

Chapter 2

Mitigating Dam Conflicts in the Mekong River Basin

Thomas B. Wild and Daniel P. Loucks

Abstract The Mekong/Lancang River Basin is undergoing a period of rapid hydro-power development, with plans to construct over 100 dams in the next several decades. These dams may alter the river's natural flow and sediment regimes, which could significantly degrade the exceptional biodiversity and productivity of the basin's ecosystems. Sediment that is trapped in reservoirs will be unavailable to support the basin's geomorphology and habitats, and by reducing reservoir water storage capacity may decrease hydropower output and reliability. This paper illustrates how alternative dam location, design and operation may have the potential to reduce reservoir sediment trapping. This paper describes the simulation model used to identify alternative siting, design and operating options for two planned dams in Cambodia: Sambor on the Mekong River and Lower Se San 2 on a tributary of the River. Lower Se San 2 Dam is particularly important with respect to biodiversity and ecological productivity. Sambor Dam could prevent significant quantities of sediment from reaching Tonle Sap Lake and the Vietnam Delta, two critically important features of the river basin. Results from daily simulations of water and sediment flows show the extent to which sediment management practices could reduce the adverse impacts of reservoir sediment trapping if conducted in an environmentally friendly manner, as well as the loss in hydropower production resulting from those practices.

Keywords Dams • Mekong River • Reservoir sediment management

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2.1 Introduction

The Mekong/Lancang River flows from the Tibetan Plateau through the Upper Mekong Basin in China (where it is called the *Lancang Jiang*) to the Lower Mekong Basin (LMB), draining parts of Myanmar, Lao PDR, Thailand, Cambodia, and Vietnam. The River discharges into the South China Sea. It has remained largely unaltered for much of its history. Recently, the construction of dams on the mainstream Lancang River, along with dams on tributaries of the Mekong River in the LMB, are signaling future changes in the course of development of this incredibly biodiverse river basin.

The Mekong basin is home to more than 60 million people. Many depend directly on the river and its tributaries as a source of income and food security (MRC 2010). The river basin is second in biodiversity to the Amazon River Basin (MRC 2010). The LMB has an estimated hydropower potential of 30,000 MW, of which only 10 % has been developed to date (MRC 2010). By 2030, the construction of 62 dams, including 6 on the Lancang River and 56 on LMB tributaries, is expected to be completed (MRC 2011b). Plans exist for a total of 134 dams to be eventually built in the LMB. The extent of river basin development planned to occur over a relatively short span of time warrants an evaluation of the potential impact of the planned development on the temporal and spatial distribution of water and sediment, both of which play critical roles in shaping the river system and maintaining its productivity.

The river's 795,000 km² watershed discharges about 460 km³ of water each year. The climate of the Mekong Basin is controlled by the Monsoon that produces annual wet and dry seasons of approximately equal length (MRC 2005). The Mekong River is among the world's largest in terms of length and sediment load, delivering approximately 160 million metric tons (Mt) of suspended sediment per year into the South China Sea (Milliman and Meade 1983).

A major flow and sediment contribution to the mainstream Mekong River, shown in Fig. 2.1, is from the Se San, Sre Pok and Se Kong (3S) River Basins. The 3S basins have a contributing watershed area of 78,650 km², covering approximately equal parts of Cambodia, Lao PDR and Vietnam. The 3S Rivers have a combined discharge of about 17–20 % of the Mekong River's annual runoff, and likely produce a similar fraction of the LMB sediment load (Kondolf et al. 2011; Sarkkula et al. 2010; ICEM 2010), as well as provide habitats for migrating fish and birds. The 3S Rivers provide fish spawning and breeding grounds to over 40 % of Mekong fish species (Baran et al. 2013).

Half of the Mekong basin's annual sediment load is likely generated in the Upper Mekong Basin (China) and the remaining half in the LMB (Clift et al. 2004). The construction of dams on the Lancang River in China is expected to trap much of the 80 Mt generated annually there (Lu and Siew 2006; Fu and He 2007; Kummur and Varis 2007; Kondolf et al. 2014), with significant trapping potential at dams in the LMB as well (Kummur et al. 2010; Kondolf et al. 2014). Sediment trapping is not just an issue in the Mekong Basin. Worldwide, reservoir storage capacity is declining due to sedimentation at an estimated average rate of 0.5–1 % per year (Mahmood 1987;



Fig. 2.1 Se San, Sre Pok, and Se Kong (3S) tributary basins to the Mekong River, showing current and future reservoir locations. The *red arrow* indicates the proposed location of the Lower Se San 2 (LSS2) Dam site, whereas the *red dashed line* indicates the proposed location of Sambor Dam on the mainstream Mekong River. Modified from Wild and Loucks (2014a).

White 2001). More than 50 % of sediment flux in regulated river basins may be getting trapped in reservoirs or other artificial impoundments (Vörösmarty et al. 2003).

Sediments that are trapped in reservoirs are unable to perform two vital functions downstream. First, sediment is needed to preserve the geomorphologic makeup (or physical structure) of the river system downstream that directly influences habitat quality and availability (Power et al. 1996). In the Mekong basin, this includes the Vietnam Delta, wetlands, the near-shore ocean ecosystem, and floodplain ecosystems. Second, fine sediments (e.g., clay) adsorb and transport nutrients, particularly phosphorus, which play an important role in primary production and floodplain fertility (Baran and Guerin 2012). In a flood pulse-driven system such as the Mekong River, the exchange of sediment and nutrients between the river and floodplains is responsible for the production of the majority of riverine biomass (Junk et al. 1989; Sverdrup-Jensen 2002; Lamberts 2006). In this study, sediment passage serves as a surrogate measure for the potential for ecosystem productivity.

Aside from geomorphologic and nutrient transport issues, sediment accumulation is undesirable from an economic perspective because it reduces reservoir storage capacity, which shortens the reservoir's useful life and flow of future benefits (e.g., power production and flood control); and increases operations and maintenance costs (Morris and Fan 1998). If a dam fills with sediment and is left in place, the dam site, of which there are a limited number, may be permanently lost for use by future generations, and can become a safety hazard Annandale (2013). Conversely, removal of a silted dam can be extremely costly and can lead to the release of large quantities of potentially environmentally harmful accumulated sediments (Baran and Nasielski 2011).

Thus far, relatively little research has been conducted in the LMB regarding the potential impact of reservoir operations on the sediment balance. Previous studies found the potential for 51–96 % of suspended sediment to be trapped throughout the Mekong basin (Kummu et al. 2010; Kondolf et al. 2014), with as much as 80 % trapping of suspended sediments in 3S basins reservoirs (Wild and Loucks 2014b). This study evaluates measures that could be taken to reduce such significant sediment accumulation in reservoirs, including alternatives to the siting (location), design (size of reservoir, and availability of mid- and low-level outlets), and operations (e.g., sediment flushing operations) of dams. We identify sediment management practices that are feasible at different planned dam sites; evaluate whether these techniques can improve reservoir sediment outflows without damaging the environmental features the practices are attempting to preserve; and evaluate what losses in typical reservoir function, primarily hydropower production, may be necessary to achieve the improved sediment passage.

