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Assessment of Suspended Sediment Load Variability in the Tonle Sap and Lower Mekong Rivers, Cambodia

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Abstract: The Mekong River in Southeast Asia, one of the world's great rivers, has been facing disruption of its sediment balance and resultant impacts on nutrient fluxes, aquatic ecology, floodplains and the delta. Using monitoring data from 1993-2018, we estimated the temporal variability of sediment loads in Tonle Sap and Lower Mekong Rivers in Cambodia, assessing the sediment linkage between the Tonle Sap Lake and the Mekong mainstem, which are connected by a seasonally reversing flow through the Tonle Sap River. We estimated the annual sediment in the Mekong mainstem of 72 ± 38 Mt/year at Kratie (upstream) and 78 ± 22 Mt/year at Chroy Changvar from 1993-2018 (just upstream of the Tonle Sap confluence). Our sediment load estimation of the Mekong River is consistent with other recent estimates of sediment load on the Lower Mekong. However, the result is lower than reported in some older studies (prior to the 2000s), which is consistent with sediment trapping by dams on Upper Mekong mainstem and major tributaries. Our analysis indicates that Tonle Sap Lake provided 0.65 ± 0.6 Mt/year of sediment annually to the Lower Mekong River from 1995 to 2000. However, since 2001, Tonle Sap Lake has become a sink for sediment, accumulating an average of 1.35 ± 0.7 Mt annually. Net storage of sediment in Tonle Sap Lake reduces the annual sediment transport to the delta, further compounding the effects of reduced sediment delivery to the delta resulting from upstream dam development and instream sand mining.

Keywords: Temporal variability, Sediment load; Mekong River; Tonle Sap Lake

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1. Introduction

In many river basins, changes in sediment supply have affected the geomorphology of river channels, floodplains, and deltas (Peng et al., 2010). Sediment transport has important influences on river morphology, water quality and persistence of geomorphic features such as deltas (Walling, 2009). In recent decades, river processes have been greatly influenced by anthropogenic activities such as hydropower dam development, which alters downstream river discharge and sediment load (Vörösmarty et al., 2003). Recent studies have shown substantial changes in water and sediment fluxes for rivers globally from prior decades (Li et al., 2020). The largest rivers of the North and East Asia in Russia and China, such as Amur, Yellow, Yangtze, Pearl, evinced sediment load changes due to human impacts (Chalov et al., 2018). Rivers with high relief and erodible lithologies like the Ganges, Danube and Amazon Rivers are likely to respond to higher than average precipitation with increased sediment yields (Cohen et al., 2014). An increasing trend is also visible in long-term records of water and sediment fluxes of the Blue Nile in Africa from 1980-2010 (Li et al., 2020). However, at global scale, the mean annual water and sediment fluxes to seas from the world's large rivers have decreased (Li et al., 2020; Walling et al., 2003; Walling, 2006). Within the same context, the estimated suspended sediment to the Arctic Ocean delivered from all Arctic rivers has declined (including Yenisei River) (Bobrovitskaya et al., 2003; Fabre et al., 2019) Suspended sediment discharge in the Mississippi River declined by at least 50% due to impoundments and other engineering alterations since the early 1950s (Meade and Moody, 2010). Declines in water discharge and suspended sediment flux of the Para Paraná River, one of the majors in South America, has been observed (Stevaux et al., 2009). The sediment flux of all the major river of Mainland China have declined below their long-term averages (Cheng et al., 2008), including about a 60-80% reduction from Qiantang and Yangtze the Pearl River Basin (Liu et al., 2007).

From its headwaters on the Tibet-Qinghai plateau in Asia and sharing the same water source Yangtze and Yellow River, the Mekong River flows 4,800 km with the average annual discharge of 470 km^3 . The river's uppermost 2,000 km ($195,000 \text{ km}^2$ basin area), flows through China (including small part in Myanmar) and is known as the Lancang. The total area of the lower Mekong Basin is approximately $600,000 \text{ km}^2$ including Thailand, Laos, Cambodia, and Vietnam. This important basin is facing extensive landuse/cover disturbance, water diversion and reservoir

construction, and mining of sediment from the river bed for construction aggregate (Lu and Siew, 2005).

Delivery of water and nutrients underpins a vibrant fishery and highly productive agriculture supporting over 60 M people, notably the highly productive Tonle Sap Lake, floodplains of Cambodia, and the Delta of Vietnam (Arias et al., 2014; Kummu et al., 2008). Changes in the Lancang-Mekong River's sediment load have attracted wide research interest because such changes can affect river channel form, nutrient fluxes, river ecology, and the sustainability of the delta. Hydropower development is altering sediment loads in the Mekong, first from dams in upper basin (Kummu and Varis, 2007). Analysis of sediment flux from Upper Mekong at Gaju to Khong Chiam at Lower Mekong at seven stations documented by Liu et al. (2013), at five stations in the Lower Mekong (from Chiang Saen to Khong Chiam located in Laos) from 1985-2000 by Wang et al. (2011), and nutrient loads for these stations from 1985–2011 by Li and Bush (2015) all show decreases. However, these studies covered the river only down to Pakse in Laos. Sediment loads in the lowermost reach of the Mekong, through Cambodia and into the delta, including 3S river system (Sekong, Sesan, and Srepok), the biggest sub-basins of the Mekong Basin, and the Tonle Sap Lake system have received more limited study. Tonle Sap Lake, connected to the Mekong River via Tonle Sap River, has a unique hydrological environment that plays an important role in the active exchange between Tonle Sap Lake and the Mekong River through the seasonal reversal in flow (Siev et al., 2016). A better understanding of the sediment exchanging between the Tonle Sap Lake system and Mekong mainstem is needed because sediment load provided by the Mekong River is pivotal for the productivity of Tonle Sap (Arias et al., 2014). Kummu et al. (2008) analysed sediment exchange between Tonle Sap Lake and Mekong River for the period 1997–2003 and found a net sediment inflow from the Mekong into the lake. In contrast, Lu et al. (2014a) studied the period 2008–2010 and concluded that the net sediment transfer was from the lake to the river.

Given the critical role of the sediment and nutrient transport linkage between the Mekong mainstem and Tonle Sap River for the highly productive Tonle Sap Lake system and for sediment delivery to the Mekong delta, the objective of our study was to comprehensively analyse the sediment exchange between Tonle Sap Lake and the mainstem Mekong River over 25 consecutive hydrological years from 1993-2018.

2. Materials and Methods

Study area

Located in Southeast Asia, the Mekong River is the world's 12th longest river (4,800 km), has the 8th largest average annual runoff (470 km³) and the 21st largest basin area (795,000 km²). The basin of Mekong River is commonly subdivided into the Upper Mekong basin (or UMB) covering 24% of total basin (21% in China, 3% in Myanmar), and the Lower Mekong basin (or LMB), with 76% of the total basin area (Laos 25%, Thailand 23%, Cambodia 20% and Vietnam 8%) (**Figure 1**).

The Mekong Basin is characterized by distinctly wet and dry seasons, driven by the Southwest Monsoon. The wet season commonly extends from May to late September (or early October). The average rainfall of Mekong floodplain of Cambodia and the delta of Vietnam annually are up to 1,500 mm, while the maximum intensity occurs in central Laos. At elevations above 500 m above mean sea-level, dry season temperatures are lower, though not by much. The average rainy season temperatures greatly decline through south to north, from 26-27°C at Phnom Penh Cambodia to 21-23°C at northern part of Thailand. The discharge of Mekong river reaching to the sea averages 15 000 m³/s (Adamson et al., 2009; Gupta and Liew, 2007).

In Cambodia, the Mekong River connects with Tonle Sap Lake (TSL) (the largest permanent freshwater lake in the Southeast Asia) via Tonle Sap River at Chaktomuk confluence at Phnom Penh (**Figure 1**). Tonle Sap Lake was seasonally influenced by Mekong River flood pulse. The lake is approximately 120 km long and 35 km wide and covers 2,500 km² in the dry season, but it expands up to 250 km long and 100 km wide, and covers 17,500 km² in the wet season because high stages in mainstem Mekong drive flow into TSL through the Tonle Sap River (Campbell et al., 2009). From October to April, flow in the mainstem Mekong recedes, and flows reverse direction, draining from Tonle Sap Lake to the Mekong mainstream via Tonle Sap River (Fujii et al., 2003; Masumoto, 2000). The majority of water in the Lake in the wet-season is from the Mekong mainstem (Lu et al., 2014b), and the delayed release of this water provides important fresh water to the Mekong delta in Cambodia and Vietnam in low flow period (dry season) and prevents saltwater intrusion from the sea into fertile agricultural lands (Hai et al., 2008).

We selected three stations with continuous records of discharge and total suspended solids: The Mekong River at Kratie, the Mekong at Chroy Changvar (just upstream of the Tonle Sap confluence) reflecting discharge and sediment load above interactions with the Tonle Sap, and the

Prek Kdam station on the Tonle Sap River. Background information on these three stations of this study is detailed in Vinhteang et al. (2019). We analyzed flow and sediment by hydrological year from May 1 to April 30 following year (Kummu and Sarkkula, 2008; Lu et al., 2014b).

