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1 **Nutrient Transport and Exchange between the Mekong River and Tonle Sap Lake in**
2 **Cambodia**

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

47 **Keywords:** Nutrient Transport, Mekong River, Tonle Sap Lake

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58 **1. Introduction**

59 One of the largest transboundary rivers in Asia and the world, the Mekong River (MK),
60 originates in the Tangelo Mountain range of the Tibetan region of China. It flows through six
61 nations: China, Cambodia, Lao People's Democratic Republic, Myanmar, Thailand, and
62 Vietnam before it enters the South China Sea in Vietnam. The physical diversity, tropical
63 location, and high productivity of the Mekong River has allowed it to become the second most
64 species rich river after the Amazon River (Froese and Pauly, 2010). There are at least 1200
65 species of fish, and potentially up to 1700, living in the Mekong River basin as a result of its
66 geological and hydrological heterogeneity (Coates et al., 2005). Lower Mekong River is the
67 most essential region both economically and environmentally and has about 60 million
68 inhabitants dependent on its water resources (MRC, 2010). Located in the Lower Mekong
69 River in Cambodia, the Tonle Sap Lake (TSL) is a productive ecosystem and the most diverse
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
73 population of more than 17 million people (Szabo et al., 2016). The agricultural, ecological,
74 and fish productivity of the Lower Mekong River, particularly Tonle Sap Lake and the Mekong
75 Delta can be largely attributed to the seasonal delivery of water, sediments, and nutrients by
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
78 water quality has recently deteriorated as a consequence of land use changes, reservoir
79 construction, population growth, and meteorological extremes (Chea et al., 2016; Campbell,
80 2009; Dudgeon, 2005). The construction of dams on the Upstream Mekong River has led to
81 the significant trapping of sediments and nutrients (Kummu and Varis, 2007; XX Lu and Siew,
82 2006), e.g Manwan dam in 1992 and Dachaoshan in 2003. The Mekong River is experiencing
83 dramatic land surface disturbances, such as forest clearing and arable land expansion, as a result
84 of rapid population growth and expanding urbanization (Lu and Siew, 2005). Land-use change
85 in the region is accelerating element cycling and appreciably altering riverine and estuarine
86 ecosystems, which is evident in dramatic shifts in the supply of nutrients (Li et al., 2015).
87 Changes in sediment and nutrient supplies are of particular concern in the tropical regions that
88 have been undergoing rapid development (change of land cover and dam development) since
89 the 1990s, where they have impacted biodiversity and the long-term stability of Tonle Sap lake
90 and the Mekong Delta (Campbell, 2007; Tamura et al., 2007). In the Mekong sub-region, such

91 as Myanmar, Laos, Cambodia, Vietnam, Thailand, and Yunnan Province, China, karst area is
92 widely spread. Geomorphological features in southwest China, including Lancang River Basin
93 upstream of Mekong River, are characterized by multiple mountains and plateaus, widely
94 distributed karst and red clay hills, deep canyons, and gorges (Kiernan, 2011). Topographically
95 impressive karst is widespread in Laos which is the main area of Mekong River basin (Kiernan,
96 2015). Karst landforms result in uneven distribution of water resources and diverse ecological
97 environment. Karst soils are typically thin, patchy, and fragile to disturbances, easily causing
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.,
101 2003; Croll and Hayes, 1988).

102 Compared with other rivers in Asia, such as the Ganges and Yangtze rivers, the annual nitrogen
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
105 increases in nutrient inputs to surface water from agricultural production and infrastructure
106 development (Liljeström et al., 2012; Galloway et al., 2004; MRC, 2003). Iida et al. (2011) and
107 Ribolzi et al. (2011) reported high nutrient concentrations (nitrate (NO_3^-) and phosphate (P)),
108 nitrogenous matter, and total suspended sediment (TSS) in the upper reach of the Mekong River
109 in the northern part of Laos People's Democratic Republic. Watanabe et al. (2003) also
110 highlighted the disturbance of the N balance in southern Vietnam, which was likely caused by
111 agricultural development. On an entire system scale, Li et al. (2015) examined the spatial,
112 monthly, and interannual fluxes of nutrients and stoichiometric ratios in the Mekong River for
113 the period 1985–2011. Kummu and Varis (2007) found that dam construction in the upstream
114 region of the Mekong River had led to the significant trapping of sediments and nutrients,
115 which could reduce the fertility of the Tonle Sap system. Considering that the sediment input
116 from the Mekong river is crucial for the ecosystem functioning of Tonle Sap Lake (Arias et al.,
117 2014), it is necessary to gain a better understanding of the sediment and nutrient linkages
118 between the mainstream part of the Mekong River and Tonle Sap Lake. The sediment exchange
119 between Tonle Sap Lake and the Mekong River was previously estimated by Kummu et al.
120 (2008), Lu et al. (2014), and Sok et al. (2021). Kummu et al. (2008) studied the sediment load
121 during 1997–2003 and showed that Tonle Sap Lake acted a sink for sediments from the
122 Mekong River. In contrast, Lu et al. (2014) found that Tonle Sap Lake was a sediment source
123 to the river during 2008–2010. A recent study by Sok et al. (2021) indicated that Tonle Sap