Decision makers in the LMB are facing an extremely difficult challenge in shaping the development paths of their respective countries, especially in the less developed nations of Lao PDR and Cambodia, where rapid economic development is internally viewed as imperative. Water is often the most abundant, valuable natural resource in LMB countries, which makes hydropower a particularly attractive energy option. This energy could nurture economic development and be exported for profit. At the same time, 47 %–80 % of the populace relies on fish and other

aquatic animals as a primary protein source (Hortle 2007) and 50 % rely on these animals for income (MRC 2010). The fish are directly dependent on the health of the riverine ecosystems that hydropower production could adversely impact. Each country's fate will be determined in part by the decisions taken with respect to these tradeoffs. Rather than arguing no dams should be built, the sediment management options discussed in this paper acknowledge that dams will be built, but suggest that more benign (with regard to sediment) alternatives to many of the currently proposed dams exist and should be considered.

This paper examines sediment management alternatives as a means of reducing conflicts, hopefully providing an acceptable outcome for all stakeholders in the basin. We are concerned about all the dams being constructed or planned in the basin, but for the purposes of this discussion we will focus on Lower Se San 2 (LSS2) Dam in the 3S basins and Sambor Dam on the mainstream Mekong River. Both are in Cambodia, but have the potential of impacting Vietnam as well.

At the LSS2 Dam site, full drawdown sediment flushing appears to be the best option for reducing sediment trapping (Annandale 2012a). The LSS2 Dam is important because it could reduce basin-wide fish biomass production by over 9 % (Ziv et al. 2012), which is the highest potential among tributary dams. Additionally, LSS2 could be constructed within the next 5 years. Thus, identification and evaluation of opportunities to increase sediment passage through the reservoir, while maintaining significant energy production at the site, is of current interest.

At Sambor Dam, both flushing and sediment bypassing could reduce sediment trapping. Sambor Dam is perhaps the most important proposed dam in the entire basin. Its proposed location at the bottom of the basin could result in sediment and nutrient reductions for two of the basin's most important features that rely on sediment: Tonle Sap Lake (in Cambodia) and the Vietnam Delta. Tonle Sap Lake is one of the most productive freshwater fisheries in the world. The Vietnam Delta produces significant quantities of rice and fish, and hence affects the lives of millions of people. Additionally, the potential for Sambor to trap significant quantities of sediment could discourage efforts to pass sediment through dams throughout the basin upstream. (The same is true of all the dams on the Se San and Sre Pok Rivers upstream of LSS2.) Finally, the proposed Sambor Dam would be the most downstream dam sited on the mainstream Mekong River, and as such would be positioned to severely disrupt fish passage, particularly for long-distance migratory species, thereby reducing LMB total fish biomass (Dugan 2008; Baran and Myschowoda 2009; Baran 2012). A natural sediment and fish bypass system, if successful, could greatly reduce the impact of Sambor Dam on the LMB fishery.

2.2 Sediment Management Options

Before discussing the sediment management alternatives for LSS2 and Sambor in more detail, it is useful to review the array of reservoir sediment management options available to better understand how sediment flushing (at LSS2 and

Sambor) and sediment bypassing (at Sambor) fit in among the range of available techniques. Annandale (2013) and Morris and Fan (1998) provide diagrams and pictures of these techniques.

A variety of options are available for managing sediment in reservoirs, and they generally fall into three categories: minimizing sediment inflow (e.g., catchment management), preventing inflowing sediment from settling by hydraulically routing sediment beyond the reservoir (sediment routing), and removing sediment after it settles (sediment removal) (Annandale 2013). Catchment management is not considered here because the goal of this study is to evaluate methods that could permit conveyance of the basin's naturally high sediment load. Sediment routing is advantageous in comparison to sediment removal in that regularly performed routing is more likely to produce reservoir sediment outflows that are consistent in timing and concentration with the natural sediment inflow regime.

Sediment routing is generally performed in one of two ways: sediment bypassing or sediment pass-through (e.g., sluicing). Both are typically performed during high flow conditions (e.g., during the monsoon season). Sediment bypassing, the option proposed for Sambor Dam, routes the sediment-laden water around the reservoir to prevent deposition in the reservoir. Sediment pass-through routes the water through the reservoir by maintaining a high sediment transport capacity. Both are implemented during high flow events when the majority of the annual sediment load is transported. Examples of bypassing include bypass tunnels (e.g., the Miwa Dam bypass system in Japan), river modification (e.g., Nagle Reservoir in South Africa), and off-channel reservoir storage (e.g., Fajardo Dam in Puerto Rico) (Annandale 2013).

Flushing can also be done in two ways: full drawdown flushing or partial drawdown flushing. Only full drawdown flushing is considered here, wherein water levels are reduced in the reservoir enough to permit free flow conditions through the low-level outlets. Flushing practices vary considerably among sites, but there exist some commonalities (Morris and Fan 1998). Flushing is typically performed during lower flow conditions, such as during the dry season or very beginning of the wet season, and for a short period of time (e.g., a week or less). From an operational standpoint, performing flushing at this time of year (1) reduces the difficulty and length of time required for drawdown because inflows are low, and (2) increases the likelihood of rapid reservoir refill (and therefore resumption of normal reservoir operations). Low reservoir water levels must be maintained during the flushing period to create high scouring velocities and retrogressive erosion. After flushing, the reservoir is refilled and normal operations are resumed. Drawdown flushing has been practiced at numerous reservoirs throughout the world (e.g., Cachi Dam in Costa Rica, Gebidem Dam in Switzerland, and Sefid-Rud Dam in Iran). Flushing is more likely than routing to adversely impact the environment, as releases typically result in a sudden increase in sediment concentration downstream. Associated impacts on fish species can be physical, chemical, and biological in nature, and are reviewed by Baran and Nasielski (2011). Concentration and duration of flushing flows have been shown to be important factors in the potential severity of flushing impacts (Newcombe and MacDonald 1991; Newcombe and Jensen 1996).

2.3 Simulating Flow and Sediment in the Mekong Basin

2.3.1 Modelling Approach

Since 1990, many hydrologic models have been used to simulate water flows in the Mekong basin (Johnston and Kummu 2012). Unfortunately, none possessed the features needed to predict in relative terms the spatial and temporal accumulation and depletion of sediment in river channels and in reservoirs under different reservoir operating and sediment management policies. Hence we developed a daily simulation model, called *SedSim*, to evaluate the performance of specific sediment management techniques (e.g., flushing, sluicing, density current venting, bypassing and dredging) in networks of reservoirs and channels (Wild and Loucks 2012). This information is used to identify the relative tradeoffs between hydro-power production, and flow and sediment regime alteration, associated with these sediment management techniques. It serves as a means of identifying the more promising sediment management alternatives that can be evaluated in more detail using more detailed and hence more data-intensive models.