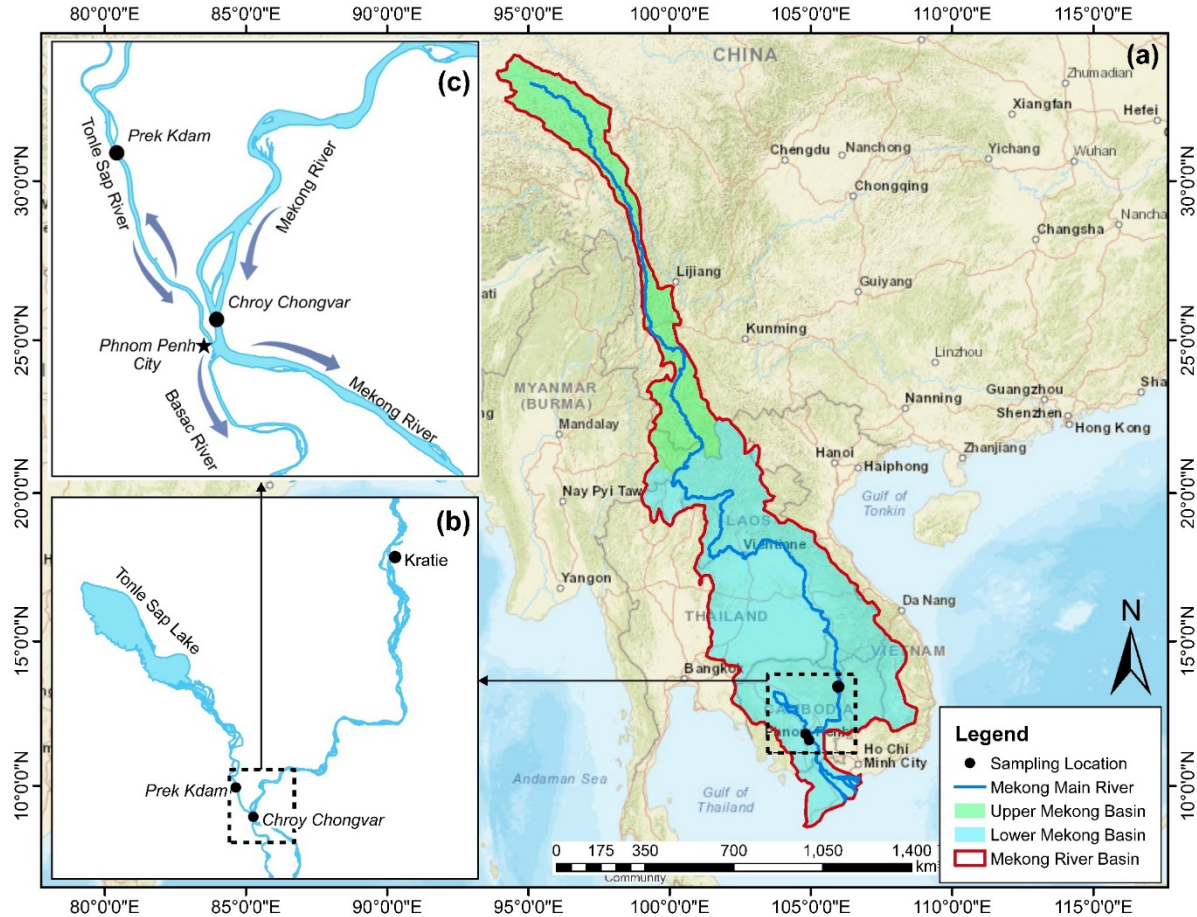


Figure 1. Maps of the study area. (a): The Mekong river Basin, (b): three sampling sites located at Kratie of the Mekong River, Chroy Changvar at Phnom Penh, and at Prek Kdam of Tonle Sap River. (c). the Chatumuk confluence located near Phnom Penh City.

Water Discharge and Total Suspended Solids Data

Daily water discharges were generated at the three sites using rating curves and water level data provided by the Cambodian Ministry of Water Resources and Meteorology (MOWRAM) during period 1993 to 2018. Also, from MOWRAM, we obtained total suspended solids (TSS, hereafter referred as suspended sediment) concentration data collected under the Mekong River Commission framework: Water Quality Monitoring Network (WQMN). The WQMN dataset has been used to estimate suspended sediment loads in previous studies such as Kummu and Varis (2007), Kummu

et al. (2008) and Wang et al. (2011). TSS concentrations were obtained from water quality sampling conducted on a monthly basis by MOWRAM from 1995 to 2018 on the Mekong at Kratie, from 1993 to 2017 on the Mekong at Chroy Changvar, and from 1995 to 2018 on the Tonle Sap River at Prek Kdam. **Table 1** summarizes the data (TSS and water discharge) coverage period and number of samples used in this study. In the WQMN sampling program, individual samples were collected 0.3 m below the surface in the middle of the river cross section. The samples were analyzed at laboratories designated by MRC, following recommended analytical methods for TSS analysis (2540-D-TSS-SM) (Kongmeng and Larsen, 2016). The reader should bear in mind that these were not depth-integrated samples, but single, near-surface “grab” samples from the approximate mid-point of the river. To the extent that the suspended sediments in the river are well-mixed, the samples may be representative of true loads, but if concentrations are heterogeneous in the vertical columns or across the channel, the measured TSS may not be representative of the average sediment concentration channel-wide, and may under-represent suspended sand especially, as sand concentrations would tend to be greater near the bed.

Moreover, total suspended solids (TSS) may not be directly comparable to suspended sediment concentration (SSC) determinations, because TSS samples are collected from only a single point (0.3 m below the water surface mid-river) in the cross section, while SSC samples are collected from the full water column and at multiple points on the cross section. If the sediments are not well-mixed through the water column but stratified, the two methods can yield different suspended sediment concentrations. Moreover, there are differences in analytical methods that can yield different particle-size distributions (Gray, 2000; Murphy and Sciences, 2020). SSC is determined by measuring the dry weight of all sediment from a water sample of a known volume, normally large samples (1 L) which to represent the entire water column. Several techniques are used to determine TSS, and most techniques similarly measure the dry weight of all sediment from a water sample of a known volume. However, as defined by the TSS protocol (APHA, 1995) this technique weighs the sediment in only a 100-250 mL sub-sample from the original water sample. As described by Gray (2000), generally, only finer suspended particle sizes are captured by TSS, while SSC characterizes the entire suspended particle-size distribution of the water column. The bias of TSS compared to SSC is most important at sites with larger proportions of sand-sized sediment. In the Lower Mekong River, the suspended sediments are generally dominated by silt and clay (Walling, 2005). Koehnken (2012) found that from downstream of Pakse, suspended

sediments are mainly composed of silt- and clay-size particles, and typically at Kratie all suspended sediments size are less than 63 μm . Generally, suspended particles smaller than 60 μm are uniformly vertically distributed in the water column (Partheniades, 1977). Given that the suspended sediments are well-mixed in the water column, the load estimation using TSS should be comparable to the load estimation using SSC in the Lower Mekong River.

Table 1: Data coverage period and the number of total suspended solids sampling and water discharge

	Kratie	Chroy Changvar	Prek Kdam		Time step
			TSL towards Mekong	Mekong towards TSL	
TSS (number of samples)	246	259	170	72	Monthly
TSS Data coverage period	1995-2018	1993-2017	1995-2018	1995-2018	-
Discharge data	1995-2018	1993-2017	1995-2018	1995-2018	Daily

Sediment Load Estimation and Trend analysis of annual sediment load

LOADEST: Sediment Loads were estimated at Kratie, Chroy Changvar, and Prek Kdam Station using the LOAD ESTimator (LOADEST) (Runkel et al., 2004). LOADEST provides three methods for load estimation, such as Maximum Likelihood Estimation (MLE), Adjusted Maximum Likelihood Estimation (AMLE), and Least Absolute Deviation (LAD) (**Table 2**) (Vinhteang et al., 2019).

Table 2. Load estimation methods in LOADEST

Loads Estimation method	Model Assumption	residuals	Function
MLE	Normal distribution		$\hat{L} = \exp(a_o + \sum_{j=1}^M a_j X_j) \cdot g_m(m, s^2, V)$
AMLE	Normal distribution		$\hat{L} = \exp(a_o + \sum_{j=1}^M a_j X_j) \cdot H(m, b, s^2, \alpha, \kappa)$

LAD	Non-normal distribution	$\hat{L} = \exp(a_o + \sum_{j=1}^M a_j X_j) \cdot \frac{\sum_{k=1}^n \exp(e_k)}{n}$
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Where

- m is the number of degree of freedom, s^2 is the residual variance, and V is a function of the explanatory variables.
- $[g_m(m, s^2, V)]$ is the bias correction factor of the maximum likelihood method.
- a and b are functions of the explanatory variables.
- α and κ are parameters of the gamma distribution.
- $[H(a, b, s^2, \alpha, \kappa)]$ is the bias correction factor.
- e is the residual error, and n is the number of uncensored observation in the calibration dataset.

Trend analysis of annual sediment load

To detect if trends can be identified in annual or seasonal series, we applied the *Mann-Kendall*, a non-parametric test originally proposed by Mann (1945) and updated later by Kendall (1975). The test has 3 alternative hypotheses in the series evolution: negative (i.e., decreasing trend), null (no trends in the series), and positive (increasing trend) (Howden and Burt, 2009). Pre-whitening (PW) is used to eliminate serial correlation (Yue and Wang, 2002).

3. Results

Water Discharge and Suspended Sediment Dynamics in the Lower Mekong River at Kratie and Chroy Changvar

Figure 2 shows the hydrographs of the daily water discharge and observed TSS at Kratie from 1995 to 2018 and Chroy Changvar from 1993 to 2017. The daily water discharge clearly reflects the annual dry and rainy seasons, with low flows in March and April (down to approximately 2,000 m³/s), followed by onset of the rainy season and increased discharges in May, and high flows in August and September (up to approximately 30,000 m³/s). At Kratie, the maximum discharge reached 58,205 m³/s in the rainy season of 1996 while the minimum discharge was 1,073 m³/s in the dry season of 1995. At Chroy Changvar station, maximum discharge reached 40,556 m³/s in the rainy season of 2014, while minimum lowest discharge was 405 m³/s in the dry season of 1995.

We calculated descriptive statistics such as minimum, maximum, mean, and standard deviation to illustrate the temporal distribution of important water quality parameters and to highlight specific characteristics. Additionally, we calculated skewness and kurtosis to determine if the data were skewed with positive or negative tails, and to determine the peakness of the distributions, respectively. The summary statistics of TSS concentrations from 1993-2017 at Kratie and Chroy Changvar are summarized in **Table 3**. Between June and October, water in the Mekong River was opaque, with TSS concentrations from 90 to 200 mg/l as it carried sediments derived from erosion across the basin. On the falling limb beginning in December, the TSS concentration drop to less than 20 mg/l on average. **Figure 3** illustrates the rating curve of observing daily water discharge and TSS at Kratie and Chroy Changvar station (1993 to 2017). Discharge and TSS concentrations showed significant statistical relations, with $R^2=0.53$ for Kratie station and $R^2=0.65$ for Chroy Changvar.