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

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

136 **2. Materials and Methods**

137 **2.1 Study area**

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

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

175

176 **Figure 1.** Map of the study site: (a) Mekong River basin, (b) sampling sites along the
177 Mekong and Tonle Sap rivers, and (c) flow directions and reverse flow at Chroy Changva site
178 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
181 and Meteorology (MOWRAM) of Cambodia under the Mekong River Commission (MRC)
182 framework: Water Quality Monitoring Network (WQMN) at the three sites in the Lower
183 Mekong River of Cambodia (Table 1). The monitoring sites started from the upstream site of
184 the Mekong River of Cambodia at Kratie moving to the Chroy Changva (near Chatumuk
185 confluence) to capture the water discharge and quality before the water changes course to the
186 Tonle Sap River and Mekong Delta. Prek Kdam station, located along the Tonle Sap River,
187 was included in the study since this station can represent the reverse system of the Mekong-
188 Tonle Sap system (Figure 1c).

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

193 of each month (Kongmeng and Larsen, 2016). The water sampling, sample preservation,
 194 sample transportation, and sample storage (Kongmeng and Larsen, 2016) were carried out in
 195 accordance with the methods outlined in the 20th edition of the Standard Methods for the
 196 Examination of Water and Wastewater (Clesceri et al., 1998). The samples were analyzed at
 197 designated laboratories by the Mekong River Commission (MRC) using the recommended
 198 analytical methods (2540-D-TSS-SM for TSS, 4500-NO₂₋₃/SM for NO₃, and 4500-P/SM for
 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
 202 example, Gong et al. (2015) studied the seasonal variation of dissolved nutrients in the Yellow
 203 River using monthly sampling. Nutrient discharge of the Yangtze River by Tong et al. (2017)
 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
 208 budgets of major rivers, including the Mekong River.

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
 212 expressed in calendar years (i.e., the calendar year is 1995-2017; thus, the study expressed as
 213 the hydrological year 1995-2016). At Prek Kdam, the observed value of water discharge and
 214 water quality parameters were distinguished to positive and negative responses corresponding
 215 to the two opposite flow directions of Tonle Sap River. In this study, the negative values of
 216 water discharge and water quality parameters are inflow into the Tonle Sap Lake from the
 217 Mekong River, while positive values correspond to the outflow from the Tonle Sap Lake
 218 towards the Mekong River.

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

Locations	Nitrate (NO ₃ -N)		Total phosphorus (TP)		Discharge
	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
Prek Kdam					
Tonle Sap towards Mekong	153	1997-2017	95	2005-2017	1997-2017
Mekong towards Tonle Sap	64	1997-2017	40	2005-2017	1997-2017

221

222 **2.3 Nutrient flux estimation**

223 Nutrient fluxes were estimated by using the LOAD ESTimator (LOADEST) model (Runkel et
224 al., 2004). LOADEST incorporates daily discharge, seasonality, and measured constituent data
225 to parameterize a multiple-regression model that allows a continuous time series to be
226 estimated from discrete measurements (Hanley et al., 2013; Bouraoui and Grizzetti, 2011b).
227 LOADEST calculates fluxes by applying the method of adjusted maximum likelihood
228 estimation while eliminating collinearity by centering discharge and concentration data. The
229 regression model is automatically selected from one of nine predefined regression models to
230 fit the data based on the Akaike Information Criterion (Johnston et al., 2018). Flux estimation
231 considers datasets of at least 120 observations (Hirsch, 2014), thus our dataset is validated.
232 LOADEST has previously been used to estimate fluxes in major rivers by Sun et al. (2013) in
233 the Yangtze River with monthly N and TP concentration and daily streamflow data, by Hanley
234 et al. (2013) in temperate North American rivers with monthly water quality parameters, and
235 by Bouraoui and Grizzetti (2011a) in rivers discharging to European seas with monthly nutrient
236 data. In our study, LOADEST was used to extrapolate the monthly NO_3^- concentration
237 measurements to daily nutrient loads with the following regression models:

238 (1) $\ln L = a_0 + a_1 \ln Q$

239 (2) $\ln L = a_0 + a_1 \ln Q + a_2 \text{dtime}$

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

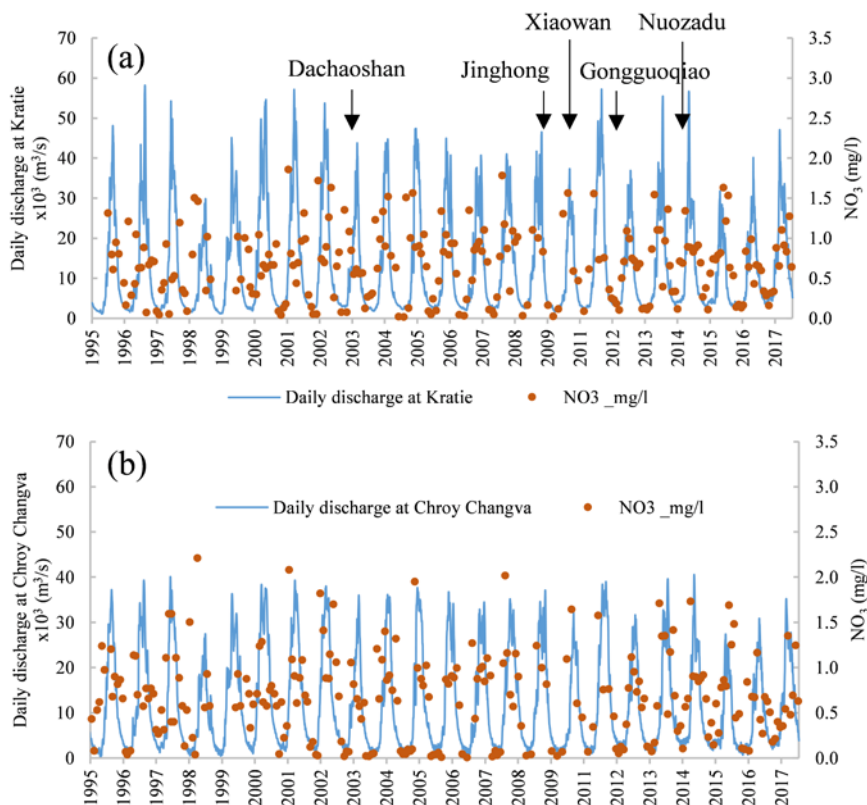
241 where L is the constituent load, a_{0-6} are coefficients obtaining from LOADEST, and Q is
242 streamflow (daily).

243 **3. Results**

244 **3.1 Nutrient concentration variations in the Lower Mekong River**

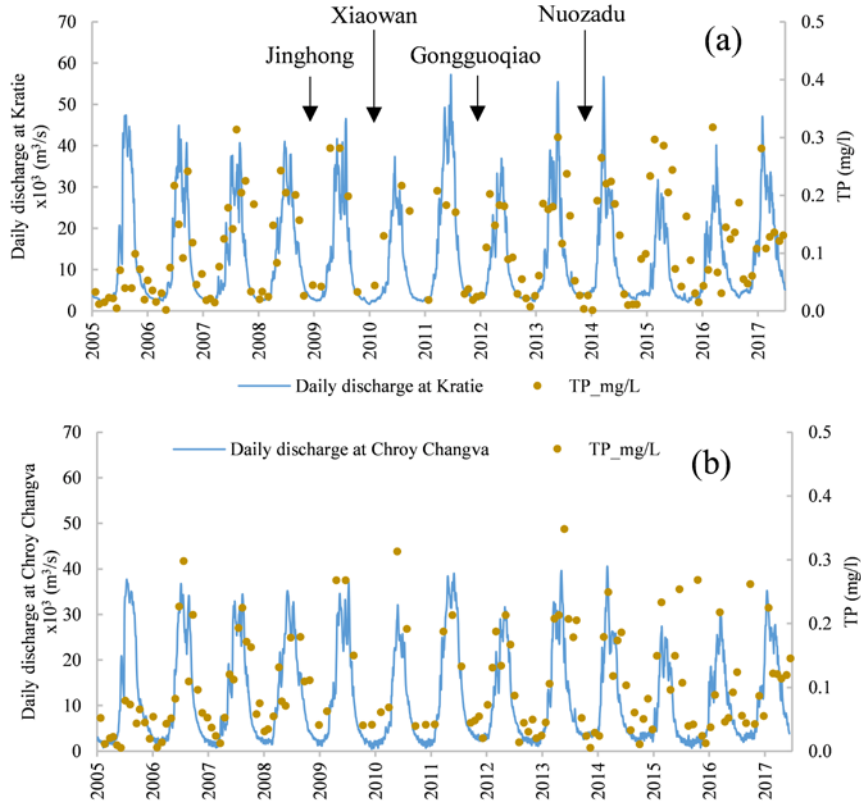
245 The hydrograph of the daily water discharge and observed monthly water quality at Kratie and
246 Chroy Changva showed obvious variations during the study period from 1995-2017 (Figure 2)
247 for NO_3^- concentrations and 2005-2017 for TP concentrations (Figure 3). At Kratie, the

