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1	Nutrient Transport and Exchange between the Mekong River and Tonle Sap Lake in
2	Cambodia
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Abstract: The Mekong River in Asia is one of the world's longest rivers. Although it has some of the highest levels of biodiversity and productivity in Asia, the water quality in the basin has recently deteriorated as a consequence of land use changes, dam reservoir construction, population growth, and climate change. For the first time, this study estimates the interannual and monthly variabilities of nutrient fluxes (nitrate - NO₃⁻) and total phosphorus - TP) in the lower Mekong River and Tonle Sap River in Cambodia, and assesses the nutrient linkage between the them. Long-term monitoring data were obtained from Kratie station (in the upper reach of the Mekong River), Chroy Changva station (just upstream of the lower Mekong River-Tonle Sap River confluence), and Prek Kdam station (on the Tonle Sap River ~40 km upstream of the confluence and 70 km downstream of Tonle Sap Lake). From 1995 to 2017, the estimated interannual flux of NO₃⁻ was 364 \pm 45 kt/y at Kratie and 557 \pm 109 kt/y at Chroy Changva. From 2005 to 2017, the estimated interannual flux of TP was 100 \pm 16 kt/y at Kratie and 73 \pm 19 kt/y at Chroy Changva. Considerable seasonal differences were observed in both fluxes in the Mekong River, with 80–90% of the annual NO_3^- flux occurring from May to October. The results of the nutrient exchange budget indicated that the NO₃⁻ and TP fluxes from the Mekong River into Tonle Sap Lake were \sim 35.8 ± 12.5 kt/y and \sim 8.7 ± 3.3 kt/y, respectively, while these were 34.0 ± 13.8 kt/y and 6.6 ± 1.4 kt/y, respectively, from Tonle Sap Lake into the Mekong system. The results demonstrate that the Mekong River is a vital nutrient source, especially during the flood season, to Tonle Sap Lake and its floodplain. Keywords: Nutrient Transport, Mekong River, Tonle Sap Lake

58 1. Introduction

One of the largest transboundary rivers in Asia and the world, the Mekong River (MK), 59 60 originates in the Tangelo Mountain range of the Tibetan region of China. It flows through six nations: China, Cambodia, Lao People's Democratic Republic, Myanmar, Thailand, and 61 Vietnam before it enters the South China Sea in Vietnam. The physical diversity, tropical 62 location, and high productivity of the Mekong River has allowed it to become the second most 63 species rich river after the Amazon River (Froese and Pauly, 2010). There are at least 1200 64 species of fish, and potentially up to 1700, living in the Mekong River basin as a result of its 65 geological and hydrological heterogeneity (Coates et al., 2005). Lower Mekong River is the 66 most essential region both economically and environmentally and has about 60 million 67 inhabitants dependent on its water resources (MRC, 2010). Located in the Lower Mekong 68 River in Cambodia, the Tonle Sap Lake (TSL) is a productive ecosystem and the most diverse 69 70 and highest yielding in inland fisheries in the world. It is supported by the sediment and 71 sediment-bound nutrients from the annual flood pulse of the Mekong River (Lamberts, 2006). 72 The Mekong Delta is an Asian center of biodiversity and rice production and supports a population of more than 17 million people (Szabo et al., 2016). The agricultural, ecological, 73 74 and fish productivity of the Lower Mekong River, particularly Tonle Sap Lake and the Mekong Delta can be largely attributed to the seasonal delivery of water, sediments, and nutrients by 75 76 the Mekong River (Arias et al., 2014; Kummu et al., 2008; Lamberts, 2006).

77 Despite the significance of the Mekong River to biodiversity and productivity of the region, its water quality has recently deteriorated as a consequence of land use changes, reservoir 78 construction, population growth, and meteorological extremes (Chea et al., 2016; Campbell, 79 2009; Dudgeon, 2005). The construction of dams on the Upstream Mekong River has led to 80 81 the significant trapping of sediments and nutrients (Kummu and Varis, 2007; XX Lu and Siew, 2006), e.g Manwan dam in 1992 and Dachaoshan in 2003. The Mekong River is experiencing 82 dramatic land surface disturbances, such as forest clearing and arable land expansion, as a result 83 of rapid population growth and expanding urbanization (Lu and Siew, 2005). Land-use change 84 in the region is accelerating element cycling and appreciably altering riverine and estuarine 85 86 ecosystems, which is evident in dramatic shifts in the supply of nutrients (Li et al., 2015). Changes in sediment and nutrient supplies are of particular concern in the tropical regions that 87 have been undergoing rapid development (change of land cover and dam development) since 88 the 1990s, where they have impacted biodiversity and the long-term stability of Tonle Sap lake 89 90 and the Mekong Delta (Campbell, 2007; Tamura et al., 2007). In the Mekong sub-region, such

as Myanmar, Laos, Cambodia, Vietnam, Thailand, and Yunnan Province, China, karst area is 91 widely spread. Geomorphological features in southwest China, including Lancang River Basin 92 upstream of Mekong River, are characterized by multiple mountains and plateaus, widely 93 distributed karst and red clay hills, deep canyons, and gorges (Kiernan, 2011). Topographically 94 impressive karst is widespread in Laos which is the main area of Mekong River basin (Kiernan, 95 96 2015). Karst landforms result in uneven distribution of water resources and diverse ecological environment. Karst soils are typically thin, patchy, and fragile to disturbances, easily causing 97 98 losses of nitrogen and phosphorus leached from those soils (Fenton et al., 2017). Nutrient 99 contamination associated in karst systems is most often associated with agricultural practices, 100 in particular fertilizer application and animal wastes (Stueber and Criss, 2005; Perrin et al., 2003; Croll and Hayes, 1988). 101