The TSS and Q relations in rivers, especially for a large river like the Mekong, are typically governed by multiple and relatively complex processes, which can produce hysteresis loops. Higgins et al. (2016) outlined four factors affecting hysteresis loops: a sudden increase in rainfall, the availability of sedimentary material in riverbeds, the interaction of deep soil layers, and aggressive flooding that causes the damming of sediment in flood plains upstream. Williams (1989) identified five common types of hysteresis loops: a single-valued line, a clockwise loop, a counter-clockwise loop, a single-valued line plus a loop, and a figure-8 loop. However, our TSS data set consists of monthly samples, and hysteresis loops would be evident only in data collected on a shorter time step, such as daily. To identify possible hysteresis loops and their possible causes would require in-depth studies such those undertaken by Pietroni et al. (2015) and Chalov et al. (2017).

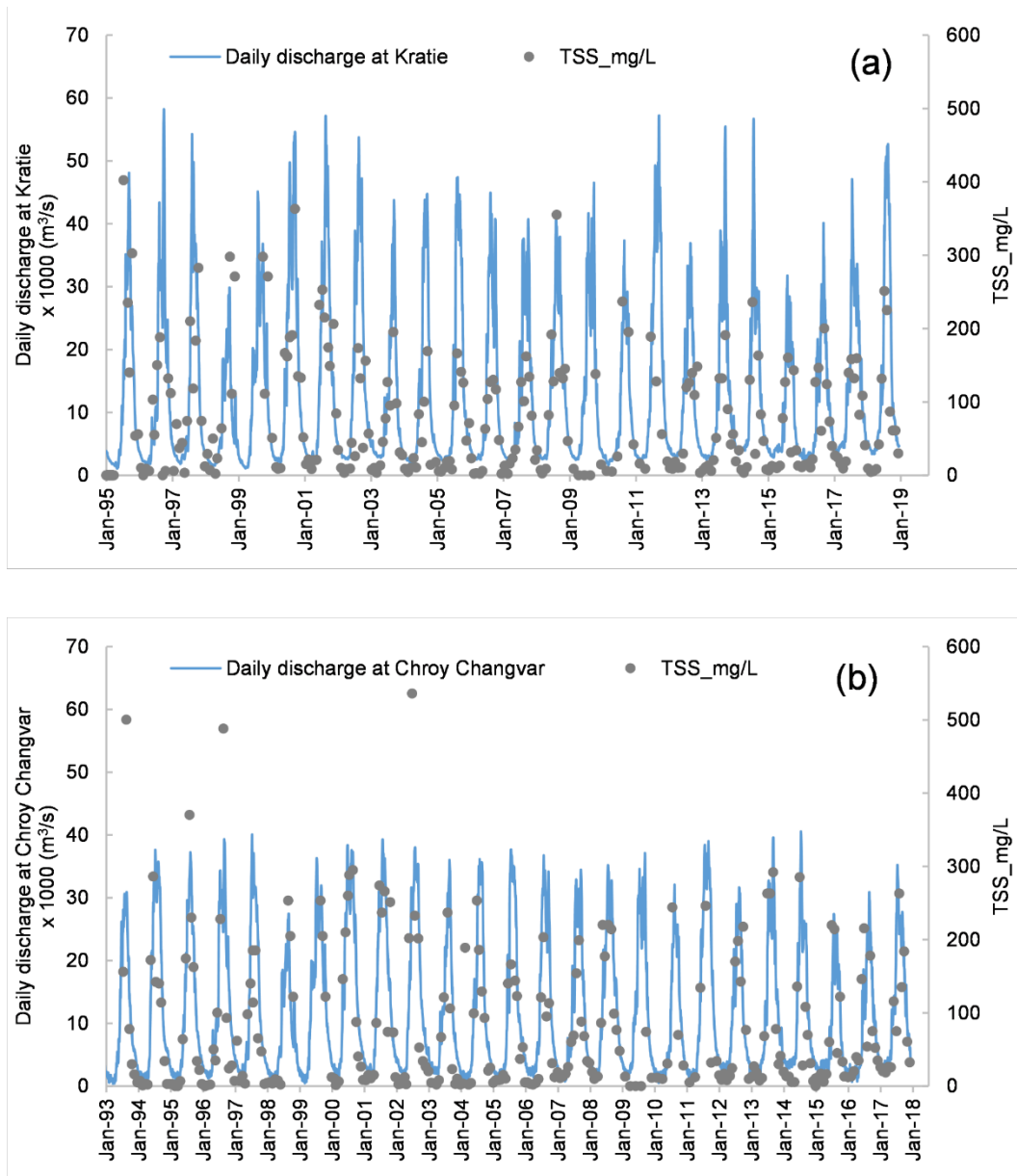


Figure 2: Variation in the water discharge at the daily time step and total suspended solids concentration (monthly time step) at (a) Kratie (1995 to 2018) and (b) Chroy Changvar (1993 to 2017). Data from Cambodia MOWRAM.

Table 3: Descriptive statistics of sediment concentration at Kratie and Chroy Changvar

Kratie	Month	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	Min	3	8	26	29	31	6	31	2	6	2	3	2
Max	167	232	402	355	363	303	271	112	51	70	50	44	
Mean	35	96	159	157	175	118	108	37	17	14	13	12	

	SD	41	61	85	72	74	69	74	28	13	15	12	10
	Skewness	2.3	0.7	1.2	0.8	0.9	1.1	1.1	1.0	1.3	2.9	2.2	2.0
	Kurtosis	5.5	-0.3	2.7	1.7	1.7	2.1	0.4	0.9	1.3	10.0	5.0	5.3
Chroy Changvar	Min	2	2	69	28	45	23	3	3	2	3	1	2
	Max	146	220	536	370	500	218	251	73	31	62	189	39
	Mean	24	93	204	204	209	104	57	26	12	12	19	10
	SD	35	67	108	74	114	53	53	17	8	13	42	9
	Skewness	2.7	0.5	1.5	-0.5	1.4	0.9	2.7	0.9	0.9	3.1	4.2	2.1
	Kurtosis	7.8	-0.7	4.0	1.4	2.0	0.1	8.6	1.1	0.4	11.7	17.9	5.3

Note: Min, max, mean, and SD are concentrations in mg/l;
Skewness and Kurtosis are dimensionless.

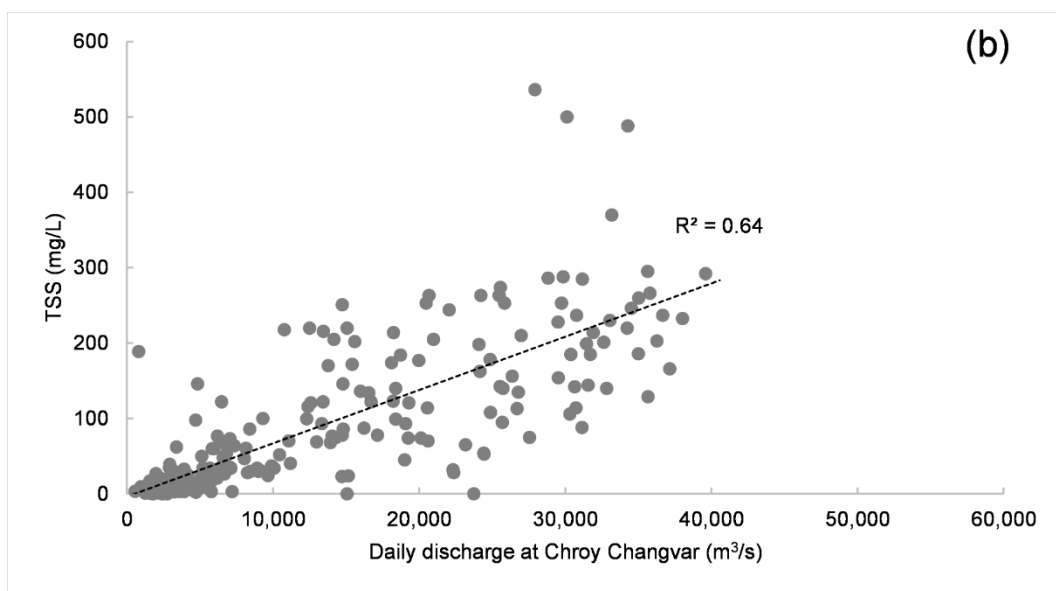
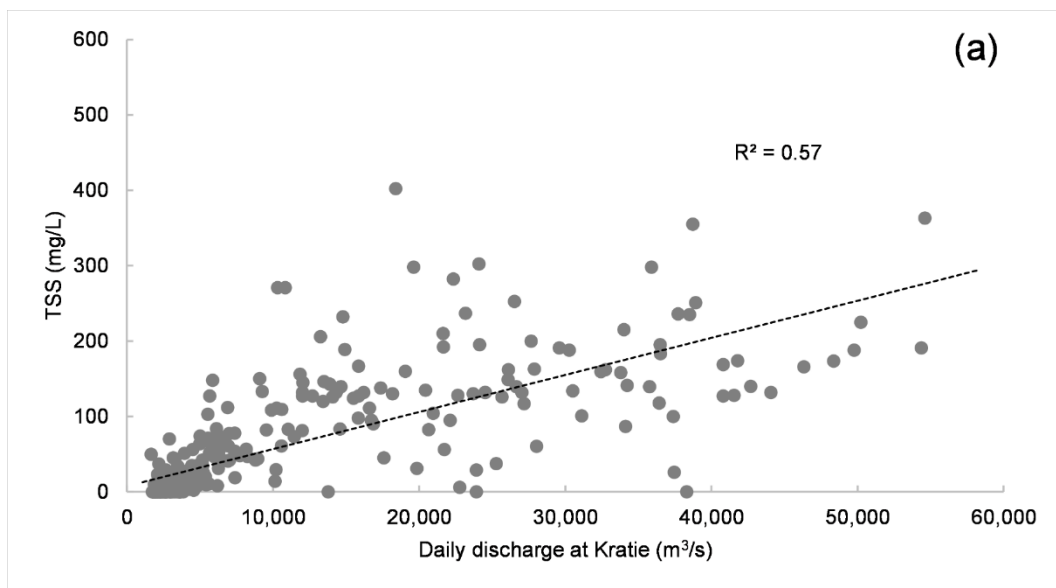


Figure 3: Relationship of TSS concentration and daily water discharge in the Lower Mekong River at (a) Kratie (from 1995 to 2018) and (b) Chroy Changvar (1993 to 2017). Data from Cambodia MOWRAM

Water Discharge and Suspended Sediment load in Tonle Sap River at Prek Kdam

Prek Kdam station records discharge and sediment of the Tonle Sap River, downstream from TSL to Mekong River during low water stage, and reverse, upstream flow during high stage of the Mekong River (**Figure 4**). We plotted inflow from the Mekong River into TSL as negative values of water discharge and sediment concentration, plotted outflow from TSL to the Mekong River as positive values.