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



258

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



262

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

265

Table 2. NO_3^- and TP concentration at Kratie and Chroy Changva

	Kratie		Chroy Changva	
	NO_3^- (mg/l)	TP (mg/l)	NO_3^- (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

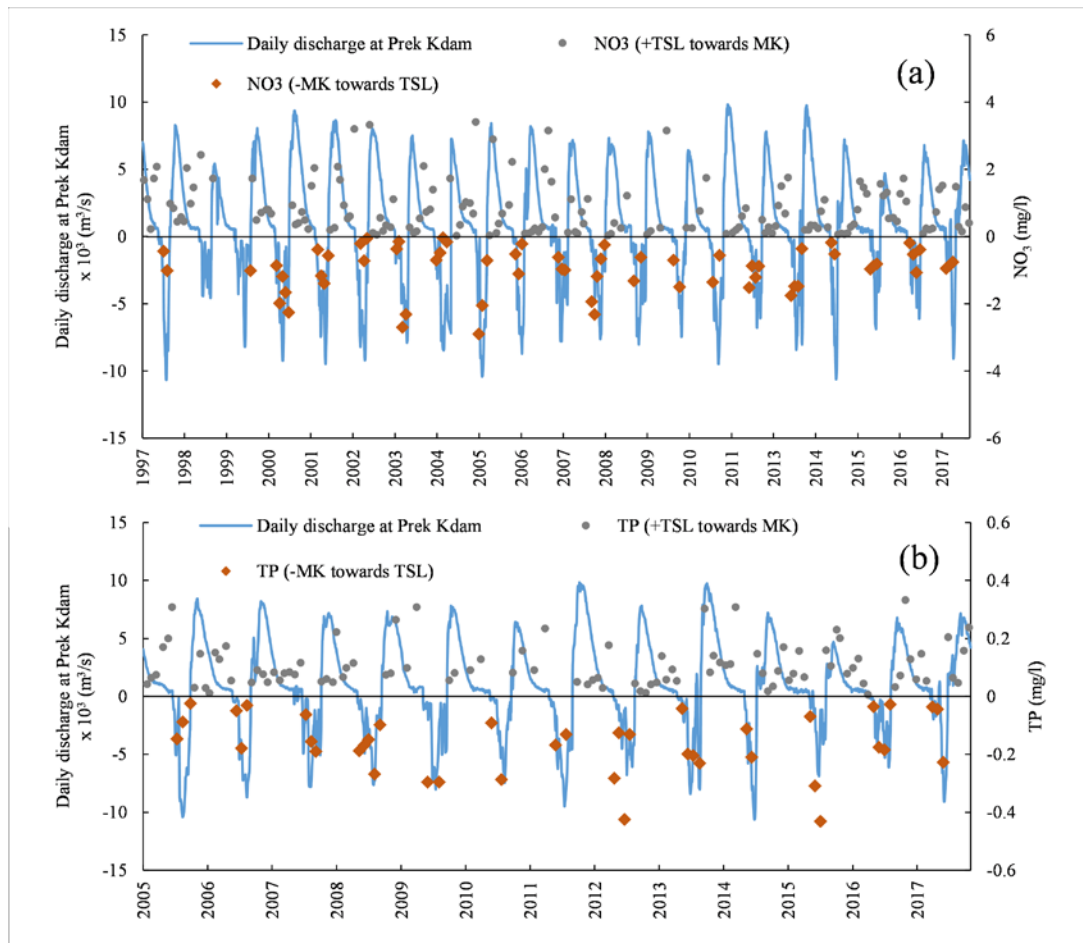
266

267 **3.2 Nutrient concentration variations in the Tonle Sap River**

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

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

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



298