In this study, 21 years of average daily reservoir inflows are generated from a calibrated Soil and Water Assessment Tool (SWAT) model (MRC 2011a). *SedSim* is used to simulate sediment production, transport and trapping, as well as reservoir operations and channel routing. The data required to conduct simulations with *SedSim* were generated by other researchers and institutions. Reliable Mekong basin sediment data useful for generating daily sediment loads are not widely available (Walling 2005, 2008; Wang et al. 2011), so estimates of annual sediment production were obtained from Kondolf et al. (2011, 2014) and converted into daily sediment loads using sediment-flow rating curves (Milliman and Meade 1983; Morehead et al. 2003). In setting parameter values we benefited from the work of Walling (2009) and Wang et al. (2011). Planned reservoir and dam characteristics and operating policies were obtained from MRC (2011a, 2012) and Piman et al. (2013). Data regarding potential alternative dam configurations were obtained from Annandale (2012a, b).

2.3.2 Sediment Management Alternatives

Sediment management measures will be very difficult to successfully implement at the currently proposed dam sites of LSS2 and Sambor (Fig. 2.1). Both reservoirs, as proposed, are too long and wide (being located in floodplains) for most sediment management practices to be feasible, and thus will trap large quantities of sediment. Alternative locations and design configurations for these dams could improve their sediment passage characteristics and make sediment management possible (Annandale 2012a, b). Specifically, relocating the dams to nearby but narrower sections of the river would permit sediment flushing, as flushing is most likely to be successful in a relatively narrow reservoir whose cross-sectional

dimensions approximate the dimensions of the incised channel formed during flushing. Additionally, reducing reservoir size (volume and length) not only reduces a reservoir's sediment trapping efficiency, but also increases the likelihood that sediment flushing will be feasible, given that the reservoir must be emptied of water before flushing can proceed, and must be refilled with water before normal operations can resume. Finally, building low-level outlets into the dam would enable flushing, and indeed is a requirement for flushing to be feasible at a dam site.

Figure 2.2 shows the alternative of replacing the currently proposed LSS2 dam with two smaller dams. The Lower Se San 2-II (LSS2-II) Dam on the Se San River, and Lower Sre Pok 2 (LSP2) Dam on the Sre Pok River could be frequently flushed. Figure 2.3 shows the alternative of replacing the currently proposed Sambor Dam with a smaller, narrower reservoir that could be frequently flushed and that would be fitted with a natural sediment bypass channel (using existing braided river channels on the East section of the main river channel). The sediment bypass would direct high sediment loads around the reservoir during the monsoon season and also serve as a natural fish passage system. The currently proposed Sambor Dam would prevent passage of numerous migratory fish species and submerge important fish breeding areas, resulting in potentially severe adverse impacts on the Mekong fishery (Campbell et al. 2009). While Sambor Dam as currently planned could include fish passage structures (e.g., ladders), such structures may achieve limited success compared to a natural channel, because these structures must be tailored to meet the needs of specific species, of which there are many in the lower portion of the LMB. Bypassing is assumed to occur during monsoonal flows, or those flows in excess of twice the mean annual inflow ($27,600 \text{ m}^3/\text{s}$). During this time, the portion of flow entering the upstream end of the reservoir site in excess of $27,600 \text{ m}^3/\text{s}$ is bypassed along with an identical portion of the suspended sediment load.

Several modeling assumptions regarding flushing and bypassing should be mentioned. Flushing at each site is assumed to proceed for 4 days, beginning around the time of year when the reservoir inflow first exceeds the mean daily unregulated inflow. This unregulated mean daily inflow rate is assumed to be the target flushing discharge rate. Flushing a reservoir with this flow rate produces a reasonable long-term sustainable storage capacity (greater than 35 %), but is not too large for reasonably-sized low-level outlets to empty the reservoir and discharge flow during flushing without ponding above the outlets. For flushing to be considered successful in a given day, the water surface elevation is required to be maintained to near the original river bed elevation (this is the optimal location of the low-level outlets), and flow is required to equal or exceed 95 % of the mean unregulated daily inflow. Drawdown is initiated when the inflow reaches the average unregulated daily value. This approach avoids drawing down a reservoir before inflows are high enough to satisfy flushing discharge requirements, which could result in substantial and uncertain hydropower losses. The quantity of sediment removed during a particular flushing event is determined in each time step using the Long Term Capacity Ratio (LTCR) (Atkinson 1996), which estimates the fraction of a reservoir's initial storage capacity that can be maintained in perpetuity by implementing flushing.