The number of outflowing and inflowing days exchanging between TSL and Mekong River fluctuated from year to year. The reversal began in late May to early June, with water flowing from Mekong River upstream into TSL for 70 to 157 days per year (average of 118 days), whereas flow downstream from TSL to the Mekong River occurred for 209 to 295 days (average 247 days). 1995 and 2014 were years with the fewest days of reverse flow, 73 and 70 days, respectively. The peak reverse flow in Prek Kdam generally occurred in July and August, before the peak discharge of Mekong River (August and September) at Chroy Changvar station. Peak outflow from the lake to Mekong River mainly took place a few months later, during the outflows from October to December. During the observed periods, the maximum water discharge of the lake was 10,679 m³/s for inflow, and 10,104 m³/s for outflow.

Suspended sediment concentrations at Prek Kdam were governed by distinct flow directions (**Table 4**). TSS concentrations for outflow from lake to the Mekong (October to March) averaged 41 mg/l, while TSS concentrations during reverse flows from the Mekong River towards TSL (May to September) averaged 74 mg/l. Thus, TSS concentrations of the inflow were nearly twice the concentrations of the outflow from TSL, implying a net transfer of sediment into the Lake. The sediment rating curves at Prek Kdam show distinct relations when plotted separately for outflow and reverse-flow periods (**Figure 5**), with TSS concentrations lower in outflows from TSL to the Mekong (**Figure 5.a**) than in reverse flows to TSL (**Figure 5.b**), with all parameters having only a weak relationship in linearity with discharge ($R^2 < 0.1$) in both flow periods.

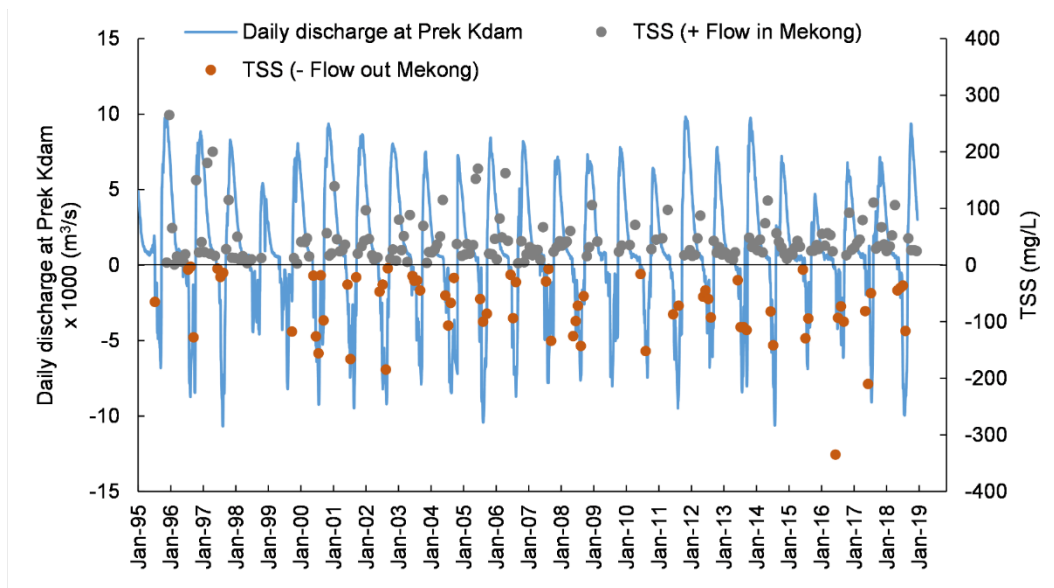


Figure 4. Variation in the water discharge at the daily time step and total suspended solids (TSS) at Prek Kdam (monthly time step). The negative values of concentration and discharge are (reverse) inflow into the TSL from Mekong River, while positive values are the outflow from the lake towards Mekong River. Data from Cambodia MOWRAM.

Table 4: Descriptive statistics include minimum values (min), maximum values (max), mean values, standard deviation (SD), skewness coefficients and Kurtosis of sediment concentration at Kratie from 1995-2018.

	From Tonle Sap Lake towards Mekong River	From Mekong River towards Tonle Sap Lake
Min	1.0	3.0
Max	265	335
Mean	41.7	74.0
SD	39.6	58.1
Skewness	2.55	1.54
Kurtosis	8.27	4.46

Note: Min, max, mean, and SD are concentrations in mg/l; Skewness and Kurtosis are dimensionless.

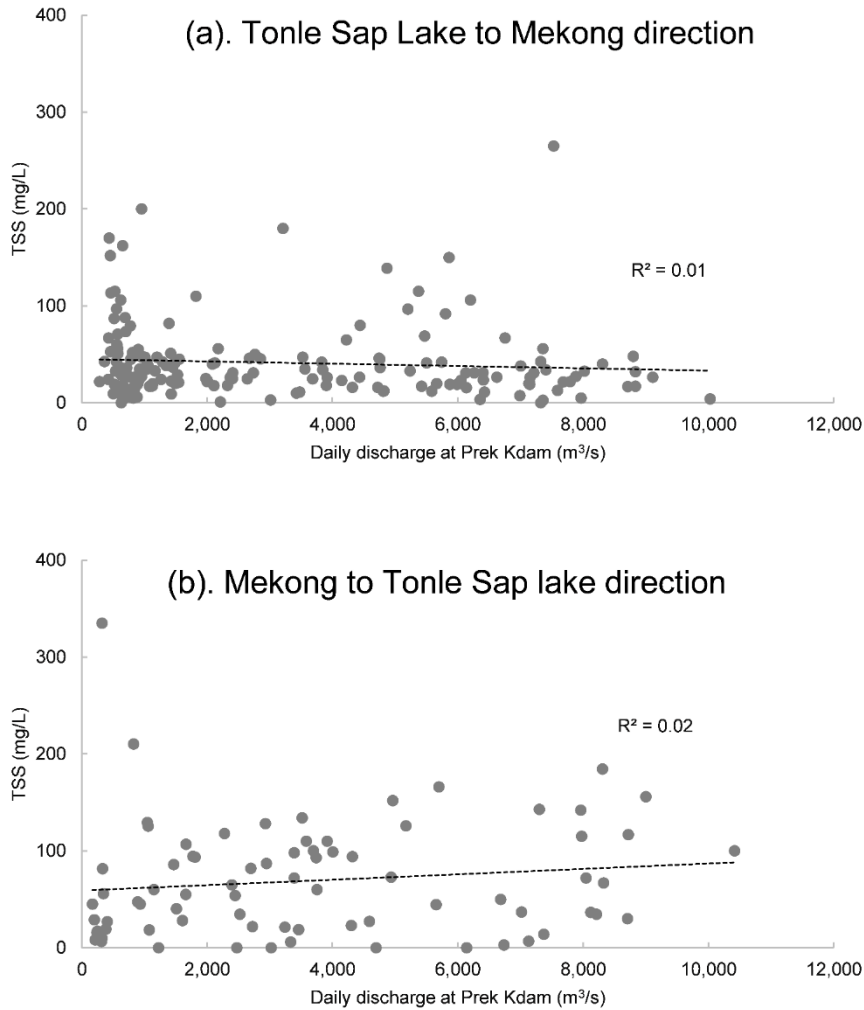


Figure 5: Relationship of TSS concentration and daily discharge of Tonle Sap River at Prek Kdam for the period 1995-2018. (a) Outflow from TSL to Mekong River (in low water stage) and (b) Reverse flow direction from Mekong River to TSL (in high water stage). Data from Cambodia MOWRAM.

Temporal Variability of Water Discharge and Sediment Load in the Mekong River at Kratie and Chroy Changvar

Annual water discharge and computed sediment loads on the mainstem show higher flows and sediment loads at Kratie than at Chroy Changvar (**Figure 6**). Annually, 80% of annual flow occurred during rainy season (from May to October), while 20% of the annual flow occurred during dry season (from November to April). On average, the annual water discharge in Kratie

was 404,000 Million cubic meters (Mm^3/yr), 36,000 Mm^3/yr higher than the annual water discharge at Chroy Changvar (368,000 Mm^3/yr). This pattern is similar to the pattern of the flow in Kratie and Stung Treng (Cambodia-Laos border, about 150 km upstream of Kratie). MRC (2019) reported in their observed flows for the Mekong mainstream stations over the period 2000-2017, Stung Treng discharge is found higher than the downstream at Kratie. After Kratie the Mekong enters extensive floodplains and then delta. Water flow in this reach is very complex (due to downstream backwater effects, overbank flows and temporary water storage on the floodplain) especially during the flood season when hydraulic conditions define the flow distribution between different river branches. The downstream reduction in gauged flow at Kratie and Chroy Changvar occurred mainly at higher flows and can be attributed to overbank flow from the Mekong River traversing the floodplain to TSL and by flow into major distributaries between Kratie and Chroy Changvar. During the flood season, water starts to spillover both banks of the Mekong River between upstream of Kompong Cham (150 km upstream of Chroy Changvar) and Chroy Changvar station. Part of the water spilling over the right bank reaches the Tonle Sap Lake as overland flow. This overland flow was reported to average 2,500 Mm^3/yr by Lu et al. (2014b). On the left bank of the main river at Kampong Cham, part of the Mekong flow is partly diverted into the Tonle Toch River, which then discharges back into the Mekong further downstream of Chroy Changvar in the Mekong delta. The bypass discharge by this river has not been previously reported in the literature. The trend analysis confirmed a decreasing trend in annual water discharge at Chroy Changvar (statistically significant ($p < 0.05$)), but we found no significant trend at Kratie upstream (**Table 5**).