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

302

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

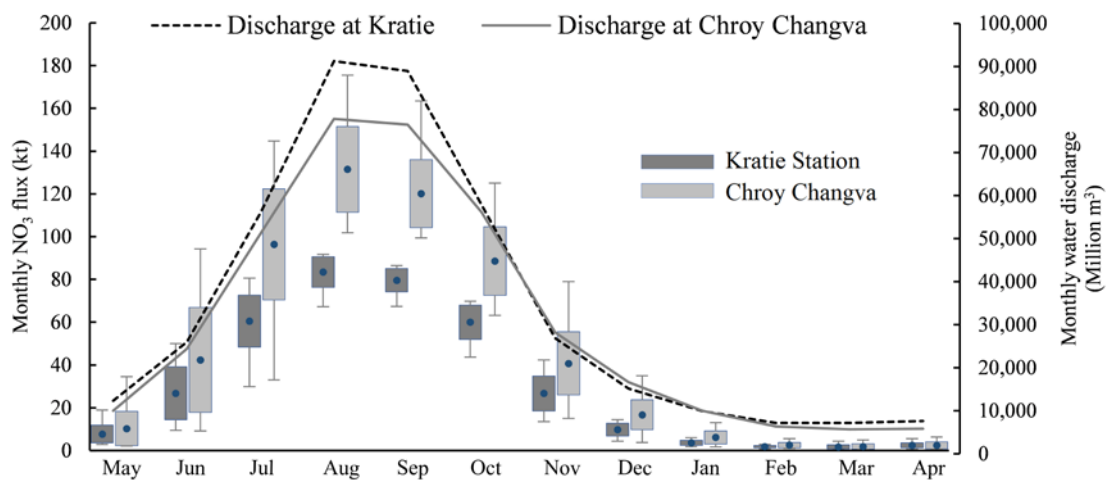
	Tonle Sap Lake towards Mekong		Mekong towards Tonle Sap Lake	
	NO ₃ ⁻ (mg/l)	TP (mg/l)	NO ₃ ⁻ (mg/l)	TP (mg/l)
Min	0.02	0.01	0.04	0.02
Max	3.40	0.33	2.90	0.43
Mean	0.81	0.11	0.98	0.16
STDEV	0.77	0.07	0.67	0.10

303

304 **3.3 Temporal variability of nutrient flux in the Mekong River**

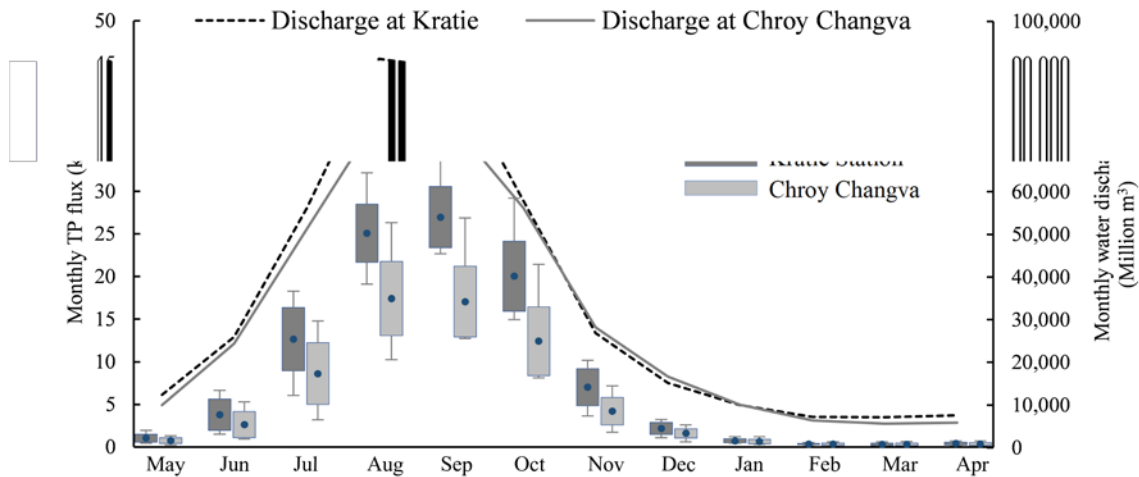
305 The variability of monthly (accumulation per month) NO₃⁻ and TP flux have been employed at
 306 both Kratie and Chroy Changva station (Figure 5 and Figure 6). The peak values of NO₃⁻ and