Compared with other rivers in Asia, such as the Ganges and Yangtze rivers, the annual nitrogen 102 103 (N) load in the Mekong River has been low in the 20th century (Seitzinger et al., 2005). 104 However, the nutrient balance of the Mekong River is currently disrupted owing to significant increases in nutrient inputs to surface water from agricultural production and infrastructure 105 development (Liljeström et al., 2012; Galloway et al., 2004; MRC, 2003). Iida et al. (2011) and 106 107 Ribolzi et al. (2011) reported high nutrient concentrations (nitrate (NO₃⁻) and phosphate (P)), nitrogenous matter, and total suspended sediment (TSS) in the upper reach of the Mekong River 108 109 in the northern part of Laos People's Democratic Republic. Watanabe et al. (2003) also highlighted the disturbance of the N balance in southern Vietnam, which was likely caused by 110 agricultural development. On an entire system scale, Li et al. (2015) examined the spatial, 111 monthly, and interannual fluxes of nutrients and stoichiometric ratios in the Mekong River for 112 the period 1985–2011. Kummu and Varis (2007) found that dam construction in the upstream 113 region of the Mekong River had led to the significant trapping of sediments and nutrients, 114 which could reduce the fertility of the Tonle Sap system. Considering that the sediment input 115 from the Mekong river is crucial for the ecosystem functioning of Tonle Sap Lake (Arias et al., 116 2014), it is necessary to gain a better understanding of the sediment and nutrient linkages 117 between the mainstream part of the Mekong River and Tonle Sap Lake. The sediment exchange 118 between Tonle Sap Lake and the Mekong River was previously estimated by Kummu et al. 119 (2008), Lu et al. (2014), and Sok et al. (2021). Kummu et al. (2008) studied the sediment load 120 during 1997-2003 and showed that Tonle Sap Lake acted a sink for sediments from the 121 Mekong River. In contrast, Lu et al. (2014) found that Tonle Sap Lake was a sediment source 122 123 to the river during 2008–2010. A recent study by Sok et al. (2021) indicated that Tonle Sap

Lake provided 0.65 ± 0.6 Mt/y of sediment to the lower Mekong River from 1995 to 2000, while the lake become a sink for sediment from 2001 to 2018. However, there is still a need for studies on the long-term nutrient transport dynamics of the system as baseline data and on the linkage between the mainstream part of the Mekong River and the Tonle Sap River.

To address the gap in knowledge, it is crucial to develop an understanding of the changing 128 nutrient fluxes in the lower Mekong River. In particular, it is necessary to estimate the nutrient 129 130 exchange between Tonle Sap Lake and the Mekong River through the Tonle Sap River and their individual nutrient inputs into the Mekong Delta over a long-term period under different 131 hydrological conditions. Accordingly, this study estimates the annual and monthly transport 132 dynamics and nutrient fluxes (NO₃⁻ and TP) in the Mekong River and Tonle Sap River in 133 134 Cambodia, and then quantifies the annual and monthly NO_3^- and TP fluxes from the Mekong River and Tonle Sap Lake into the Mekong Delta through the hydrological reversal system. 135

136 **2.** Materials and Methods

137 **<u>2.1 Study area</u>**

The Mekong River spans a total length of 4800 km and drains an area of 795 000 km². It has a 138 mean annual water discharge of 470 km³, making it one of the largest rivers in the world (XX 139 Lu and Siew, 2006). By convention, the Mekong River basin is divided into two sub-basins: 140 The Upper Mekong River basin (24% of the total drainage area) and the Lower Mekong River 141 basin (76% of the total drainage area). The distinguished two main sub-basins are illustrated in 142 143 Figure 1a. The climate of the Mekong River basin is dominated by the Southwest Monsoon, 144 which generates rainy and dry seasons of more or less equal length. The monsoon season usually lasts from May until October. Annual average rainfalls over the Cambodian floodplain 145 146 and the Vietnamese delta are equally low and less than 1,500 mm. Elsewhere, the highest rainfalls are as expected-in the Central Highlands and within the mainstream valley at the 147 middle part of Lao. In the warmest months of March and April, the average temperature ranges 148 from 30°C to 38°C. Rainy season means temperatures decrease significantly from south to 149 north, from 26°-27°C in Phnom Penh to 21°-23°C in Thailand northern part. The Mekong 150 River's average discharge to the sea is about 15,000 m³/s (Adamson et al., 2009; Gupta and 151 152 Liew, 2007).

153 Tonle Sap Lake and the Tonle Sap River are located in central Cambodia (Figure 1b). They 154 are a sub-catchment of the Mekong River and an integral part of the system. The lake is the 155 largest permanent freshwater body in Southeast Asia and is an important natural reservoir for

the Mekong River. The lake covers an area of 2 500 km² in the dry season and 16 000 km² in 156 the wet season. It extends over 300 km from northwest Cambodia to the Mekong River at 157 Phnom Penh by the Tonle Sap River. Tonle Sap Lake has a unique hydrological system 158 characterized by a flood pulse from the Mekong River. The Tonle Sap River flows from the 159 southeastern end of Tonle Sap Lake and joins the Mekong River at the Chaktomuk confluence 160 at Phnom Penh (Figure 1c). The water from the Mekong River flows up to the Tonle Sap River 161 to fill Tonle Sap Lake and its floodplain during the rainy season (May–October). During the 162 dry season (late October-April), the water starts flowing back from Tonle Sap Lake to the 163 164 Mekong River by crossing the Tonle Sap River. This phenomenon occurs annually in late May/early June. In September/October, when the water level in the Mekong River starts to 165 recede, this stored water starts to drain back into the lower Mekong and Bassac Rivers (Fujii 166 et al., 2003; Masumoto et al., 2001). The lake receives most of its water from the Mekong 167 mainstream; thus, the lake's water level is directly controlled by the water level of the Mekong 168 River (Kummu et al., 2014). Besides the water from the Mekong River, Tonle Sap Lake 169 receives water from its drainage basin through 11 local tributaries for about 34% of the total 170 inflow (Kummu et al., 2014). Every hydrological cycle, the 11 local tributaries contribute 171 inflow to the lake for approximately six months, generally from November to May. Along with 172 173 the inflow, they act as annual sediment sink of nutrients supplying the Tonle Sap Lake system (Sok et al., 2021; Kummu et al., 2008). 174

Figure 1. Map of the study site: (a) Mekong River basin, (b) sampling sites along the
 Mekong and Tonle Sap rivers, and (c) flow directions and reverse flow at Chroy Changva site
 near Chaktomuk confluence at Phnom Penh