The annual sediment load over the 24-year period averaged 72 ± 26 Mt/yr at Kratie, 78 ± 22 Mt/yr at Chroy Changar (**Figure 6**). A pronounced temporal trend was visible at Kratie, where annual sediment loads decreased from 123 Mt/yr in 1995 to 40 Mt/yr in recent years, with the MK test documenting a statistically significant ($p < 0.05$) decreasing trend. At Chroy Changar, sediment loads fluctuated over the study period (from 32 Mt in the dry year 1998 to 128 Mt in 2011), but no temporal trend was detected (**Table 6**).

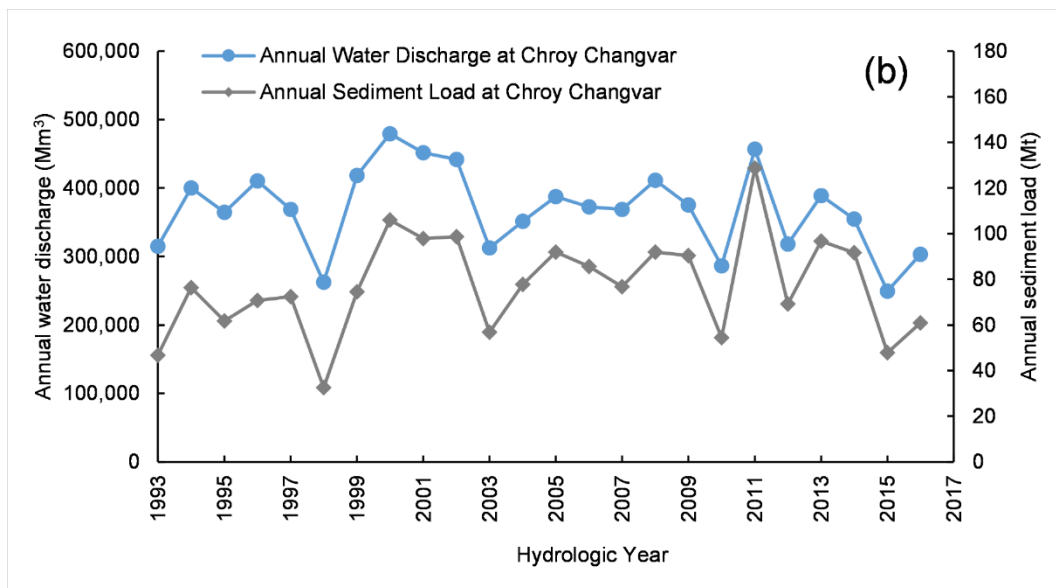
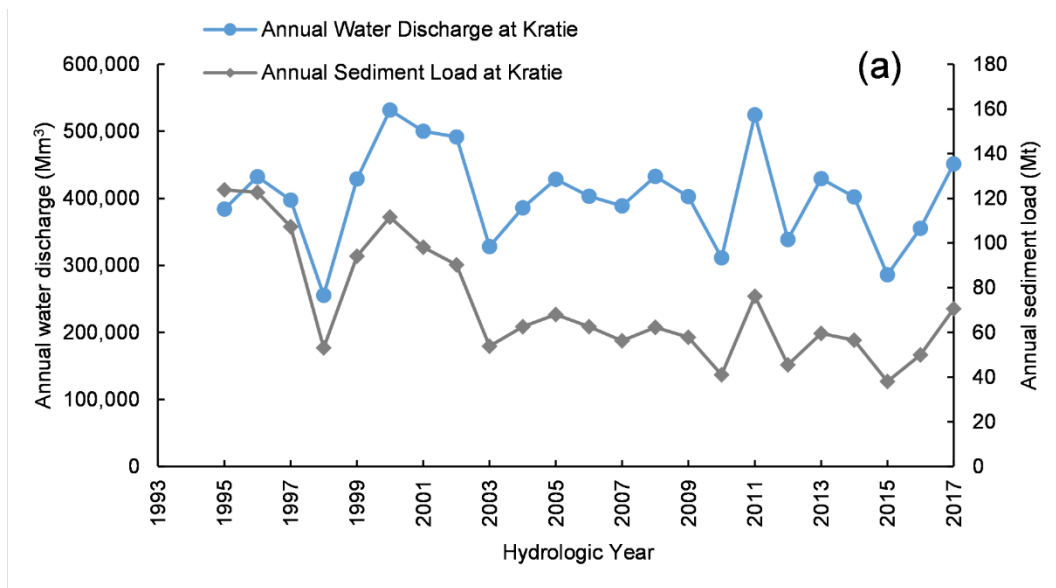


Figure 6: Annual sediment load dynamics and water discharge in the Mekong river at (a) Kratie (hydrological year 1995-2017) and (b) Chroy Changvar stations (hydrological year 1993-2016).

Table 5: Summary of annual water Discharge and sediment load in the Mekong River at Kratie and Chroy Changvar

Location	Average	Maximum	Minimum	Trend direction	Significant level
Water Discharge at Kratie (Mm³)	404,000	532,000	256,000	No trend	

Water Discharge at Chroy Changvar (Mm ³)	368,000	480,000	250,000	Decrease	Significant at $\alpha=0.05$
Sediment Load at Kratie (Mt)	72	124	38	Decrease	Significant at $\alpha=0.05$
Sediment Load at Chroy Changvar (Mt)	78	129	33	No trend	

The monthly discharge and sediment load distribution curves of the entire recorded periods (hydrological year 1995-2017 at Kratie, hydrological year 1993-2016 at Chroy Changvar) (**Figure 7**) show similar monthly patterns in high and low sediment load (i.e., equal or exceeding 5% and 95%). However, monthly highest discharge differed significantly. The flow distribution at Kratie and Chroy Changvar confirmed the downstream reduction in gaged flow at Chroy Changvar occurring at higher flows. The peaks of discharge and sediment loads were 133 km³/month and 40 Mt/month at Kratie, 95 km³/month and 33 Mt/month at Chroy Changvar.

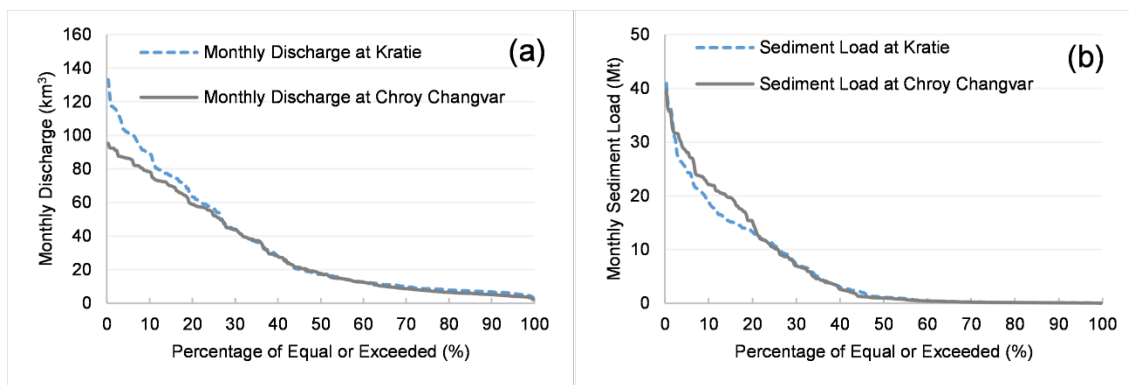


Figure 7: Monthly water discharge and loads sediment load distribution curves at Kratie and Chroy Changvar station.

Temporal Variability of Water Discharge and Sediment Load in the Tonle Sap River at Prek Kdam

Cumulative seasonal flow volumes are presented in **Figure 8**, with negative values indicating inflow from the Mekong to TSL, and positive values for outflow from TSL to the Mekong River. The seasonal outflow of TSL averaged 68,000 Mm³, which was equivalent to 18% of annual discharge of Mekong River at Chroy Changvar. The seasonal reverse flow into the lake from the Mekong River averaged 36,000 Mm³, about 10% of annual discharge of Lower Mekong River at

Chroy Changvar. Thus, the outflow from the lake was almost twice the reverse flow from the Mekong River. Some of this difference can be attributed to runoff from the 760,000 km² drainage lake basin, some to overbank flow from the Mekong mainstem across floodplains into the lake. Mean annual overland runoff into the lake was estimated as 2,600 Mm³, while runoff from the drainage basin of the lake was nearly the same, about 2,700 Mm³ (Lu et al., 2014b). Looking at temporal trends, the reverse flows to the lake showed decreases over the 24-year period, but these were not statistically significant ($p, 0.05$); outflows also showed decreases, which were significant ($p < 0.05$) (**Table 6**).

Net annual sediment loads averaged 3.7 Mt in reverse flows into Tonle Sap Lake, equivalent to 4.8% of annual average sediment load at Chroy Changvar of the Mekong mainstem. (**Figure 9**). The sediment load from the lake to Mekong River was 2.9 Mt/yr, which is equal to 3.7% of average annual sediment load in Chroy Changvar. Thus, we can estimate that Tonle Sap Lake gained an average of 0.8 Mt of sediment annually from the Mekong River. However, as this term is calculated as a residual, it must be treated with caution, as such residual terms incorporate and hide errors in other terms (Kondolf and Matthews, 1991). Sediment loads in reverse flow increased over the observed period (statistically significant at $p < 0.05$), while sediment load of the lake outflow evinced no trend.