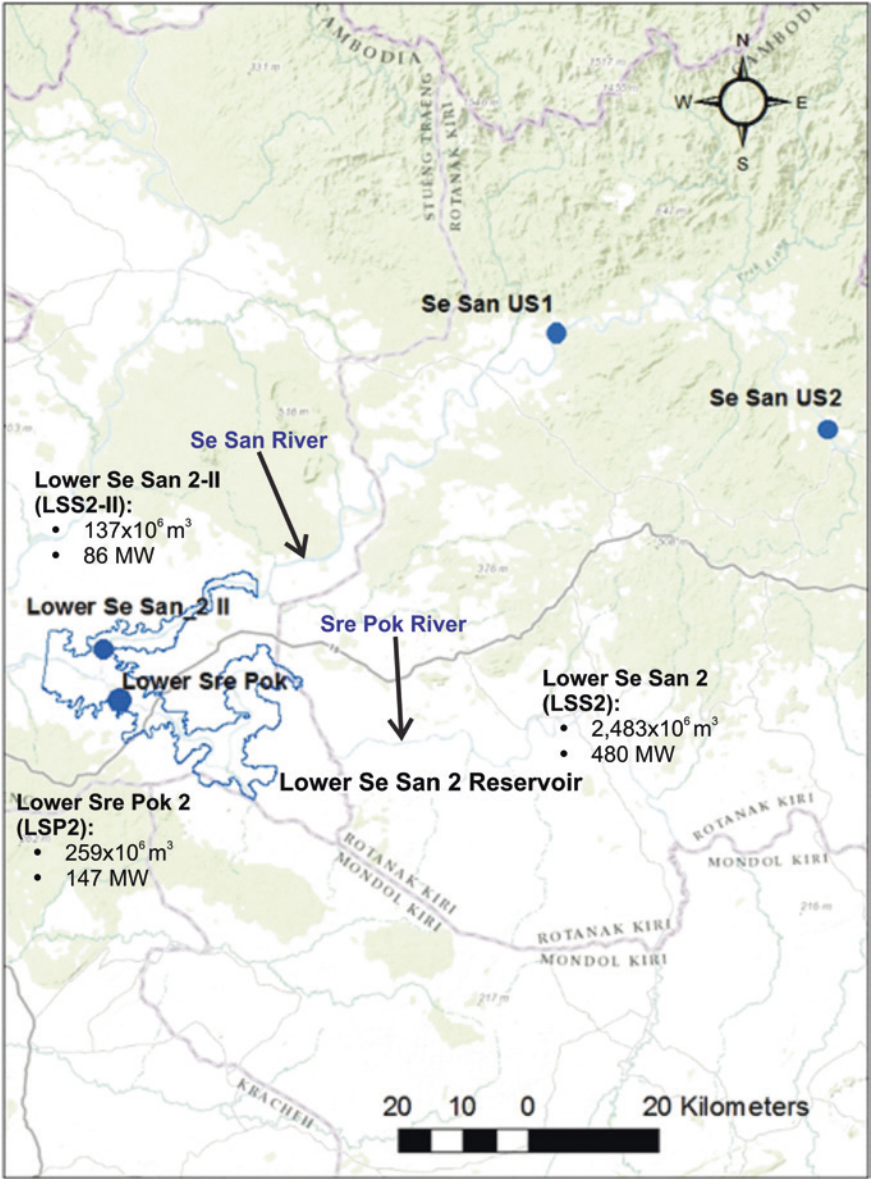


Fig. 2.2 Diagram of the currently proposed Lower Se San 2 (LSS2) Dam, which is proposed to be constructed at the confluence of the Se San and Sre Pok Rivers, and two smaller alternative dams that this study proposes should be considered: Lower Se San 2-II (LSS2-II) and Lower Sre Pok 2 (LSP2). LSS2-II and LSP2, marked by *blue circles*, are proposed within the bounds of LSS2 reservoir as currently planned. Reservoirs Se San US1 and Se San US2, also marked by *blue circles*, are two additional alternative reservoirs that could be sited upstream on the Se San River to make up for the losses in energy generation that would be associated with not building LSS2 as planned. Proposed reservoir storage capacity (m^3) and power plant installed capacity (Megawatts MW) are provided for LSS2, LSS2-II and LSP2. Figure adapted from Annandale (2012a)

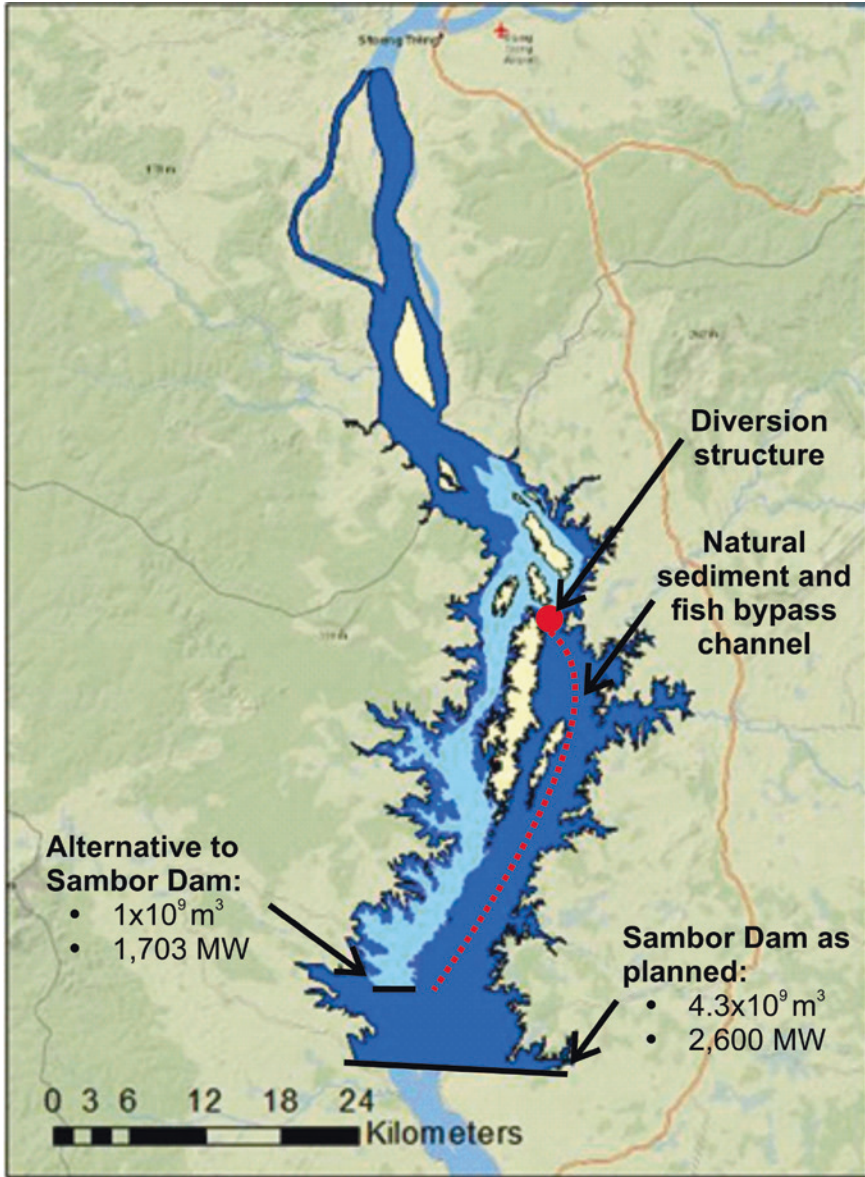


Fig. 2.3 Diagram of the currently proposed Sambor Dam and smaller alternative dam on the Mekong River. The alternative reservoir, appearing in *lighter blue*, would be sited within the bounds of the currently planned reservoir, which appears in a *darker blue*. The *red dashed line* indicates the location of the natural sediment and fish bypassing channels on the East of the alternative site, and the *red dot* indicates the location of a diversion structure that would direct flow and sediment into the diversion channel. Proposed reservoir storage capacity (m^3) and power plant installed capacity (Megawatts *MW*) are provided for the proposed and alternative Sambor Dam. Figure adapted from Annandale (2012b)

To define the range of possible tradeoffs between sediment and hydropower for the possible alternatives, five LSS2 scenarios were considered and six Sambor scenarios were considered. Aside from the unregulated basin scenario, simulations of LSS2 assume the future condition in which the Sre Pok River and Se San River are developed to the maximum extent that is currently planned (19 dams upstream of the LSS2 site, as seen in Fig. 2.1). While 14.3 Mt/yr of sediment is generated upstream of LSS2, only 7 Mt/yr reaches LSS2 in this scenario due to upstream trapping. Simulations of Sambor Dam and alternatives assume the basin upstream of Sambor is developed to the extent of the MRC definite future development scenario (MRC 2011b), or 47 existing and planned dams. While 156 Mt/yr of sediment is generated upstream of Sambor, only 80 Mt/yr reaches Sambor due to upstream trapping (Kondolf et al. 2014).