179 **2.2 Water discharge and nutrient data**

180 Nutrient data and daily water discharge were obtained from the Ministry of Water Resources and Meteorology (MOWRAM) of Cambodia under the Mekong River Commission (MRC) 181 framework: Water Quality Monitoring Network (WQMN) at the three sites in the Lower 182 Mekong River of Cambodia (Table 1). The monitoring sites started from the upstream site of 183 the Mekong River of Cambodia at Kratie moving to the Chroy Changva (near Chatumuk 184 confluence) to capture the water discharge and quality before the water changes course to the 185 Tonle Sap River and Mekong Delta. Prek Kdam station, located along the Tonle Sap River, 186 was included in the study since this station can represent the reverse system of the Mekong-187 Tonle Sap system (Figure 1c). 188

This study used NO₃-N and TP concentration data. Data in the Water Quality Monitoring Network (WQMN) database relate to water samples collected at a depth of 0.3–0.5 m below the water surface in the middle of the river cross-section where free flowing water was observed at each station. For consistency, water quality was determined between the day 13 and day 18

of each month (Kongmeng and Larsen, 2016). The water sampling, sample preservation, 193 sample transportation, and sample storage (Kongmeng and Larsen, 2016) were carried out in 194 accordance with the methods outlined in the 20th edition of the Standard Methods for the 195 Examination of Water and Wastewater (Clesceri et al., 1998). The samples were analyzed at 196 designated laboratories by the Mekong River Commission (MRC) using the recommended 197 analytical methods (2540-D-TSS-SM for TSS, 4500-NO₂₋₃/SM for NO₃, and 4500-P/SM for 198 199 TP) (Kongmeng and Larsen, 2014). These data were confirmed to be of satisfactory quality by 200 Hedlund et al. (2005) and Li et al. (2015).

201 The studies of the nutrient fluxes of the Asian Monsoon Rivers also used monthly data. For example, Gong et al. (2015) studied the seasonal variation of dissolved nutrients in the Yellow 202 River using monthly sampling. Nutrient discharge of the Yangtze River by Tong et al. (2017) 203 204 was also based on monthly sampling. Even in the studies of many rivers' nutrient fluxes and 205 budgets of China's estuaries, such as the studies of Liu et al. (2009) and Wu et al. (2019), the 206 analyses were based on monthly data. These studies indicate that monthly nutrient data is a 207 satisfactory and reliable method of estimating both seasonal and annual nutrient fluxes and budgets of major rivers, including the Mekong River. 208

209 Flow and nutrient analysis were calculated based on the hydrological year: from the 1st of May 210 to the 30th of April the next year (Kummu et al., 2014; Kummu and Sarkkula, 2008). Thus, our 211 period of record analyzed by hydrological year is one year shorter than period of available data expressed in calendar years (i.e., the calendar year is 1995-2017; thus, the study expressed as 212 the hydrological year 1995-2016). At Prek Kdam, the observed value of water discharge and 213 water quality parameters were distinguished to positive and negative responses corresponding 214 to the two opposite flow directions of Tonle Sap River. In this study, the negative values of 215 water discharge and water quality parameters are inflow into the Tonle Sap Lake from the 216 Mekong River, while positive values correspond to the outflow from the Tonle Sap Lake 217 towards the Mekong River. 218

Table 1. Data coverage period and the number of nutrient records and water discharge data
used in the study.

Locations	Nitrate (NO	93-N)	Total phosp	Discharge	
Locations	Number of samples	Data coverage	Number of samples	Data coverage	Data coverage
Kraite	235	1995-2017	133	2005-2017	1995-2017

Chroy Changva		243	1995-2017	136	2005-2017	2005-2017
Drok V dom	Tonle Sap towards Mekong	153	1997-2017	95	2005-2017	1997-2017
Flek Kualli	Mekong towards Tonle Sap	64	1997-2017	40	2005-2017	1997-2017

2.3 Nutrient flux estimation 222

Nutrient fluxes were estimated by using the LOAD ESTimator (LOADEST) model (Runkel et 223 al., 2004). LOADEST incorporates daily discharge, seasonality, and measured constituent data 224 to parameterize a multiple-regression model that allows a continuous time series to be 225 226 estimated from discrete measurements (Hanley et al., 2013; Bouraoui and Grizzetti, 2011b). LOADEST calculates fluxes by applying the method of adjusted maximum likelihood 227 228 estimation while eliminating collinearity by centering discharge and concentration data. The regression model is automatically selected from one of nine predefined regression models to 229 230 fit the data based on the Akaike Information Criterion (Johnston et al., 2018). Flux estimation considers datasets of at least 120 observations (Hirsch, 2014), thus our dataset is validated. 231 232 LOADEST has previously been used to estimate fluxes in major rivers by Sun et al. (2013) in the Yangtze River with monthly N and TP concentration and daily streamflow data, by Hanley 233 et al. (2013) in temperate North American rivers with monthly water quality parameters, and 234 235 by Bouraoui and Grizzetti (2011a) in rivers discharging to European seas with monthly nutrient data. In our study, LOADEST was used to extrapolate the monthly NO3⁻ concentration 236 measurements to daily nutrient loads with the following regression models: 237

- (1) $\ln L = a_0 + a_1 \ln Q$ 238
- (2) $\ln L = a_0 + a_1 \ln Q + a_2 dtime$ 239

(3) $\ln L = a_0 + a_1 \ln Q + a_2 \ln Q^2 + a_3 \sin(2\pi . dtime) + a_4 \cos(2\pi . dtime) + a_5 dtime + a_6 . dtime^2$ 240

where L is the constituent load, a_{0-6} are coefficients obtaining from LOADEST, and Q is 241 streamflow (daily). 242

Results 243 3.

3.1 Nutrient concertation variations in the Lower Mekong River 244

The hydrograph of the daily water discharge and observed monthly water quality at Kratie and 245 246 Chroy Changva showed obvious variations during the study period from 1995-2017 (Figure 2) for NO₃⁻ concentrations and 2005-2017 for TP concentrations (Figure 3). At Kratie, the 247

maximum discharge reached about 58 000 m³/s in the rainy season of 1996, while minimum 248 discharge was 1 073 m³/s in the dry season of 1995. At Chroy Changva, the maximum 249 discharge was 40 500 m^3 /s in the rainy season of 2014, and the minimum discharge was 405 250 m^{3}/s in the dry season of 1995. The concentrations of NO₃⁻ and TP observed at both stations 251 252 were nearly equal (Table 2). NO₃⁻ concentrations averaged 0.67 ± 0.43 mg/L (from 0.02-1.86 mg/L) at Kratie and 0.67 ± 0.47 mg/L (from 0.01-2.21 mg/L) at Chroy Changva. The average 253 254 TP concentration was 0.11 ± 0.09 mg/L (from 0.01-0.32 mg/L) at Kratie and 0.10 ± 0.08 mg/L (from 0.01-0.35 mg/L) at Chroy Changva. The concentrations of both NO₃⁻ and TP were 255 256 generally high during high discharge and low during low discharge; thus, concentrations exhibit strong seasonal variations. 257



Figure 2. Variation of daily water discharge and NO₃⁻ concentration at (a) Kratie and (b)
 Chroy Changva from 1995 to 2017. The arrow indicates the major dams operating year in the
 Upper Mekong part.