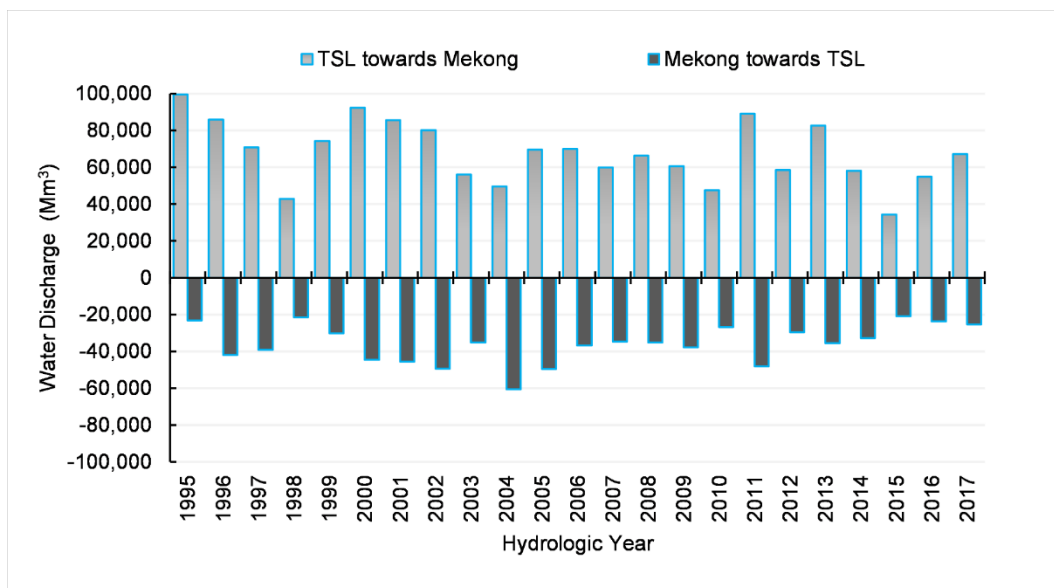


Figure 8: Seasonal water discharge exchange between TSL and Mekong River at Prek Kdam station for the hydrological year 1995 to 2017. The negative values of discharge are (reverse)

inflow into the Tonle Sap Lake from Mekong River, while positive values are the outflow from the lake towards Mekong River

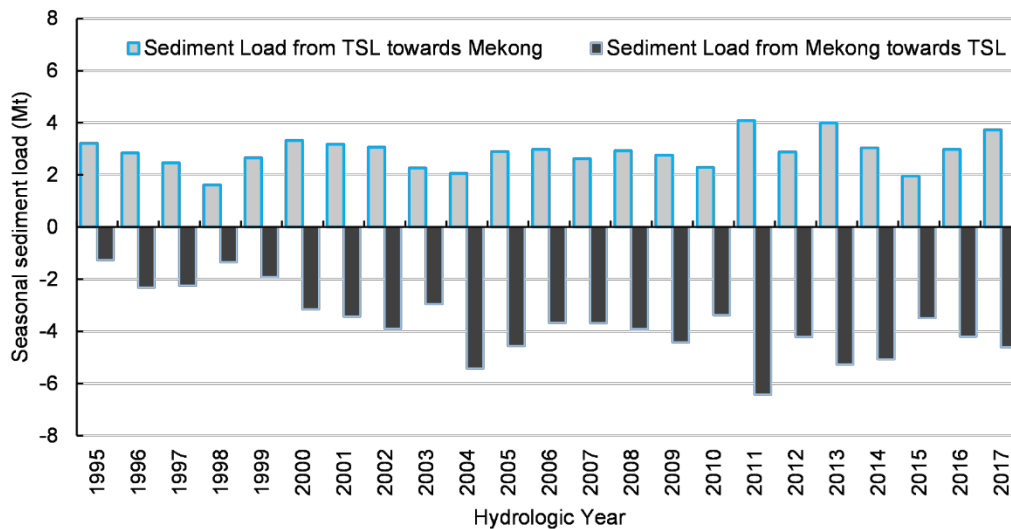


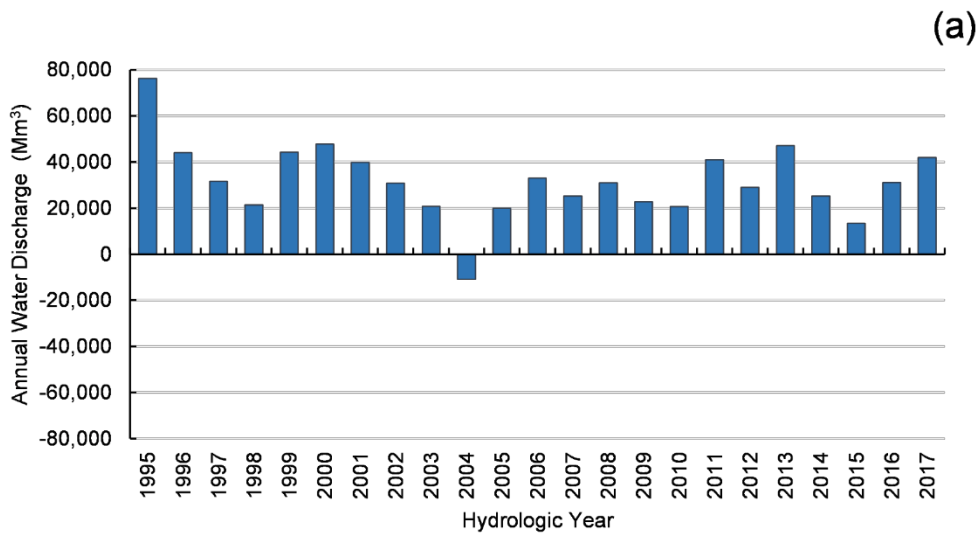
Figure 9: Seasonal sediment load exchange between TSL and Mekong River through Tonle Sap River at Prek Kdam for the hydrological year 1995 to 2017. The negative values of sediment load are (reverse) inflow into the TSL from Mekong River, while positive values are the outflow from the lake towards Mekong River

Table 6: The percentage share of water discharge and sediment load between TSL and Mekong River at Chroy Changvar, averaged over hydrological year 1995-2017.

Flow stations/Direction	Water discharge (Million m ³)	Percentage sharing with Mekong at Chroy Changvar (%)	Annual Trend	
			Trend direction	Significant level
TSL to Mekong River	67 600	18	Decrease	Significant at $\alpha= 0.05$
Mekong River to TSL	3 600	10	No trend	
Mekong mainstem at Chroy Changvar	368 000			
Sediment stations/Direction	Sediment Load (Mt)	Percentage sharing with Mekong at Chroy Changvar (%)	Annual Trend	
			Trend direction	Significant level
TSL to Mekong River	2.9	3.7	No trend	
Mekong River to TSL	3.7	4.8	Increase	Significant at $\alpha= 0.05$

Sediment Load Linkage between Tonle Sap Lake and Mekong River and Towards the Mekong Delta

The overall balance of flow and sediment load between TSL and Mekong River over the observation hydrological year 1995-2017 shows a net contribution of water from Tonle Sap Basin, as would be expected from such a large drainage area (**Figure 10.a**). 2004 was an exception, when the Mekong River at Chroy Changvar reached its maximum discharge 60,000 Mm³. The annual water balance indicates that TSL contributes an average of 33,000 Mm³ during the low-flow period to the Mekong delta. However, the net sediment transfers changed over the observation period. From hydrological year 1995 to 2000, Tonle Sap River contributed more sediment load to Mekong River than it received via reverse flows, but from hydrological year 2001-2017 the lake received more sediment from the Mekong River than it contributed (**Figure 10.b**), averaging 1.35±0.7 Mt per year.



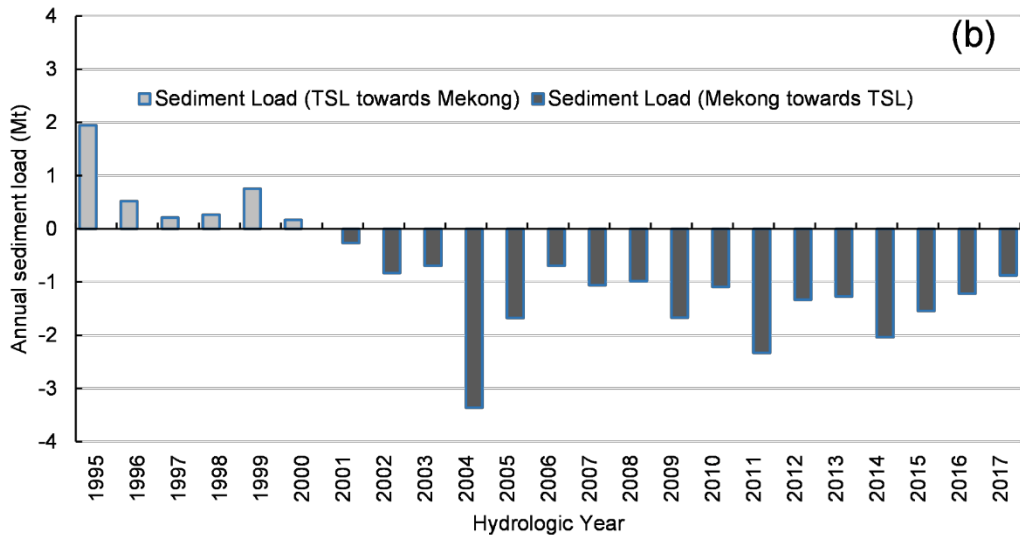


Figure 10: Water discharge and sediment loads balance between TSL and Mekong River through Tonle Sap River at Prek Kdam station for hydrological years 1995 to 2017. (a) Net water discharge, (b) Net sediment load. Annual water discharge and sediment load obtained as residuals by subtracting seasonal water discharge and load in reserve flow from Mekong River and outflow from TSL. Negative values reflect net inflow to the TSL from Mekong River, while positive values are the net outflow from the lake to the Mekong River.