The five LSS2 scenarios were as follows:

1. Unregulated 3S basins (no reservoirs).
2. Currently proposed Lower Se San 2 (LSS2).
3. Alternatives Lower Se San 2-II (LSS2-II) and Lower Sre Pok 2 (LSP2). No flushing.
4. Alternatives LSS2-II and LSP2. Annual flushing.
5. Alternatives LSS2-II and LSP2. Biannual flushing (every 2 years), both reservoirs being flushed during the same year.

The six scenarios considered for the Sambor alternatives are listed below. Compared to LSS2, flushing frequency is not varied for the Sambor alternative because the results of varying flushing frequency at Sambor are similar to the results shown for LSS2-II and LSP2.

1. Unregulated Mekong Basin (no reservoirs constructed upstream of Sambor).
2. Currently proposed Sambor Dam without sediment management.
3. Alternative Sambor Dam without sediment management.
4. Alternative Sambor Dam with annual flushing.
5. Alternative Sambor Dam with a sediment bypass channel.
6. Alternative Sambor Dam with a sediment bypass channel and annual flushing.

2.4 Results and Discussion

Presenting a comprehensive assessment of the tradeoffs between sediment passage and hydropower production is difficult because the tradeoffs occur over different time scales. For example, the results here will focus on tradeoffs between annual and mean monthly sediment loads and energy production, whereas in reality many other time scales and measures are just as important for sediment, energy and indirectly, biodiversity.

Beginning with LSS2 at the annual time scale, Fig. 2.4 demonstrates the potential impact of LSS2 Dam as currently planned, as well as the potential

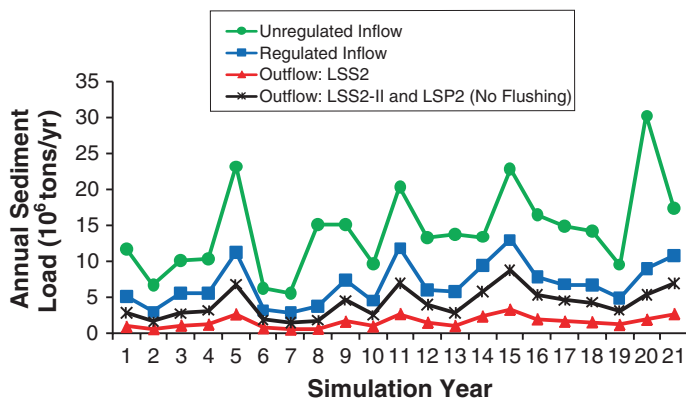


Fig. 2.4 Simulated annual sediment load (10^6 t) inflows and outflows for 21 years for the currently proposed Lower Se San 2 (LSS2) Dam site, and for two alternative dams, Lower Se San 2-II (LSS2-II) and Lower Sre Pok 2 (LSP2), excluding flushing practices. The outflow time series corresponding to LSS2-II and LSP2 are combined into one time series. (Wild and Loucks 2013, with permission from ASCE)

improvement in sediment passage that could be achieved by implementing sediment management practices. Aside from the regulated and unregulated sediment inflow to the LSS2 site, Fig. 2.4 includes cases in which (1) LSS2 is built as planned, and (2) LSS2 is divided into two smaller reservoirs (LSS2-II and LSP2), without any form of sediment management implemented. The purpose of Fig. 2.4 is to highlight what potential impact any form of sediment management (e.g., flushing) could have if implemented.

Figure 2.4 illustrates several important points. First, the unregulated sediment load at the LSS2 site will be significantly reduced due to trapping by the 19 reservoirs expected to be constructed upstream. The simulated effect of the upstream reservoirs is to reduce the mean annual sediment inflow to the site by 51 % (from 14.3 Mt/yr to about 7 Mt/yr). The proposed LSS2 reservoir would then trap 77 % of the remaining load on average, reducing the annual discharged load from 7 to 1.6 Mt/yr. While the significant difference between unregulated inflow and sediment outflow for each management scenario is largely driven by the trapping of sediment in the 19 reservoirs upstream, in the absence of extensive upstream reservoir development, LSS2 would still have the potential alone to trap much of the sediment expected to be trapped in reservoirs upstream, given its high average trapping efficiency of 77 %.

To increase the discharged load from 1.6 Mt/yr to a value that more closely resembles the inflow, LSS2 could be replaced with two smaller reservoirs: LSS2-II and LSP2. The combined effect of the smaller two dams would be to reduce the average trapping efficiency from 77 % (LSS2) to 40 %, which would reduce the trapped load from 7 to 4.1 Mt/yr. This is more than a 150 % increase in annual sediment load discharge compared to LSS2. This improvement is attributed only

to reservoir resizing and relocation, which naturally reduces sediment trapping without implementing any sediment management techniques. Appropriate sediment management practices have the potential to produce additional increases in sediment discharge (i.e., to produce an annual sediment load time series that lies somewhere between the middle two time series in Fig. 2.4).

If LSS2 is constructed as planned, approximately 18 % of its 2.5 billion m³ storage capacity would be lost to sedimentation after 100 years, assuming an average bulk density of 1,200 kg/m³ for deposited sediment (Xue et al. 2010). Thus, the potential ecological benefit of increasing sediment discharge through the LSS2 site is more likely to serve as motivation for conducting sediment management than a desire to mitigate impacts on long-term energy production. However, if the Sre Pok and Se San basins are ultimately developed to a lesser extent than expected (i.e., if fewer than 19 dams upstream of LSS2 are ultimately constructed), sedimentation at LSS2 could increase significantly, thereby increasing the likelihood of long-term energy production impacts if sediment is not managed.

Having described the potential for sediment management to improve sediment flows downstream of the LSS2 site, Fig. 2.5 demonstrates the impact that specific management techniques could have on the sediment regime downstream. This figure focuses on mean monthly sediment loads, instead of annual sediment loads, because the monthly time scale reveals that sediment management methods such as flushing can alter the seasonal distribution of sediment loads. This in turn may have important ecological consequences.

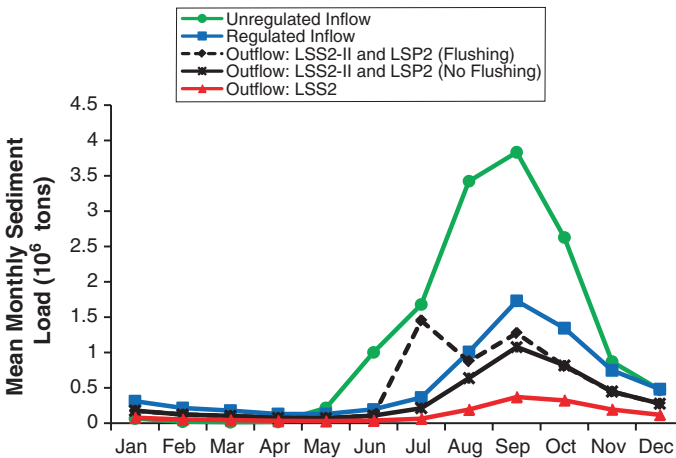


Fig. 2.5 Mean monthly sediment load (10⁶ t) inflows and outflows at Lower Se San 2 (LSS2) Dam site. All outflow time series result from the regulated inflow time series. This demonstrates the simulated potential for alternative reservoirs Lower Se San 2-II (LSS2-II) and Lower Sre Pok 2 (LSP2), combined with flushing, to improve sediment passage compared to current plans for LSS2. The outflow time series corresponding to LSS2-II and LSP2 are combined into one time series for comparison to LSS2. Annual and biannual flushing produce similar mean monthly sediment outflows, so they are represented by the same time series