Figure 3. Variation of daily water discharge and TP concentration at (a) Kratie and (b) Chroy
 Changva from 2005 to 2017.

265

Table 2. NO₃⁻ and TP concentration at Kratie and Chroy Changva

	Krat	tie	Chroy Changva		
-	NO3 ⁻ (mg/l)	TP (mg/l)	NO3 ⁻ (mg/l)	TP (mg/l)	
Min	0.02	0.01	0.01	0.01	
Max	1.86	0.32	2.21	0.35	
Mean	0.67	0.11	0.67	0.10	
STDEV	0.43	0.09	0.47	0.08	

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267 <u>3.2 Nutrient concentration variations in the Tonle Sap River</u>

The Prek Kdam station recorded flow and nutrient concentrations for the Tonle Sap River, which connects Tonle Sap Lake and the Mekong River (Figure 4). The water discharge and water quality data that represent the reverse system of the Tonle Sap River were also recorded at the Prek Kdam station. From the observed water discharge at Prek Kdam, the reverse system

started to change direction from Tonle Sap Lake towards the Mekong River in October. 272 Generally, water flow from the Mekong River into Tonle Sap Lake lasted from 70 to 157 days 273 per year or, on average, 118 days per year between late May and the end of September. Flow 274 in the opposite direction from Tonle Sap Lake towards the Mekong River varies annually from 275 209 to 295 days or, on average, 247 days per year in between October and April/May. The peak 276 inflow discharge into the lake generally occurred in July and August, while the periods of peak 277 discharge from the Mekong River occurred in August and September at the Chroy Changva 278 station. Otherwise, peak outflow from the lake to the Mekong River mainly took place a few 279 280 months later, from October to December. During the observed period from January 1997 to 2017, maximum inflow discharge into the lake was 10 680 m^3/s . Regarding the outflow water 281 from the Tonle Sap Lake, the maximum water flowing out from the lake was 10 100 m³/s. The 282 lowest water discharge flowing into the lake regularly appeared in late May when the water 283 level in the Mekong River was higher than Tonle Sap Lake. The water started to change flow 284 285 direction from the Mekong to the lake in September when the water in the lake reached the highest level and the largest volume, therefore, the lake's water level was equal to the Mekong 286 River's and the lake received less inflow water from the Mekong River. 287

288 To understand the behavior of nutrient concentrations in the inflow/outflow of the lake, the observed nutrient concentrations were calculated basic statistic inflow and outflow separately. 289 290 Due to data availability, we used observed NO₃⁻ concentrations from 1997-2017 and observed 291 TP concentrations from 2005-2017. In terms of water quality in the flow from Tonle Sap Lake towards the Mekong River, NO₃⁻ concentration was 0.81 ± 0.77 mg/L (from 0.02-3.4 mg/L) and 292 TP concentration was 0.11 ± 0.07 mg/L (from 0.01-0.33 mg/L). For flow from the Mekong 293 towards Tonle Sap Lake, NO₃⁻ concentration was 0.98 ± 0.67 mg/L (from 0.04-2.9 mg/L) and 294 TP was 0.16 ± 0.1 mg/L (from 0.02-0.43 mg/L). On average, nutrient concentrations from the 295 Mekong River to Tonle Sap Lake were higher than from the lake to the Mekong River (Table 296 297 3).



298

Figure 4. Variation of daily water discharge and nutrient concentration at Prek Kdam, (a)
 NO3⁻ concentration from 1997-2017, and (b) TP concentration from 2005-2017. Positive
 values correspond to the lake outflow, while negative values are lake inflow (reverse flow).

Table 3. NO₃⁻ and TP concentration at Prek Kdam.

	Tonle Sap Lake to	wards Mekong	Mekong towards Tonle Sap Lake			
	NO3 ⁻ (mg/l)	TP (mg/l)	NO ₃ ⁻ (mg/l)	TP (mg/l)		
Min	0.02	0.01	0.04	0.02		
Max	3.40	0.33	2.90	0.43		
Mean	0.81	0.11	0.98	0.16		
STDEV	0.77	0.07	0.67	0.10		

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304 **<u>3.3 Temporal variability of nutrient flux in the Mekong River</u>**

The variability of monthly (accumulation per month) NO_3^- and TP flux have been employed at both Kratie and Chroy Changva station (Figure 5 and Figure 6). The peak values of NO_3^- and

TP flux occurred in August and September, corresponding to the peak runoff period. The 307 maximum monthly NO_3^- fluxes at Kratie and Chroy Changva were about 85×10^3 tons and 308 138×10^3 tons (kt), respectively. Maximum TP flux was approximately 28 kt/month at Kratie 309 and 18 kt/month at Chroy Changva. Moreover, the lowest fluxes appeared in low runoff periods 310 from February to March with less than 5 kt of NO₃⁻ and 2 kt of TP flux. Overall, monthly NO₃⁻ 311 flux at Chroy Changva was higher than at Kratie, whereas monthly TP flux at Chroy Changva 312 was lower than at Kratie. Furthermore, the monthly runoff in the rainy season at Kratie was 313 higher than at Chroy Changva. The downstream reduction in gauged flow at Kratie and Chroy 314 315 Changva occurred mainly at higher flows and can be attributed to overland flow from the Mekong River traversing the floodplain to the Tonle Sap Lake and by flow into major 316 distributaries between Kratie and Chroy Changva. MRC (2019) reported in their observed 317 flows for the Mekong mainstream stations over the period 2000-2017 from Stung Treng 318 (Cambodia-Laos border, about 150 km upstream of Kratie). Sok et al. (2021) mentioned that 319 during the flood season, water starts to spillover both banks of the Mekong River between 320 upstream of Kompong Cham (150 km upstream of Chroy Changva) and the Chroy Changva 321 station. Part of the water spilling over the right bank reaches the Tonle Sap Lake as overland 322 flow. This overland flow was reported to average 2,500 Mm³/y by Lu et al. (2014). On the left 323 324 bank of the main river, part of the Mekong River flow is diverted into the Tonle Toch River, which then discharges back into the Mekong River further downstream of Chroy Changva in 325 326 the Mekong delta. Sok et al. (2021) found that the flow distribution at Kratie and Chroy Changva confirmed the downstream reduction in gauged flow at Chroy Changva occurring at 327 328 higher flows.