4. Discussion

Sediment load in the Lower Mekong River

Estimation of the total flux of Mekong to the delta is complicated by interactions with the Tonle Sap system (Kummu and Varis, 2007) since large volumes of flood water enter the Tonle Sap floodplain, where a part of the sediment loads deposited. Our estimated loads at Kratie (72 ± 38 Mt from 1993-2017) and Chroy Changvar (78 ± 22 Mt from 1995-2018) are similar to those proposed by prior authors, such as Dang et al. (2016), who reported suspended sediment flux of 87 ± 28 Mt/year (1981–2005), Lu et al. (2014a), who reported 50-91 Mt/year of suspended sediment load from 2008 to 2010, and Manh et al. (2014), who estimated 106 Mt/year at Kratie (2010-2011). However, the more recent estimates cover relatively short periods after major dam construction in the upper Mekong mainstem. Looking over longer time scales reflected in stratigraphic analysis of Holocene sediment cores, Ta et al. (2002) proposed 144 ± 34 Mt/year of long-term mean

sediment load to the sea, which is consistent with pre-dam estimate of 145 Mt/year by Liu et al. (2013).

As noted above, our study used TSS data from single-depth, mid-channel samples collected as part of a larger water quality dataset (WQMN). It would be preferable to use depth-integrated samples, but these data are extremely limited in time and space (Koehnken, 2012). Prior studies also relied on TSS from single-depth mid-channel samples to estimate sediment load in the Lower Mekong River (Kummu and Varis, 2007), (Kummu et al., 2008) and (Wang et al., 2011). Wang et al. (2011) compared the sediment loads calculated at Chiang Saen in Laos (the most upstream of Lower Mekong) using both the TSS data from the WQMN database and the suspended sediment concentrations (SSC) derived from depth-integrated sampling from the HYMOS dataset (another MRC dataset). This comparison revealed no underestimation using the TSS data at Luang Prabang and Khong Chiam (Laos). For 2008-2010, Lu et al. (2014a) collected suspended sediment samples at 3 evenly-spaced points across the Mekong and Tonle Sap rivers, at 3 depths each (0.5m, 0.2 and 0.8 depth), and found “no major differences in suspended sediment concentrations within the profile.”

The results of our trend analysis of sediment load are broadly consistent with patterns observed in major rivers in the region and the world. With the exception of the Amazon, whose suspended sediment discharge increased about 20% 1995-2007 (while water discharge held steady) (Martinez et al., 2009), most rivers have displayed decreases in sediment load. Vörösmarty et al. (2003) suggested that large reservoirs controlled over 40% of runoff of global rivers and trap more than half of the pre-dam sediment load. Walling and Fang (2003) assessed sediment load trends for 145 rivers globally and found that most showed decreasing sediment loads. Li et al. (2020) assessed water and sediment fluxes measured at 138 rivers and found that finding 50 rivers had stable water flows but decreasing sediment flux, while 41 rivers decreased in both water and sediment fluxes. Mean annual water and sediment fluxes to sea from the world’s large rivers decreased by 58–98 km³/yr (0.25%) and 2617–2715 Mt/yr (20.8%) respectively over the recent five to ten year timescale, mainly due to the reduction in water and sediment fluxes that occurred in Asia (by 1.6%–2.0% in water discharge, and by 13.1%–13.2% in sediment fluxes (Li et al., 2020). Displaying a different trend, the largest rivers of North and East Asia (Russia and China), such as Yenisei, Amur, Yellow, Yangtze, Pearl Rivers have experienced suspended sediment load

reduction attributed to sediment trapping by dams (Chalov et al., 2018). An earlier study by Liu et al. (2007) found that major rivers in Southern China (e.g., Yangtze, Qiantang, and Pearl rivers) were transporting only about 60% to 80% of their pre-dam loads, while their annual runoff was reported relatively stable. Gupta et al. (2012) estimated that the combined annual sediment flux of the large Chinese rivers decreased from 1800 Mt to about 370 Mt over the previous five decades.

On the Mekong itself, a number of authors have converged on significant impacts to the river's sediment load. The first mainstem dam was the Manwan Dam on the Upper Mekong (Lancang) in China in 1993, which reduced sediment loads by about 60% (Fu et al., 2008). Projecting effects of completing 8 large mainstem dams on the Lancang, Kummu et al. (2010) estimated a cumulative reduction by half of the river's annual load of 140 million tons. On the Lower Mekong, 11 mainstream dams are planned, of which three (Xayaburi, Pak Beng and DonSahong) are built or under construction (Fox and Sneddon, 2019). The future of the proposed Sambor dam in the Kratie Province of Cambodia is uncertain, but if built as originally proposed, it would likely trap 38Mt/y of an estimated 77Mt/y that would be delivered to the dam under a scenario of 38 dams built on the mainstem and tributaries (Wild and Loucks, 2015).

The concern stems not only from dam development on Mekong mainstem but also on its main tributaries. For example, the Sekong, Sesan, and Srepok basin (so-called '3S basin', the largest tributary of the Mekong) formerly contributed a large portion of the sediment load reaching TSL and the Delta (Wild and Loucks, 2014), but this has been mostly cut off by the recently completed Lower Sesan 2 dam, which blocks the Srepok and Sesan. Overall, construction of the approximately 140 dams planned for the Mekong and its tributaries would trap 96% of the sediment that was naturally delivered to the Mekong Delta (Kondolf et al., 2014). Reduced sediment supply threatens the long-term sustainability of the Mekong Delta (Campbell, 2007; Saito et al., 2007). Beside the dam development in Mekong River Basin, climate change and land-use change are also the crucial factors affecting sediment transport in the basin. Deforestation alters basin erosion, increases sediment delivery to reservoirs and can decrease productivity of hydropower (Kaura et al., 2019). Shrestha et al. (2013) point to uncertainties in the direction and magnitude of variability of flow and sediment yields due to climate change, and Darby et al. (2016) have documented reductions in sediment supply from the basin as runoff from tropical cyclones,

delivering about 32% of the suspended sediment load reaching the delta, has been halved since 1981 as cyclone tracks shifted north.

Our study did not explicitly include bed-load due to a lack of data. Suspended sediment load data are more common globally because suspended sediment load is the dominant component of total load and is easier to measure (Milliman and Farnsworth, 2013; Walling, 2009). In the absence of direct measurements of bed load transport, it is frequently assumed that the bed load is up to 10% of the total load (Gregory and Walling, 1973; Milliman and Meade, 1983). For most larger rivers, the bed load much less, e.g. <2% for the Yukon River of North America (Brabets et al., 2000); < 5% for the lowermost Mississippi River (Nittrouer et al., 2008). On the Mekong River, (Koehnken, 2012) reported bed-load in Kratie measured in 2011 was only 1.6 Mt/year, approximately 1.4% of suspended sediment load.

The Mekong River and major regional rivers in term of sediment

Of the total natural global sediment flux to the oceans of about 12.6 to 18 Gt/year, Asia exported the most sediments (~4.8 Gt/year) among continents (Gordeev, 2006; Syvitski et al., 2011; Syvitski et al., 2005). High sediment loads are a common feature of many Asian rivers, especially those originating from the Himalayan-Tibetan Plateau, such as the Yellow Rivers, the Yangtze, the Red and the Mekong, and due to the pronounced topographic relief of the region (Evans et al., 2012; Ludwig and Probst, 1998; Milliman and Syvitski, 1992). However, Africa and Asia showed the largest reduction in sediment flux to the coast in rivers (such as the Nile, Orange, Niger, and Zambezi in Africa and the Yangtze, Indus, and Yellow in Asia), and 31% of the total sediment load retained in reservoirs were indicated in Asia and 25% in Africa (Syvitski et al., 2005). The world’s largest river, the Amazon exports around ~550–1500 Mt/yr of sediment to the Atlantic (Dunne et al., 1998; Gaillardet et al., 1997; Guyot et al., 2005; Martinez et al., 2009; Meade et al., 1979). The Mekong’s annual sediment load is comparable to loads reported for other major rivers in Asia and elsewhere (**Table 7**).

Table 7: The annual mean of sediment is comparable with other major rivers in Asia and continents.

River	Region	Basin area	References
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		(10 ⁶ km ²)	River length (km)	Water Discharge km ³ /yr	Sediment yield t/km ² /yr	Sediment load (Mt/yr)	
Yenisei	North Asia	2.5	4800	630	9.54	23.85	Fabre et al., (2019)
Yellow	East Asia	0.77	5464	49	1400	1080	Wang et al., (2011)
Yangtze	East Asia	1.94	6300	900	250	480	Wang et al., (2011)
Pearl	East Asia	0.44	2129	302	88.6	39	Chalov et al., (2018); Lai et al., (2016)
Red	East Asia	0.12	1139	123	780	107	Wei et al., (2021)
Mekong	Southeast Asia	0.79	4800	ND 404	202 102	160 78	Walling, (2008) (This study)
Irrawaddy	Southeast Asia	0.43	2210	410	846	364	Robinson et al., (2007)
Brahmaputra	South Asia	0.61	2900	625	819	500	Rahman et al., (2018)
Congo	Africa	3.7	4700	1300	9.4	33	Laraque et al., (2013)
Mississippi	North American	1.15	3778	530	120	400	Allison and Neill, (2002)
Orinoco	South America	1.0	2140	1000	88	74	Laraque et al., (2013)
Amazon	South America	6.1	6400	6600	100	610	Wittmann et al., (2011)

Sediment exchange between Tonle Sap River and Mekong mainstream

As reported above, our analysis shows that from 1995 to 2000, the Tonle Sap contributed more sediment load to Mekong River than was deposited in the lake, on the average 0.65 Mt annually, but the rate decreased, and then since 2001, an average net 1.35±0.7 Mt of sediment has been deposited in the lake annually. Our results are in the same range but differ from prior studies, which covered shorter time periods, such as Kummu et al. (2008) who estimated for the period 1997-2003 that the TSL received a net transfer of sediment from the Mekong of 3.7 Mt/y, from an average of 5.1 Mt/year to TSL from the Mekong by reverse flow, and an average of 1.4 Mt/year from TSL to the Mekong via outflow. For the period 2008-2010, Lu et al. (2014a) estimated average sediment load inflow of 6.3 Mt/year into the lake from Mekong mainstem and 7 Mt/year in the outflow, for a net deposition within Tonle Sap Lake, inconsistent with our results. Our

estimate of mean annual sediment load in reverse flow from the Mekong River mainstem to Tonle Sap lake of 4.2 Mt/year is lower than the estimation of Kummu et al. (2008) (5.1 Mt) and Lu et al. (2014a) (6.3 Mt). The mean annual sediment outflow from the Tonle Sap lake estimated in our study (3.1 Mt /year) is higher than mean value (1.4 Mt/year) estimated by Kummu et al. (2008) but lower than the mean value of 7 Mt/year calculated by Lu et al. (2014a).