Figure 2.5 demonstrates that the currently proposed LSS2 Dam will significantly reduce the regulated sediment load inflow at the LSS2 site, despite the significant trapping that will already take place in upstream reservoirs. (The uppermost time series in Fig. 2.5, which represents the unregulated inflow into the site, does not serve as sediment inflow in the simulations used to create the sediment outflows in Fig. 2.5. Rather, the regulated time series represents the inflow pattern used to produce the simulation results.) The combined mean monthly sediment outflow from the smaller two reservoirs (LSS2-II and LSP2), without any sediment management implemented, is a clear seasonal improvement to the proposed LSS2. Figure 2.5 demonstrates that annual and biannual flushing could further increase sediment passage at the alternative sites.

Flushing significantly increases sediment load discharge compared to the currently proposed LSS2 and to the alternatives LSS2-II and LSP2 without any sediment management implemented. However, the extent to which this increased sediment discharge represents an improvement depends on the time scale of interest. In general, annual sediment loads, which are not shown here, are significantly increased as a result of the alternative configurations and sediment management practices. This represents a major improvement to the integrity of the geomorphologic system. For example, annually flushing LSS2-II and LSP2 results in a reduction in mean annual sediment load of only 16 % compared to the regulated inflow (i.e., 5.8 Mt/yr discharge is produced from 7 Mt/yr inflow), meaning that only 16 % of the inflowing sediment load is trapped in the two alternative reservoirs. The case in which flushing is performed biannually results in similar average trapping (18 %). Importantly, while less frequent flushing has the potential to produce similar long-term mean annual sediment loads to more frequent flushing, the variance in loading associated with less frequent flushing is far less environmentally friendly, producing larger sediment loads when flushing events occur, and at intervals less frequent than the natural annual intervals to which the aquatic ecosystem has likely adapted.

Transitioning now to the monthly time scale, flushing alters the timing and distribution of mean monthly sediment loads. This is primarily because sediment flushing is performed for a short duration of time during periods of relatively lower flows. Thus, all flushing scenarios result in a mean peak sediment load occurring on average 2 months before the natural mean peak. On average, these values are 300–400 % higher than the mean regulated sediment inflows. However, the flushing spike in mean sediment discharge at the end of the wet season is still enclosed within the bounds of the unregulated mean monthly sediment load inflows. This is an important result because one of the goals of sediment management in this region should be to maintain some consistency with the natural seasonal sediment load regime.

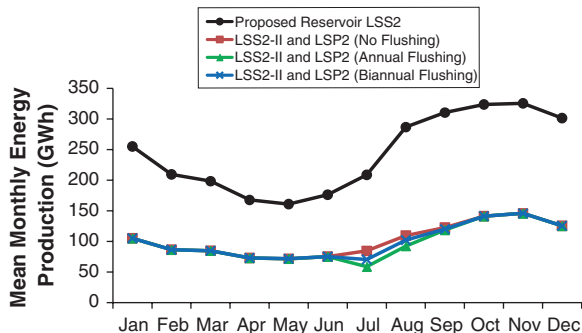
The visible spike in sediment load released from LSS2-II and LSP2 (Fig. 2.5) does not exceed the mean monthly unregulated sediment load inflow, but could still be a significant ecological problem if the loads released produce high enough concentrations for a long enough period of time (Newcombe and MacDonald 1991; Newcombe and Jensen 1996). Additionally, if the downstream channel does

not have sufficient capacity to transport the flushed sediment loads downstream of the reservoir, large quantities of sediment may settle in the channel, which can kill larvae and juveniles, and destroy spawning grounds (Hess and Newcomb 1982; Buermann et al. 1995; Brandt and Swenning 1999). These issues require further investigation in the Mekong Basin, as specific impacts will depend on the sensitivity of particular plant and animal species to spikes in concentration and changes in riverine habitats. Previous studies have not assessed such possible flushing impacts on the large diversity of fish species living in the Mekong basin. Ultimately, the environmental impact of flushing will depend on how flushing is implemented in practice. For example, after flushing is completed, clear water should be released from mid-level outlets to wash away flushed sediment that may accumulate in the downstream channel (Fruchart 2008).

It is also useful to assess the wet season implications of conducting sediment management, as the annual flood pulse drives the Mekong basin's productivity through the transport of most of the annual flow, sediment and nutrients. Referring to the results of implementing flushing displayed in Fig. 2.5, after the two mean monthly sediment peaks in July and August, a second, lower peak then occurs in September. This peak would have occurred in the absence of sediment management (note the similarity in September to the case in which no sediment management is attempted). The 19 reservoirs to be constructed upstream of the LSS2 site would reduce the mean sediment load in the three wettest months (August, September and October) by 58 % (9.9–4.2 Mt). The currently proposed LSS2 would further reduce the sediment load in the wettest 3 months by about 79 % (from 4.2 Mt to 0.9 Mt). LSS2-II and LSP2 without flushing reduce wet season sediment outflows by only 40 % (4.2–2.5 Mt). Reduction in the mean sediment inflow (4.2 Mt) in the 3 month peak wet period is only about 28 % when flushing is conducted.

Sediment management measures clearly have the potential to increase sediment discharge downstream of dams in the Mekong basin. However, the sediment management measures proposed here have significant implications for hydropower production. Conducting sediment management has two primary impacts on the sediment regime, and two primary impacts on energy production. Reducing the volume of water storage at the LSS2 site by constructing the two smaller reservoirs, as well as flushing the two smaller reservoirs, creates two sediment impacts: less sediment is trapped, and sediment that is trapped can be removed via flushing. With regard to hydropower, reducing reservoir size, and conducting flushing at those smaller reservoirs, have two primary impacts: smaller reservoirs produce less energy due to reduced operating head and installed capacity, and flushing reduces energy production as generators are taken offline when the reservoir is emptied to conduct flushing. Figure 2.6 highlights these two hydropower impacts by plotting monthly mean energy production for the same scenarios for which the sediment implications are displayed in Fig. 2.5. Due to their reduced combined installed capacity (233 MW), LSS2-II and LSP2 are not capable of combining to entirely replace the energy production of the proposed LSS2 (480 MW). The reduced combined generating capacity is responsible for the majority of the 58 %

Fig. 2.6 Simulated mean monthly hydropower energy production in Gigawatt hours (GWh) associated with the currently proposed Lower Se San 2 (LSS2) Dam and two alternative dams, Lower Se San 2-II (LSS2-II) and Lower Sre Pok 2 (LSP2), with flushing implemented (Wild and Loucks 2013, with permission from ASCE)



reduction in mean annual energy (2,925–1,225 GWh) that would result from building LSS2-II and LSP2 instead of LSS2.

