13*).

The low amounts of sediment released were due to the large dead storage of the Lancang reservoirs. Even when the reservoirs are at their lowest level, there would still be a combined 19.2 km^3 of water present in dead storage of the Lancang dams or about 45% of their total reservoir capacities (Fig. 2). Comparing sediment loads at Chiang Saen measured pre-dam and during the mega-dam era, we estimate the trapping efficiency of the entire Lancang cascade to be about 86.5%. With such a huge sink, sediment could still deposit within the cascades even when all the flood gates are opened, impeding the effectiveness of any sluicing operation. Particularly, Nuozhadu reservoir, with its dead capacity of 10.4 km^3 and located near the end of the cascade, would be a big obstacle for sediment to bypass because it would take almost 13.5 billion tonnes of sediment or about 170 years of the pre-dam SSL load at Chiang Saen (79.2 Mt), to fill it up. By then, rising sea levels would have submerged the VMD (*13*, *50*). Unless the sediment is physically removed via dredging or bypass tunnels, the only way sediment connectivity could be restored would be to wait for the dead capacity to be filled (*33*, *34*).

To allow more sediment to pass through the reservoirs, one solution would be installation of lower gates. Doing so will reduce the dead storage levels, thereby lowering the sediment trapping efficiency of the reservoirs. Retrofitting existing dams with low-level outlets can create risks to the integrity of the dam, and thus their suitability would depend on the dam design and setting. Another alternative would be bypass tunnels, if the reservoir geometry and rock type are favorable. If low-level outlets were installed in the dams such that the combined dead capacities of the Lancang cascade were reduced to 10% of their original volumes, then the expected sediment at Chiang Saen with around 2 months of sluicing operation under CompS will be 31.8 ± 2.2 Mt (Fig. 5), which is 70% greater than that with current dead storage levels. Correspondingly, sediment delivery to the VMD would rise to 63.6 ± 7.5 Mt, an ~50% increase from current mega-dam levels, indicating some potential to partially mitigate sediment starvation in the VMD.

DISCUSSION

Although reoperating the mega-dam cascade can partially restore water connectivity to downstream regions, the additional sediment released is insufficient. In essence, merely reoperating the mega-dam cascade would not suffice to halt the subsidence of downstream delta and coasts. The Mekong River illustrates how the design of mega dams can impede efforts to restore sediment connectivity, with implications for both upstream and downstream regions. If those dams had been designed with low-level outlets and thus less dead storage from the onset, then both water and sediment connectivity for the river could be reasonably maintained. While short-term profitability would be reduced by the lack of generation during periods of sluicing, the reservoirs would be more sustainable and not doomed to eventually fill with sediment. Moreover, they would not contribute so much to long-term consequences such as the sinking delta landform and salt-water intrusion.

The Mekong River holds lessons for designers and operators of future mega dams across the globe, indicating the potential value of operational strategies that facilitate sediment routing through or around dams. Implementing these sustainable sediment

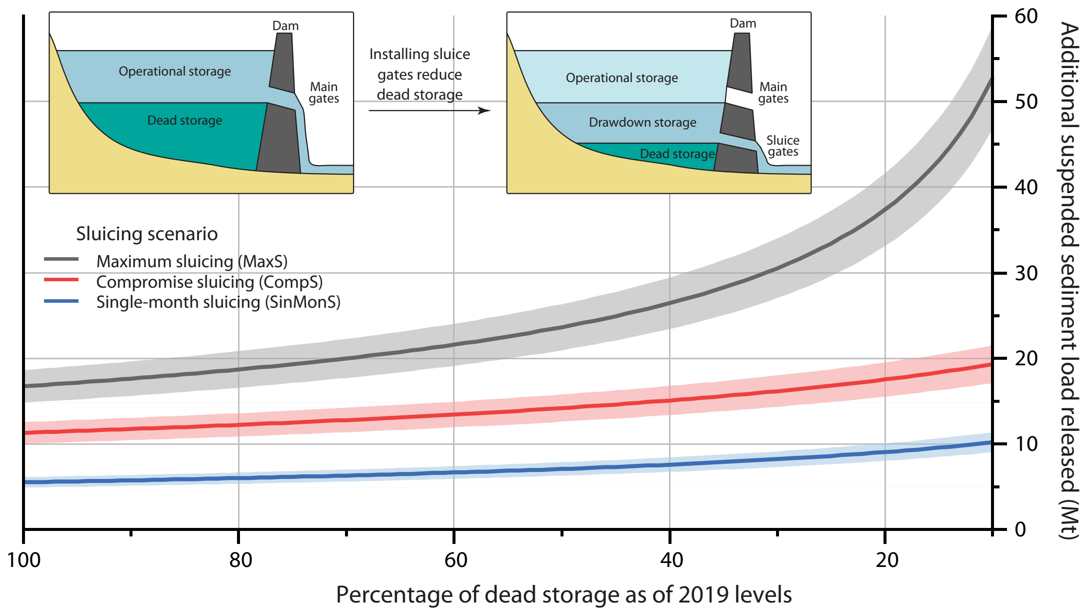

Fig. 5. Cumulative SSL released with reduced dead storage levels under the various sluicing scenarios: MaxS, CompS, and SinMonS. Dead storage levels were taken as a percentage of 2019 levels which is 19.2 km^3. Shaded regions represent error margins between maximum and minimum values. If hydrometeorological conditions and dam operations were as during 2015 to 2019, then lower levels of dead storages would have increased total amount of SSL released to Chiang Saen. Installing sluice gates near the base of the dam for flushing purposes could be one of the mechanisms to reduce the dead storage, allowing more sediment to bypass the dam during sluicing.