Figure 5. Monthly variation of NO₃⁻ flux and monthly water discharge at Kratie and Chroy
 Changva. (mean, standard deviation value, minimum and maximum)







Figure 6. Monthly variation of TP flux and monthly water at Kratie and Chroy Changva. (mean, standard deviation value, minimum and maximum).

The annual water discharges, NO₃⁻ and TP fluxes at Kratie and Chroy Changva are presented 335 in Figure 7. On average, the annual water yield in Kratie was 40,400 million m^3/y (Mm³) and 336 was higher than the annual water discharge at Chroy Changva $(3,700 \text{ Mm}^3)$. The NO₃⁻ flux 337 results demonstrate two things. Firstly, NO₃⁻ flux in Kratie keeps a slightly constant pattern, in 338 particular, from the year 2002 to 2016. Second, NO₃⁻ flux in Chroy Changva continuously 339 340 fluctuated over the study period 1995-2017. NO₃⁻ flux at Kratie has low variability (272-441 kt/y) compared to the Chroy Changva station (380 to 739 kt/y). The annual TP fluxes in Kratie 341 342 and Chroy Changva fluctuated over the study period from 77-137 kt/y for Kratie and 46-116 kt/y for Chroy Changva (Figure 8). On average, NO₃⁻ flux was estimated at about 364 kt/y and 343 344 557 kt/y, and TP was approximately 100 kt/y and 73 kt/y at Kratie and Chroy Changva, respectively (Table 4). It is interesting to note that annual NO₃⁻ flux at Chroy Changva was 345 346 higher than flux at Kratie, even though the water discharge at Chroy Changva was less than at Kratie. However, TP flux differed from values for NO₃⁻, and less was found at Chroy Changva 347 than at Kratie. To be discussed, the flux results for NO_3^- and TP had a tendency to be opposite 348 between Kratie and Chroy Changva. This contrast signifies two key points; NO3⁻ and 349 phosphorus are different in dynamic across the basin, and a large amount of water discharge 350 does not always transport a large amount of nutrients. 351



Figure 7. Annual NO₃⁻ flux dynamics in the Mekong River for the period of 1995 to 2016 (a)
at Kratie and (b) at Chroy Changva.



Figure 8. Annual TP flux dynamics in the Mekong River for the period of hydrological year
through hydrological year 2005 to 2016 (a) at Kratie and (b) at Chroy Changva.

Table 4. Annual NO₃⁻ and TP flux dynamics in the Mekong River for the period of 1995 to
 2016 at Kratie and Chroy Changva

	K	Cratie			Chroy Changva			
	Water Discharge	NO3 ⁻ Flux	TP Flux		Water Discharge	NO3 ⁻ Flux	TP Flux	
	(Million m ³ /year)	(kt/year)			(Million m ³ /year)	(kt/year)		
Mean	401 812	364.08 100.45			369 762	557.38	72.74	
Min	255 561 272.46 77.06			249 279	378.72	46.08		
Max	531 813	441.31	137.27		479 066	739.15	116.06	
STDEV	72 106	45.39	15.89		62 099	109.47	19.37	

361 <u>3.4 Temporal variations in the inputs/outputs of water and nutrients from Tonle Sap</u> 362 Lake

To assess the temporal variations in the exchange of nutrients between Tonle Sap Lake and the 363 Mekong River, it is very important to understand the inflow and outflow of lake water to the 364 Mekong River. In general, with the timing and magnitude of flow, the Mekong River provides 365 less water to Tonle Sap Lake than it receives. Inflow to the lake from the Mekong River starts 366 in May or very early June, whereas flow reversal occurs in October (Figure 9). The seasonal 367 variations in the fluxes of NO₃⁻ and TP from the Tonle Sap River were calculated to represent 368 opposite flow directions; from Tonle Sap Lake towards the Mekong River and from the 369 Mekong River towards Tonle Sap Lake (Figure 10). Generally, nutrient fluxes into Tonle Sap 370 371 Lake were observed during the rainy season (May–October), corresponding to flow discharge from the Mekong River to the lake, while the reverse flux was observed in the dry season 372 373 (October–May). The estimated monthly fluxes of NO₃⁻ and TP from Tonle Sap Lake into the 374 Mekong River were 0.4–1.84 kt and 0.06–0.18 kt, respectively, with the peak nutrient fluxes observed in August. The estimated monthly fluxes of NO₃⁻ and TP from the Mekong River to 375 the lake were 0.88–1.72 kt and 0.04–1.14 kt, respectively. Thus, the TP flux from the Mekong 376 377 River into Tonle Sap Lake reached considerably higher values than that from the lake to the Mekong River. 378



Figure 9. Monthly variation in water discharge between the Mekong River and Tonle Sap
Lake at Prek Kdam from 1997 to 2017 (mean, standard deviation, minimum, and maximum)

379



Figure 10. Monthly variations in the (a) NO₃⁻ flux (1997–2017) and (b) TP flux (2005–2017)
at Prek Kdam (mean, standard deviation, minimum, and maximum)

The results of the annual water balance revealed that Tonle Sap Lake contributed ~36 000 Mm³ 385 of water to the Mekong River during the low-flow season from October to May. The cumulative 386 seasonal water volumes are presented in Figure 11, whereby negative values indicate a reverse 387 flow from the Mekong River to Tonle Sap Lake, and positive values indicate outflow from the 388 lake to the Mekong River. The mean seasonal outflow from the lake was 68 000 Mm³, 389 corresponding to 18% of the total annual discharge of the Mekong River at Chroy Changva. 390 The mean seasonal reverse flow into the lake from the Mekong River was 36 000 Mm³, 391 corresponding to ~10% of the total annual discharge of the Mekong River at Chroy Changva. 392 Moreover, Lu et al. (2014) estimated that approximately 2500 Mm³ of water spilled over the 393 right bank and reached Tonle Sap Lake as overland flow. Thus, the outflow from the lake was 394 almost twice the reverse flow from the Mekong River, both via channel flow and overland 395 396 flow.