There is also a loss in power production associated with flushing. Annually flushing LSS2-II and LSP2 reduces mean annual energy production (compared to not managing sediment in these reservoirs) by only about 4 %, whereas biannual flushing results in mean annual reductions of only 2 %. Flushing avoids significant losses in annual power generation because the process can be conducted relatively quickly. Thus, flushing alone does not critically impact average annual or monthly power production. This is a significant result because one or two more dams could be constructed upstream of LSS2-II and LSP2 (e.g., Se San US1 and Se San US 2 in Fig. 2.2) to continue to replace the installed energy generating capacity that is lost by not constructing LSS2 as planned. While potentially more costly to construct several dams instead of one, such a system of dams could replace much of the energy generating capacity of LSS2, with potentially relatively insignificant energy losses from the flushing process and increased sediment outflows. The latter statement, however, ignores two critical issues that will be addressed next.

First, while flushing is taking place, no power is being produced because generators are taken offline. This will impact the reliability of power production. Performing flushing at LSS2-II and LSP2, compared to when no sediment management is performed, results in a loss in reliability for every level of power production, especially firm power. Reliability impacts will be assessed in the future as more information becomes available about the role these reservoirs play in the energy grid. Second, Fig. 2.6 focuses on short-term energy production, whereas the positive impacts of sediment management become more visible in the long term, as sediment accumulation progressively impacts operations at dams where sediment (and therefore the reservoir's storage capacity) is not sustainably managed.

The sediment management alternatives for Sambor Dam offer a similar set of tradeoffs between sediment passage and hydropower production. That is, the alternative Sambor Dam is smaller, which improves sediment passage and makes flushing feasible. However, the smaller installed capacity and flushing process reduce energy production. The reduced reservoir storage means the alternative Sambor

reservoir has an average trapping efficiency of 32 % compared to the currently proposed Sambor (50 %). This reduction translates into a large increase in sediment load passage, given the location of Sambor at the lower end of the river basin. In an unregulated system (about 160 Mt/yr inflow), this 18 % reduction in trapping efficiency would result in a sediment discharge increase of about 29 Mt/yr, whereas in the system regulated to the extent of the MRC definite future scenario (80 Mt/yr inflow), the increase is about 14.5 Mt/yr. As with the LSS2 alternative discussed previously, the Sambor alternative has the additional advantage that sediment flushing is feasible. The associated increases in sediment passage depend on the frequency with which flushing is conducted. Additionally, the different location of the Sambor alternative compared to the currently proposed location creates the possibility of a natural sediment bypass. The potential impacts of both flushing and the sediment bypass are demonstrated in Fig. 2.7. This figure shows the mean monthly sediment loads flowing into and discharged from the proposed and alternative Sambor Dam configurations.

If Sambor Dam is constructed as planned, much of its storage capacity could be lost due to sedimentation during the operating lifetime of the dam. The approximately 50 % trapping efficiency of the planned dam suggests an annual sedimentation of 40 Mt, which is more than 33 million m³ of sediment per year assuming an average bulk density of 1,200 kg/m³ for deposited sediment (Xue et al. 2010). In 50 years, almost 40 % of the initial storage capacity could be lost to sedimentation. The storage capacity lost after 100 years will depend on how trapping efficiency declines at the site over time due to reduced storage capacity, but certainly more than 50 % loss in initial storage capacity appears possible. Such a significant loss in storage capacity could potentially impact energy production and other

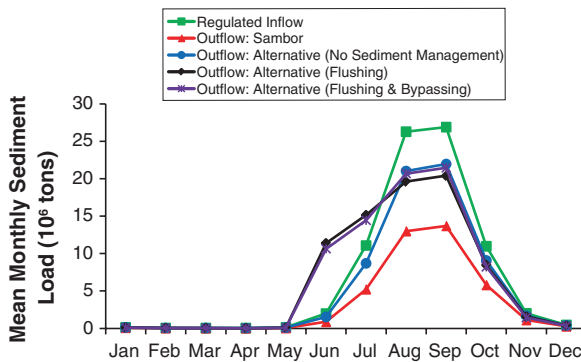


Fig. 2.7 Mean monthly sediment load (10^6 t) inflows and outflows at Sambor Dam site. All outflow time series result from the regulated inflow time series. This demonstrates the simulated potential for the Sambor alternative reservoir proposed here, combined with flushing and sediment bypassing, to improve sediment passage compared to current plans. The case in which bypassing is conducted without flushing is not shown, as sediment outflows were not significantly different from the outflows corresponding to no sediment management

dam functions, though the specific impacts will depend on the reservoir's operating policy, which is not known at this time. (Note that these assessments assume a consistent 80 Mt/yr mean annual influx of sediment. Declining sediment inflows due to construction of reservoirs throughout the LMB upstream could reduce sedimentation impacts at Sambor.) Clearly, constructing a smaller reservoir with flushing and bypassing capabilities may be ecologically and operationally beneficial.

Simulation results indicate that implementing annual or biannual flushing at the site would increase sediment discharge by about 19 % compared to the case in which no sediment management is implemented at the same alternative dam (77.3 Mt/yr instead of 64.7 Mt/yr). As was the case with LSS2 flushing alternatives, the increased sediment discharge during flushing is produced on average early in the wet season (or late in the dry season). Once again this may have important ecological implications.

Surprisingly, conducting sediment bypassing does not produce any increase in mean monthly sediment discharge compared to the case in which no sediment management is implemented at the same alternative dam. This does not mean that the sediment bypass does not work. In fact, the sediment bypass effectively diverts about 28 % of the inflowing sediment around the reservoir, resulting in reduced sediment inflows to the reservoir. However, the sediment bypass diverts large quantities of water around the reservoir during the flood season. This in turn increases the residence time of water and sediment in the reservoir during this period, thereby increasing the trapping efficiency from what it would otherwise be. Thus, the benefit of diverting 21.8 Mt/yr of sediment around the reservoir is offset by the increased trapping efficiency for the 72 % of sediment that is not bypassed.

The relative improvement in sediment discharge that is possible with the sediment bypass depends on the trapping efficiency of the reservoir. For example, results from other simulations (not discussed here) demonstrate that if the trapping efficiency of the reservoir without sediment management is 45 % instead of 32 %, the bypass would instead produce an increase in sediment load discharge of 22 % compared to the reservoir without sediment management implemented. When both flushing and bypassing are implemented at the same time, there is only a very slight improvement in sediment discharge (0.25 Mt/yr) compared to the case in which the reservoir is only flushed (and no bypass exists).