management strategies can enhance the lifespan of these large reservoirs by preventing sediment accumulation within their reservoirs, which ultimately benefits the dam operators themselves. Concurrently, through reducing impacts on downstream ecosystems and communities, dam proponents can enhance the appeal of dam projects, particularly on transboundary rivers.

Again, we emphasize and advocate that sediment routing plans should be an integral part of dam design, rather than an afterthought. Particularly as dams continue to grow ever larger with limited room for renovation or reengineering, any oversight in this regard poses critical challenges to the feasibility of implementing rehabilitation measures once the dam is operational, ultimately sealing the fate of downstream regions. With an increasing number of hydropower dams being constructed on large rivers (*5*, *6*, *61*), our study contributes to the ongoing research on better dam design and remediation strategies so that disturbance to the riverine system is minimized, thereby allowing for sustainable hydropower generation while safeguarding the long-term health of our rivers.

MATERIALS AND METHODS

Discharge and sediment data and estimate

Data on discharge and sediment from 14 stations on mainstream Mekong River were collated. Periods of hydrological data availability and sources are documented in table S6.

Discharge data from the stations—Jiuzhou, Gajiu, Yunjinghong, Chiang Saen, Luang Prabang, Nong Khai, Mukdahan, Khong Chiam, Kratie, Chroy Changvar, and VMD—were split between the wet season from July to November and the dry season from December to May, in line with the official definition by the Mekong River Commission (MRC) (*62*). For "VMD," discharge data were a sum of discharge from Neak Luong and Kol Khel, located on the two distributaries of the Mekong River as it enters the deltaic region.

SSL data were either obtained from providing data sources or calculated from rating curves. See Supplementary Text A for information about SSL data preprocessing.

The time series were divided into three main periods: the predam (before 1991), growth (1992 to 2009), and the mega-dam (after 2010) periods. Such a temporal division had also been used in other studies (*52*, *63*) and reflected the changing circumstances caused by water infrastructure developments along the Mekong River.

Estimate of trapped sediments

We estimated the sediment trapped in some of the Lancang dams from SSL and rainfall records at various hydrometeorological stations. Differences between the observed versus expected SSL at Gajiu and Yunjinghong gave an estimate of the amount of sediment trapped. Note that, because bedload or bank erosion contributions were not computed, our calculated values were underestimates; real values were likely to be much higher. More details regarding estimation of trapped SSL in the Lancang cascade are in Supplementary Text C.

Design of sluicing operation

Three options were considered for the sluicing operations: (i) MaxS, (ii) CompS, and (iii) SinMonS. During MaxS, the cascade will be sluiced for almost the entire wet-season for 120 days from 1 June onward. Therefore, the water and sediment released then will be the upper limit of sluicing operations. During CompS, the cascade gates will be kept opened for 76 days starting from 17 July. To calculate this start date and duration for CompS, we derived a SI as detailed in Eq. 1. SI is thus a function of the amount of sediment and water released from the sluicing and the percentage of active storage that can be maintained at the end of the wet-season in spite of the sluicing (fig. S6). A high value of SI will imply a balance between these competing variables and represented the "compromise" between upstream and downstream users. Last, with SinMonS, 8 July, as compared to other possible start dates, was determined to be the best day to start the 30-day sluice because the most sediment can be released. Note that these determinations of start date and/or sluicing durations assumed that the Lancang cascade operated according to 2015 to 2019 patterns.

$$\mathrm{SI} = \text{Amount sediment released (Mt)} \times \text{Amount water released } (\mathrm{km}^3) \times \text{Percentage active storage filled} \tag{1}$$

Estimate of changes downstream

A "water and energy transfer processes in large river basins" (WEP-L) model was used to simulate discharge and sediment flows at Chiang Saen. Details of the model structure are in Supplementary Text D.

The sources of the data input for the model are listed in table S7. Calibration of the model was performed with the multi-objective generalized likelihood uncertainty estimation method (*64*). The calibration and validation period were during 1965 to 1980 and 1981 to 1985, respectively. The model achieved relatively good fit with coefficient of determination (R^2) and Nash-Sutcliffe efficiency values between 0.5 and 0.8 (fig. S7).