The average annual NO_3^- and TP fluxes from Tonle Sap Lake to the Mekong River were approximately 33.96 ± 13.77 kt/y and 6.55 ± 1.37 kt/y, respectively. The estimated NO_3^- and TP fluxes to the lake from the Mekong River were 35.76 ± 12.47 kt/y and 8.67 ± 3.34 kt/y, respectively (Figure 12). These results indicate that Tonle Sap Lake received higher annual fluxes of NO_3^- and TP from the Mekong system than it provided to the Mekong River.



403 Figure 11. Seasonal water discharge exchange between Tonle Sap Lake and the Mekong
404 River through the Tonle Sap River at Prek Kdam from 1997 to 2017



Figure 12. Seasonal NO₃⁻ and TP fluxes between Tonle Sap Lake and the Mekong River
through the Tonle Sap River at Prek Kdam. (a) Seasonal NO₃⁻ flux from 1997 to 2016 and (b)
seasonal TP flux from 2005 to 2016

409 <u>3.5 Changes in the nutrient exchange between Tonle Sap Lake and the Mekong River</u>

Tonle Sap Lake received less water than it contributed to the Mekong River system, except in 410 2004. This was because the Mekong River at Chroy Changva reached its maximum discharge 411 of 60 000 Mm³ in 2004, while the mean discharge was 36 000 Mm³. The annual water balance 412 showed that, during the low-flow season, Tonle Sap Lake generally contributed ~65 000 Mm³ 413 414 (i.e., 18% of the total annual discharge of the Mekong River) of water to the Mekong River and Mekong Delta (Figure 13). Even though the Mekong River has been reported to provide 415 416 water and a potential source of nutrients to the lake through overland flow during the peak flow period (~2500 Mm³), the present study only investigated the amount of nutrients exchanged 417 through the channel of the Tonle Sap River. 418

- To comprehensively understand whether the lake gained or lost nutrients during each 419 hydrological year, the seasonal NO₃⁻ and TP fluxes of the Tonle Sap River inflow/outflow were 420 subtracted each other. During 2000–2012, the NO_3^- flux into the lake from the Mekong River 421 was higher than the outflow flux from the lake (Figure 13). This means that Tonle Sap Lake 422 acted as a sink for NO₃⁻ during 2000–2012 and as a sink for TP during 2007–2015. Based on 423 the analysis of NO₃⁻ during 1997–2016 and TP during 2005–2016, Tonle Sap Lake contributed 424 425 34 kt/y of NO₃⁻ and 6.6 kt/y of TP to the Mekong system or delta, while the Mekong River contributed 35.8 kt/y of NO₃⁻ and 8.7 kt/y of TP to Tonle Sap Lake and its floodplain during 426 427 high flow season. Table 5 summarizes the exchange of NO₃⁻ and phosphorus between Tonle Sap Lake and the Mekong River. This result can lead to the conclusion that Tonle Sap Lake 428 gains from the nutrient flux (NO₃⁻ and TP) from the Mekong River. In other words, the Mekong 429 River plays the role of the source of nutrients, especially TP, to Tonle Sap Lake and its 430 floodplain. Overall, the Tonle Sap Lake is a sink for nutrients even if only the inflow from the 431
- 432 Mekong River through channel is considered.



Figure 13. Annual water discharge and nutrient flux balance between Tonle Sap Lake and
the Mekong River through the Tonle Sap River at Prek Kdam station from 1997 to 2016. (a)
Net water discharge, (b) net NO₃⁻ flux, and (c) net TP flux. The annual water discharge and
nutrient fluxes were obtained by subtracting the seasonal water discharge and inflow/outflow
nutrient fluxes from Tonle Sap Lake.

Table 5. NO₃⁻ and TP flux exchange between Tonle Sap Lake and the Mekong River through
Tonle Sap River at Prek Kdam.

Nutrient Flux		Flux of Mekong mainstem at Chroy Changva	Flux from Tonle Sap Lake towards Mekong	Flux from Mekong towards Tonle Sap Lake
		(kt/y)	(kt/y)	(kt/y)
NO -	Mean	557	34.0	35.8
INO ₃	STDEV	109	13.8	12.5
ТР	Mean	73	6.6	8.7
Ir	STDEV	19	1.4	3.3

441

442 **4. Discussion**

This study makes a first attempt to quantify the nutrient transport linkages between the 443 mainstream part of the Mekong River and Tonle Sap Lake, and to estimate the nutrient fluxes 444 in the lower reach of the Mekong River at Kratie and Chroy Changva. The annual NO₃⁻ flux 445 along the Mekong River exhibited a considerable seasonal variation during the study period, 446 with 80–88% of the total annual NO_3^- flux occurring from May to October. Similarly, 447 448 approximately 90% of the annual TP flux occurred between May and October. The peak NO3⁻ flux was observed in August at Kratie and Chroy Changva stations, whereas the peak TP fluxed 449 450 was observed in September. The estimated annual NO₃⁻ flux was 364 ± 45 kt/y and 557 ± 109 kt/y at Kratie and Chroy Changva stations, respectively, while the estimated annual TP flux 451 was 100 \pm 16 kt/y and 73 \pm 19 kt/y at Kratie and Chroy Changva stations, respectively. 452 Liljeström et al. (2012) reported that the TP flux from the Mekong River basin to the South 453 454 China Sea was 55 kt/y during 2003–2005, and that the total inorganic N and TP fluxes increased during 1985-2005. Yoshimura et al. (2009) predicted that the total N (TN) and TP 455 concentrations in the lower part of the Mekong River would increase by 13–25% by the 2020s 456 relative to the 1990s. The long-term mean NO₃⁻ flux (1985–2005) from Sekong, Sesan, and 457 Srepok rivers (3S rivers) to the Mekong River was estimated to be 57.6 kt/y, which is 458 approximately 30% of the total annual NO₃⁻ flux of the Mekong River in Pakse (Oeurng et al., 459 2016). These flux estimation results could be associated with agricultural expansion over the 460 last two decades (i.e., an increase from 50 000 ha in 1997 to 120 000 ha in 2007 for the Laos 461 part of the Mekong River basin) (Li et al., 2015; MRC, 2003). 462