By consider the same period (1997-2003) with Kummu et al. (2008), we found that Tonle Sap Lake obtained 2.7 Mt from Mekong mainstem and returned 2.65 Mt annually while Kummu et al. (2008) suggested Tonle Sap Lake obtained 5.1 Mt from Mekong mainstem and returned 1.4 Mt. Kummu et al. (2008) used single-point surface water sample measuring TSS at Prek Kdam with monthly basis from MRC, which is the same data source as our study. This should be the reason, we come up with consistency. Whereas, the different in value might be from the different of method as we applied load estimator, LOADEST base on Least Absolute Deviation (LAD) method, while Kummu et al. (2008) applied sediment transport module of 3D EIA model. With the same study period (2008-2010), we estimated the lake system received 3.9 Mt and shared 2.66 Mt of sediment annual from and to the Mekong mainstem. These values are lower than those suggested by Lu et al. (2014a) which was 6.3 Mt and 7 Mt. The inconsistency of the lake sink or source of sediment and the value between our study and Lu et al. (2014a) might come from various reasons. Firstly, the sampling points are different. We estimated the load from Prek Kdam stations in the Tonle Sap River, while Lu et al. (2014a) from Phom Penh port, which is only located few kilometers toward the Mekong mainstem. Secondly, the different in data source, we used water and sediment data collected by MOWRAM under the MRC water quality program. As noted above, these were not depth-integrated samples, so the accuracy of suspended load estimates from these depends on how well mixed are sediment concentrations vertically and horizontally.

Prior studies also relied on TSS from single-depth mid-channel samples to estimate sediment load in the Lower Mekong River e.g. Kummu and Varis (2007), Kummu et al. (2008) and Wang et al. (2011). While, sampling in 2008-2010 at multiple depths across the cross section of the Mekong at Chroy Changvar and the Tonle Sap River at Phnom Penh Port by Lu et al. (2014a) indicated that suspended sediment was well-mixed. However, within the MRC depth-integrated measurement campaign for year 2011, the inflow (6.4 t/yr) and outflow (1.5 Mt/yr) at Prek Kdam (Koehnken, 2012) were in line with our finding and Kummu et al. (2008). Thirdly, we used

different method for load estimation, Lu et al. (2014a) estimated sediment load based on the developed sediment rating curve and discharge at a given station. By using this, the estimated load can be represented as a natural characteristic flow and concentration with a specific time, however, it cannot be represented or cannot cover the range of characteristic of the water and sediment dynamic in the past and near future. While our estimation based on regression model that developed based on wide range of dataset that would be able to capture characteristic of the water and sediment dynamic for long period. Even there are some inconsistency, our study can provide another confirmation to the conflict of previous study and better understand the sediment dynamic between Mekong River and Tonle Sap Lake with longer study periods and extend the discussion within basin scale and regional scale.

An assessment of water discharge and sediment loads variability of Mekong River and Tonle Sap system presented in this study helps clarify the exchange annual discharge and sediment load toward the Mekong delta. Tonle Sap Lake provided sediment load to the Mekong system and delta annually 0.65 ± 0.6 Mt from 1995 to 2000, but since 2001 Tonle Sap Lake has become a sediment sink for about 1.35 ± 0.7 Mt annually, thereby reducing the annual sediment transport to the Mekong delta. This reduction in sediment supply compounds the threat to the delta from accelerated subsidence and sea level rise (Pokhrel et al., 2018; Syvitski and Higgins, 2012). Decreased sediment loads to the delta and altered sediment transport processes will impact numerous livelihoods which depend on ecosystem services (Kondolf et al., 2018). The sudden change appears to be due to increased TSS concentrations from the Mekong to Tonle Sap Lake. The concentration of TSS in Kratie appears to have been largely unchanged, but the river could have picked up sediment as it overflowed the wide floodplain, used for agriculture and thus exposed to erosion without the protection of native vegetation (Chea et al., 2016). The instream TSS levels in the lower part of the Mekong River are likely influenced by the interaction between land use/land cover, rainfall-runoff, and anthropogenic activities within the basin (Ly et al., 2020).

The Tonle Sap Compared with Other Lake-Channel Systems

The Tonle Sap is an example of a lake-channel system, a lake (usually on a floodplain) that connects with a main river (via defined channels as well as overbank flow), and that absorbs flood peaks and releases waters gradually back into the main river as flood stage recedes. Retaining

floodwaters in the lake for extended periods of time can result in substantial deposition of sediment from suspension, with potentially significant influences on the riverine sediment budget. Thus, we can ask how the Tonle Sap system compares with other major lake-channel systems, such as Dongting Lake on the Yangtze River floodplain, the second largest freshwater lake in China, and the channel-floodplain systems of the Amazon River.

The Dongting Lake- Yangtze River system is similar to the floodplain lake-channel exchanges of TSL and Mekong River, in that Dongting Lake plays an important role in regulating flood stage and is an important sink of sediments. In flood season water pours into Dongting Lake through three natural distributary channels from the Yangtze (just downstream of its exit from Three Gorges onto the broad alluvial plain) to Dongting Lake. Unlike the Tonle Sap system, when Dongting Lake drains, it does not flow back through the same channel to the river, but drains through different channels back to the river when river stage declines. (Thus, the lake and its connecting channels function as a flood bypass and backwater.) The Yangtze River and Dongting Lake are strongly influenced by operation of The Three Gorges Project upstream. In addition to an important flood-flow-regulating function, Datong Lake functions as sediment sink, receiving 110 Mt/yr from the Yangtze River, while losing only 39 Mt/yr via return flow back to the Yangtze (Dai et al., 2017). The area of Dongting Lake has been reduced over the centuries by construction of dykes to protect farmland encroaching onto the fertile lake bottom during dry years between big floods, a problem that was documented at least back to the Ming Dynasty and continued through the 20th century (Perdue, 1982).

The Amazon is characterized by strong exchanges of water, sediment, nutrients, and biota between channel and its extensive floodplains. The Lago Grand de Curuai' floodplain is a complex system of more than 30 interconnected lakes, linked to the Amazon River by several channels, two of which (both with permanent flow) carry return flow from the floodplain into the mainstream (Bourgoin et al., 2007). Lago Grand de Curuai' floodplain is a sediment sink, with more than 80% of the suspended solids entering the floodplains deposited (Mertes et al., 1996), but the water storage in the floodplain is more transient than that of the Tonle Sap Lake system, which contributes baseflow back to Mekong River and delta through most of the dry season, as demonstrated in our analysis. On the Amazon floodplain, sediment accumulation (simulated deposition rate is of about $0.3 \text{ Mt km}^{-1} \text{ yr}^{-1}$) occurs during the five months of the flood rise, and

export of sediments to the mainstream occurs during the recession limb of the seasonal hydrograph (Bourgoin et al., 2007; Mangiarotti et al., 2013).

Thus, the channel-floodplain systems of the Amazon River can act as important sinks of sediments, not only via channelized flow to the Lago Grand de Curuai´ complex, but also via diffuse overbank flow. However, unlike the Amazon, most of the Mekong’s course follows a narrow bedrock-controlled path, so there is very limited exchange of sediment between channel and floodplain, until the reach downstream of Kratie, where the floodplains of the Cambodian lowlands and the Mekong delta are inundated, allowing important fluxes of material and energy between the floodplain and mainstem river channel (Gupta and Liew, 2007). With its channel sized reverse flow pattern, combined with broad, shallow lateral inundation of floodplains during the wet season, the Tonle-Sap-Mekong exchange represents a uniquely developed and important channel-floodplain exchange. In fact, the Mekong-Tonle-Sap exchange is arguably among the best developed such river-floodplain-lake exchange systems in the world, and it supports a fishery that is globally exceptional in many respects (Campbell et al., 2009).

5. Conclusion

The study assessed temporal variability of sediment loads in Lower Mekong River in Cambodia and the sediment linkage between Tonle Sap Lake and Mekong River from 1993 to 2017. Sediment load in the main Mekong River averaged 72 ± 38 Mt at Kratie and 78 ± 22 Mt at Chroy Changvar from 1993-2018, showing a significant decrease in sediment load, consistent with trends documented in other major rivers in the region and globally. The seasonal and annual sediment load linkage between the Mekong mainstem and Tonle Sap Lake are controlled principally by suspended sediment concentrations and water discharge, in both the reverse flows into the lake and outflows from the lake, both via the Tonle Sap River. The annual water inflow to the lake via reverse flow was 36 km^3 , while outflow to the Mekong was 68 km^3 . The great water outflow can be attributed to runoff from the Tonle Sap Lake basin and also flows across the floodplain lying to the west of the Mekong River. TSS concentrations of the reverse flows to TSL from Mekong river were nearly twice the concentrations of the outflow from TSL, resulting in a net transfer of sediment into the Lake. The net sediment loads averaged 3.7 Mt in reverse flows into Tonle Sap

Lake, 2.9 Mt/yr in flows from the lake to Mekong River. We found Tonle Sap Lake provided 0.65 ± 0.6 Mt of net sediment to the Mekong annually from 1995 to 2000, but was a sediment sink for an average of 1.35 ± 0.7 Mt annually from 2001 onwards. The change pattern of sediment load linkage can be attributed to a trend of increased TSS concentrations from the Mekong to Tonle Sap Lake. This change in sediment concentration constitutes the most important variable in explaining sediment linkages between the Mekong River and Tonle Sap Lake. This study helps clarify the sediment exchange between Mekong River and Tonle Sap Lake and reveals an important change since 2001, with implications for the sustainability of the delta.

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