To further explore this result regarding the bypass, future work should include sensitivity analysis that explicitly accounts for the impact of the following factors on the relative effectiveness of the sediment bypass: (1) the fraction of the suspended sediment load that is distributed into the bypassed flow versus into the reservoir; and (2) trapping efficiency, which affects the incremental sediment benefit bypassing offers when both flushing and bypassing are conducted. Regarding the former factor, if the bypass diversion structure is constructed such that much of the suspended load in the water column can be distributed into the bypassed flow, the bypass could be much more effective than is reported here. Regardless of its potential influence on the sediment balance at Sambor, the sediment bypass option is important to consider because it offers a natural fish passage system; would inundate less surface area; and would likely be much more effective than flushing at preventing accumulation of bedload in the reservoir.

Just as with LSS2, the Sambor Dam alternative produces two primary impacts to power production: a loss in energy production due to reduced installed capacity, and a loss in energy production associated with the requirement that generators be taken offline during flushing. The results are not shown here because they are similar in appearance to the LSS2 energy impacts shown in Fig. 2.6. The reduced size of the Sambor Dam alternative results in about a 35 % loss in annual energy production, mostly due to reduced installed capacity. Conversely, annual flushing further reduces annual energy production by only about 2 %. Regarding the bypass, aside from the potential sediment and fish passage benefits, an additional advantage is that hydropower production can proceed normally during the bypassing process every year. This is because the installed turbine flow capacity at the currently proposed dam (and the Sambor alternative discussed here) is only twice the mean annual inflow rate (27,600 m³/s). During the monsoon season the sediment bypass only diverts the portion of reservoir inflow that exceeds twice the mean annual inflow rate, so water that is diverted during bypassing would not have produced hydropower anyway.

2.5 Uncertainty Issues

The results presented in this paper rely on a variety of assumptions regarding the values of uncertain model parameters, for both the proposed dams (LSS2 and Sambor) and the multitude of dams that are proposed to be constructed upstream of them. The largest sources of uncertainty in the results presented here are related to inaccurate estimates of (1) sediment production and (2) sediment trapping efficiency. Regarding sediment production, the quantity of sediment produced in the Mekong basin is currently uncertain. Particularly in the 3S basins and on the mainstream Mekong River near Sambor, more frequent and spatially distributed sediment sampling, including grain size distributions and bedload estimates, are necessary to prepare more certain estimates of sediment production. Grain size distribution data will also enable improved estimates of reservoir sediment trapping efficiency, as will sedimentation records from existing reservoir sites. Both can be used to calibrate modeling assumptions regarding trapping efficiency.

Ultimately, both the quantity of sediment produced and the trapping efficiency of that sediment load (not just at LSS2 and Sambor, but at upstream reservoirs) will determine the quantity of sediment that is trapped. This controls (1) the potential impact that neglecting to conduct sediment management has on storage capacity and long-term energy production, and (2) the magnitude of sediment that could be released when flushing is conducted. Additional data, such as reservoir operating policies and improved total storage estimates, will enable improved predictions of sediment trapping and an improved understanding of the roles particular reservoirs (e.g., LSS2 and Sambor) play in the energy grids they serve. In the absence of the data outlined above, future work should include sensitivity analysis that explicitly varies assumptions regarding sediment production, sediment

trapping efficiency (based on sediment size), and reservoir operating policies to capture the range of potential tradeoffs between sediment regime restoration and energy production.

2.6 Conclusions

Water resources infrastructure in the Mekong River Basin is growing at a rapid pace. This infrastructure will impact the natural flow and sediment regimes that in turn can impact the natural ecosystem of this biodiverse river and its basin. Sediment management opportunities should be considered for two reasons. First, it is important that lessons about successful implementation of sediment management practices be learned soon, so they can be applied throughout the basin to achieve sediment goals for the entire system. Second, retrofitting existing dams with sediment management facilities (e.g., low- and mid-level outlets) can be costly, so it is critical that dams be designed and constructed with sediment management goals in mind.

Our simulations suggest that as currently proposed, LSS2 Dam and Sambor Dam would trap large quantities of sediment, starving downstream ecosystems of this resource that transports nutrients and maintains the geomorphic makeup of the system, among other functions. Results of simulations also suggest that sediment management practices have the potential to reduce these adverse impacts. Reservoir re-location and resizing, along with frequent implementation of sediment flushing, could significantly increase sediment discharge compared to the current plans for LSS2 and Sambor. An additional opportunity at Sambor is a sediment bypass, the potential effectiveness of which appears promising but must be further evaluated. In addition to improved sediment passage (particularly for bed-load), the Sambor alternative provides a natural fish passage channel. This could mitigate the potentially severe consequences (for the Mekong fishery) of building a dam on the Mekong River that would block major fish migration routes in the vicinity of critical ecosystems (Tonle Sap Lake and the Vietnam Delta).

While the management techniques evaluated here enable increased sediment passage, this benefit comes at a cost: diminished short-term energy production. Energy production is reduced for reservoirs at which sediment management is practiced, due to (1) the reduced reservoir size required to conduct sediment management, and (2) the flushing process itself that requires generators be taken offline. The majority of hydropower energy is lost because the smaller alternative reservoirs have smaller installed plant capacities, rather than due to the implementation of the sediment management practices (e.g., flushing and bypassing). This creates the possibility that numerous smaller dams could be constructed to replace the energy lost from one larger dam, particularly in the case of LSS2. The cost and long-term energy implications of this approach, as well as the potential increased difficulty of managing sediment in multiple dams, should be explored in future work. These lessons about tradeoffs are not limited to LSS2 and Sambor; rather,

the findings discussed here have important implications for dams throughout the Mekong Basin, given the similarity in the monsoon-driven inflow and sediment conditions for various planned dams. Of course, the cost of sediment management with regard to hydropower losses will vary among sites, depending upon the objectives of different reservoirs, including the roles they serve in the energy grid.

Several issues highlighted in this paper should be investigated in future work. To begin, sensitivity analysis is required to better understand the effect of a variety of modeling assumptions on the results shown here. The effectiveness of different sediment management approaches, such as sediment bypassing, change depending upon various assumptions. The relative importance of these assumptions should be identified so data collection efforts can be prioritized. Next, the timing and magnitude of sediment released during flushing in the simulations described here are potentially inconsistent with the system's natural sediment regime, and could thus be harmful to the basin's ecosystems. Discussion in this paper has revolved around mean monthly and annual sediment loading released during flushing, whereas maximum daily sediment concentrations during flushing, and the duration of those concentrations, may be more important metrics for assessing potential impacts to the health of aquatic species and their habitats. These potential effects can be quantified with more detailed modeling and observation to assess the true potential of the techniques discussed here. Finally, assessment of the potential benefits of sediment management must account for the long-term benefits that are possible by maintaining a sustainable storage capacity. This study focused on short-term losses in hydropower production associated with sediment management, whereas the true benefit of flushing is more visible in the long term, when sedimentation will result in diminished functionality at reservoirs where sediment is not managed.

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