Lake and river floodplains are among the most biologically productive and diverse ecosystems, and have extremely important cultural, socioeconomic, and ecological value (Noe et al., 2013;

Lamberts, 2006; Tockner and Stanford, 2002). This study determined the nutrient budget of 465 Tonle Sap Lake and the Mekong River, revealing that Tonle Sap Lake and its floodplain are 466 nutrient sinks. The Mekong River promotes the sustainable biodiversity of Tonle Sap Lake and 467 provides local benefits, particularly socioeconomic benefits in Cambodia (Lamberts, 2006). 468 Considering the use of nutrient concentrations as ecological indicators, on a larger scale, the 469 470 results of our study could contribute to the understanding of the nutrient budget and phytoplankton community in the South China Sea, which is the main outlet of the Mekong 471 472 River. The South China Sea has been reported to be a nutrient deplete region (Dippner et al., 473 2007), which may be due to biological uptake of nutrients and nutrient enrichment via the decomposition of organic material in deep waters in such high salinity regions (Zhang, 1996). 474 On the other hand, increased nutrient fluxes in the Mekong River (e.g., TN, TP, total inorganic 475 N) due to anthropogenic activity and climate change in the basin (Liljeström et al., 2012; 476 Yoshimura et al., 2009) could threaten the ecosystem; for example, algal blooms caused by 477 478 excessive nutrient inputs. Nitrogen and phosphorus are important nutrients for aquatic life and are mainly involved in the eutrophication process (Shannon and Brezonik, 1972). Recently, the 479 480 low-water period and high TP concentrations during the dry season have become a major concern with respect to the eutrophication of Tonle Sap Lake; thus, it is important to understand 481 482 the outflow during the dry season and the annual nutrient balance (Sovannara et al., 2021). Furthermore, the change in nutrient limitation in the lake can be attributed to changes in the 483 source and supply of nutrient, as well as other factors such as changes in the hydrological and 484 ecological conditions, which can decrease the quantity of food (zooplankton) for secondary 485 486 producers and the quality of zooplankton as food for fish (Malzahn et al., 2007). In Tonle Sap Lake, fish catches and fish sizes declined during 2000–2015 (Ngor et al., 2018) and 1994–2000 487 (Chan et al., 2017), respectively. 488

Nitrogen and phosphorus in rivers mainly originate from two sources: non-point sources (e.g., 489 agricultural fertilizers, basin soil erosion, and precipitation) and point sources (i.e., industrial 490 491 and domestic wastewaters) (Seitzinger et al., 2005). Globally, anthropogenic non-point sources have been estimated to account for 62% of dissolved inorganic N (DIN) (Seitzinger et al., 492 2005). Precipitation and agricultural sources dominate the pools of NO_3^- and DIN in the 493 Mekong River basin, which is an area of relatively low development and intensive agricultural 494 practices. The analysis of the fluxes of NO₃⁻ and TP in this study highlighted their relationships 495 496 with water discharge, demonstrating the continuous transport of NO₃⁻ and P from basin runoff. As N and P are mainly from agricultural non-point sources (MRC, 2003; Jarvie et al., 1998), 497

such as the massive amounts of fertilizer used in Thailand (100 kg of mineral fertilizer per hectare), such inputs could increase the nutrient load in the lower part of the Mekong River. However, estimates of NO_3^- loading based on concentration and discharge data do not provide much information about the corresponding sources. Hence, further studies are required to identify nutrient sources (e.g., by using stable isotopes) (Chang et al., 2002). Anthropogenic activities may also significantly increase the concentrations and fluxes of nutrients in the Mekong River basin (Li et al., 2015).

- Nitrogen occurs in freshwater ecosystems in three forms: DIN (including ammonium (NH₄-505 N), NO₃–N, and nitrite (NO₂–N)), dissolved organic N (DON, e.g., amino acids and 506 polypeptides), and particulate organic N (PON) (Allan and Castillo, 2007). In addition, N 507 508 occurs in gaseous forms, such as dinitrogen gas (N_2) and nitrous oxide (N_2O) , which is a potent greenhouse gas. Among these, DIN is biologically available for aquatic primary producers and 509 510 microorganisms, with NH₄–N being taken up more readily by aquatic organisms because of 511 the lower physiological costs (Burgin and Hamilton, 2007). The mean DIN concentration may comprise 0.1 mg/L of NO₃–N, 0.015 mg/L of NH₄–N, and 0.001 mg/L of NO₂–N (Allan et al., 512 2020). It has been estimated that DON accounts for 40%–90% of the total N concentration; 513 514 thus, it often constitutes a major component of the nutrients within an ecosystem (Weigelhofer et al., 2018). Therefore, NO₃⁻ represents a relatively small portion of the total N flux in an 515 516 ecosystem. This study investigated the dynamic flux of NO₃⁻ based on the available data for the study area. Although NO₃⁻ is not the dominant constituent of the total N pool, it is a basic 517 form of DIN required by primary producers and microorganisms in the aquatic ecosystem. 518 When data on DIN and total N data are not available, NO_3^- is often assessed in nutrient studies. 519 For example, Bussi et al. (2017) investigated the impact of land use and climate on the nutrients 520 in the Thames River in the United Kingdom, whereby NO₃⁻ and P were the target parameters. 521 Trang et al. (2017) also used NO₃⁻ as an indicator to study the impacts of climate and land use 522 changes on nutrient yields in the 3S basin of the lower part of the Mekong River basin, while 523 Oeurng et al. (2016) used NO₃⁻ as an indicator to investigate the variation in riverine nutrients. 524 The upper part of the Mekong River basin is characterized by fissured rocks and karst aquifers. 525 526 In contrast, the Mekong Delta is extensively covered by nutrient-containing unconsolidated alluvial sediments, which extend from the coast to the northwest in Cambodia, including Tonle 527 Sap Lake (Lee et al., 2018). Sinkholes, which may be connected to subterranean rivers, are 528
- 529 widely distributed in karst catchments (Li et al., 2010). During rainfall events, especially during
- extreme storms, sediment-laden flows can drain out through sinkholes (Bai et al., 2013). Thus,