As the models were run without the influence of dams, the simulated values corresponded to the discharge that would have reached Chiang Saen if there were no operating dams in the UMB. The difference between the simulated and observed values represented the amount of water released/stored by the dams. Thus, the additional water (million cubic meters per day) that would reach Chiang Saen because of sluicing operations would be the difference between simulated discharge and observed discharge.

The total SSL reaching Chiang Saen depended on the suspended sediment concentration (SSC) and discharge. We did not consider additional bedload increases as the heavier bedload would be trapped within the dead storages of the Lancang cascades. SSC at Chiang Saen, in turn, was affected the trapping efficiency of the upstream cascade dams. We used a modified Brune's curve (*65*) to estimate the trapping efficiency of the entire cascade ($\mathrm{TE}_{\mathrm{cascade}}$) based on its total storage capacity in million cubic meters (S_{cascade}) and the mean discharge at Chiang Saen ($Q_{\mathrm{Chaing\ Saen}}$) as per Eqs. 2 and 3.

$$\mathrm{TE}_{\mathrm{cascade}} = 1 - \frac{a}{\sqrt{\text{Residence time}}} \tag{2}$$

where a is a constant.

$$\text{Residence time} = \frac{S_{\mathrm{cascade}}}{Q_{\mathrm{Chiang\ Saen}}} \tag{3}$$

Monthly data documenting changes in reservoir storage volumes from 2008 to 2019 were obtained from Vu *et al.* (*66*), and $Q_{\mathrm{Chaing\ Saen}}$ values were expressed as mean discharge (cubic meter per second) for each month. The fitted curve had an R^2 of 0.52, and the value of a was determined to be $0.48 \pm 0.02\ \mathrm{Ms}^{0.5}$ (fig. S8).

Thereafter, the expected SSL reaching Chiang Saen is given by Eq. 4

$$\mathrm{SSL}_{\mathrm{expected}} = (1 - \mathrm{TE}_{\mathrm{cascade}}) \times \mathrm{SSC}_{\mathrm{expected}} \times Q_{\mathrm{expected}} \quad (4)$$

where $\mathrm{SSC}_{\mathrm{expected}}$ and Q_{expected} were obtained from the WEP-L model output and $\mathrm{TE}_{\mathrm{cascade}}$ is given by the modified Brune relation (Eq. 2).

For future discharge and sediments projections beyond 2020, meteorological data from CMIP6 under the SSP2-4.5 scenario (middle-of-the-road intermediate emissions) generated from five models—namely, CESM2, INM-CM5, MPI-ESM1, NorESM2-MM, and TaiESM1—were obtained and then averaged before being input into the WEP-L hydrological model. The forecast data were grouped by near term (2020 to 2029), medium term (2030 to 2049), and far term (2050 to 2099).

We assumed an optimistic scenario that there will be zero loss in water discharge from the sluicing, meaning that the volume of additional water at Khong Chiam and other downstream stations will be the same as that in Chiang Saen. In contrast, estimates for sediment load at downstream stations would have to factor in both SSL and discharge changes because increased discharge can remobilize loose riverbank sediments (*49*). Thus, annual wet-season discharge (Q) and sediment (SSL) changes at Chiang Saen were empirically correlated with those at Khong Chiam, a station located approximately midpoint of the LMB, with Eq. 5. Annual data from 1966 to 2017 were used for the fitting.

$$\frac{Q_{\text{Khong Chiam}}}{\mathrm{SSL}_{\text{Khong Chiam}}} = c\left(\frac{Q_{\text{Chiang Saen}}}{\mathrm{SSL}_{\text{Chiang Saen}}}\right)^{d} \quad (5)$$

The fitted curve achieved an R^2 of 0.48, with c and d being dimensionless constants with values of 0.46 ± 0.01 and 0.22 ± 0.04, respectively (fig. S9). Note that the empirical function operated under the assumptions that contributions from tributaries and rainfall changes between the two stations remained constant or unimportant. While these assumptions might not be realistic, the simplicity of the function allowed the clear observation of direct relationships between hydrological variables at Chiang Saen and Khong Chiam. In other words, expected SSL at Khong Chiam (dependant variable) can be expressed as a mathematical function of SSL at Chiang Saen, and wet-season discharges at Chiang Saen and Khong Chiam (independent variables).

At stations downstream of Khong Chiam, the hydrology become more complex as other major tributaries such as the Chi-Mun river and 3S rivers join the mainstream. Furthermore, the Mekong meanders across the Cambodian floodplains over multiple paths over the wet season (*67*, *68*), creating many challenges for modeling water and sediment flux over the region. Assuming that extra water and sediment at Khong Chiam is conveyed to the downstream regions without loss was probably an overestimate because water and sediment will be inevitably lost through anthropogenic extraction, sediment deposition, or overland transport. Thus, our estimates can be taken as the upper limit of additional water and sediment from the sluicing operations.

Supplementary Materials

This PDF file includes:

Supplementary Texts A to D
Figs. S1 to S11
Tables S1 to S8
References

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