large amounts of sediments and nutrients are lost from sinkholes to the underground drainage 531 system. Moreover, the effectiveness of vegetation cover in reducing soil erosion and nutrient 532 loss is considerably limited in karst areas. Seasonal changes in particulate nutrient exports from 533 intensive agricultural catchments have been found to be dominated by dry season surface runoff 534 in the Mekong River basin. Another study suggested that the nutrient export flux of runoff was 535 mainly controlled by the time and pattern of fertilization use, as well as ground cover (Li et al., 536 2020). With the increasing demand for food, the application of chemical fertilizers in 537 agriculture has increased considerably in the Mekong River basin, while the efficiency of 538 539 nitrogen use for agricultural production has dramatically decreased in recent years. The change in agricultural practices combined with the highly permeable characteristics of karst soils and 540 subsurface hydrological systems make these areas prone to NO₃⁻ pollution due to 541 anthropogenic activities (Yu et al., 2019; Yue et al., 2019; Yue et al., 2015). Excessive 542 fertilization results in a large export of nutrients from agricultural lands to rivers (Li et al., 543 544 2020). High rainfall events can lead to the rapid transport of large amounts of nutrients to drainage systems in karst regions (Wang et al., 2020). In karst and non-karst areas, dams can 545 546 significantly reduce the discharge amounts of sediment and nutrients in rivers, although the magnitudes of such reductions vary between different rivers. In some rivers with high sediment 547 548 discharge, such as many rivers in Asia, the effectiveness of dams decreases over time as they are progressively filled with deposited sediments (Wang et al., 2016). 549

Dam construction may affect nutrient transport processes in rivers (Supit and Ohgushi, 2012), 550 and can also reduce the amount of downstream nutrient fluxes, thereby changing the spatial 551 distribution of riverine nutrients, which eventually results in changes in the river ecosystem 552 (Chai et al., 2009; Paul, 2003). From the mid-1990s to the early 2000s, dam development 553 accelerated in China and Vietnam with the construction of mainstream dams on the lower 554 Mekong and tributary dams (Kondolf et al., 2018). Hydropower reservoir storage in the basin 555 was $\sim 2\%$ of the mean annual flow in 2008, and is expect to increase to $\sim 20\%$ of the mean 556 annual flow by 2025. Hydropower reservoir storage attenuates the seasonal flow variability in 557 the downstream regions of many dams with integral powerhouses and large storage reservoirs 558 (Hecht et al., 2019). Under a scenario of 38 dams being either built or under construction (main 559 river and tributary), an approximate sediment load of 77 Mt/y (or ~50% of the long-term load) 560 only would be transported downstream (from Kratie downward). This would significantly 561 562 affect sediment delivery to downstream reaches (Kondolf et al., 2018). Dams are known to 563 affect nutrient fluxes in rivers (Bosch, 2008). Water impoundment due to dam construction can

increase the water depth and residence time compared with pre-dam conditions. Phosphorus, 564 which is mainly attached to soil particles, is heavily influenced by the trapping of sediment in 565 reservoirs (Oeurng et al., 2016). A study on the effects of dams on nutrients in the Huron and 566 Raisin rivers demonstrated that dams can play a vital role in effectively removing excess 567 nutrients (Bosch, 2008). Eight main rivers (the Yangtze, Huanghe, Liaohe, Haihe, Huaihe, 568 Qiangtangjiang, Minjiang, and Zhujiang rivers) account for the majority of the discharge into 569 the coastal waters of China. Nutrient fluxes have also been reported for other East Asian 570 monsoon rivers, such as the Yangtze River (Shen and Liu, 2009) and the Red River (Li et al., 571 572 2015), and are compared with those of the Mekong River in Table 6.

573

Table 6. Nutrient fluxes of Mekong comparing to others Asian Monsoon Rivers.

River	Region	Basin area	River length	Water Discharge	NO3 ⁻ flux	TP flux	Reference
		$(10^6 \mathrm{km^2})$	(km)	(km ³ /y)	(kt/y)	(kt/y)	
Yellow	East Asia	0.77	5464	49	214.8	0.21 (DIP)	Wu et al. (2019)
Yangtze	East Asia	1.94	6300	900	5516.2	110	Hua et al. (2019)
Pearl	East Asia	0.44	2129	302	559 (DIN)	10 (DIP)	Hu and Li (2009)
Red	East Asia	0.12	1139	123	296 (TIN)	46	Le et al. (2015)
Mekong	Southeast Asia	0.79	4800	404	557	73	This study

574 Note: DIN: dissolve inorganic nitrogen. (DIP): dissolved inorganic phosphorus. TIN: total inorganic nitrogen

575

576 **5.** Conclusions

This study first assessed the dynamics of nutrient transport in the Mekong River in Cambodia 577 and then quantified the NO3- and TP fluxes between the Mekong River and Tonle Sap Lake. 578 The results showed that downstream reductions in gauged flows at Kratie and Chroy Changva 579 mainly occurred at high flows. These reductions of high flow were attributed to overland flow 580 from the Mekong River traversing the floodplain to Tonle Sap Lake, and to flow into major 581 tributaries between Kratie and Chroy Changva. Opposite tendencies were observed for the 582 fluxes of NO3- and TP in the mainstream part of the Mekong River, indicating that these two 583 fluxes had different dynamics across the basin, and that large discharge volumes did not always 584 transport large amounts of nutrients. For the nutrient exchange between Tonle Sap Lake and 585 the Mekong River during the hydrological cycle, the TP flux from the Mekong River into Tonle 586 Sap Lake reached considerably higher values than that from the lake to the Mekong River. This 587

- study contributes information on the nutrient budget of Tonle Sap Lake and the Mekong River.
- 589 The findings indicate that Tonle Sap Lake was a nutrient sink during the study period, and that
- the Mekong River provided an important source of nutrients to the lake and its floodplain. This
- study provides the first findings on the exchange of nutrients between the Mekong River and
- 592 Tonle Sap Lake, and establishes a baseline for investigating the long-term nutrient dynamics
- 593 and loads in the Tonle Sap River.

594 Data availability statement

595 The data that support the findings of this study are available from the corresponding author 596 upon reasonable request.

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