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



329

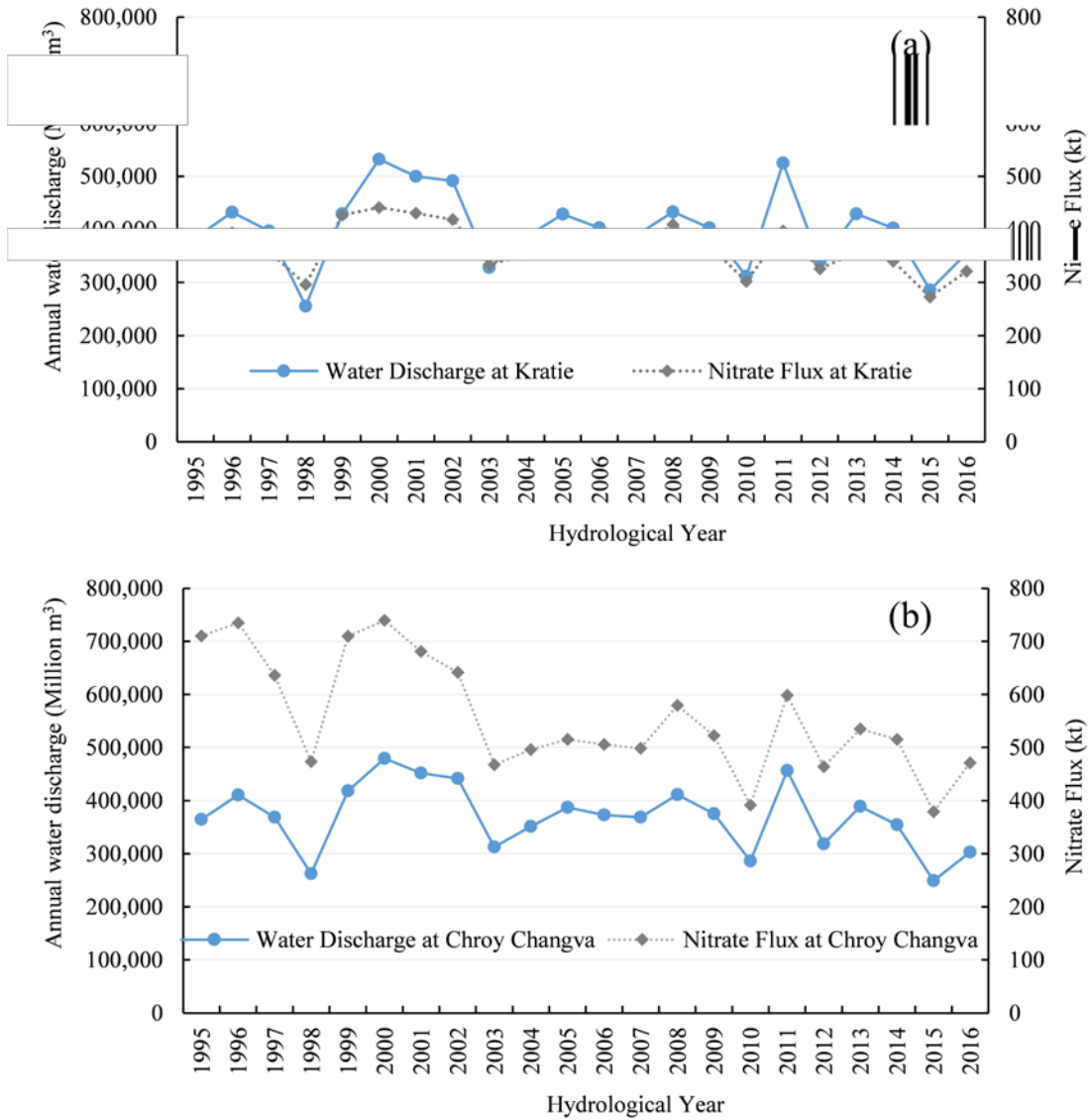
330 **Figure 5.** Monthly variation of NO_3^- flux and monthly water discharge at Kratie and Chroy
 331 Changva. (mean, standard deviation value, minimum and maximum)



332

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

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

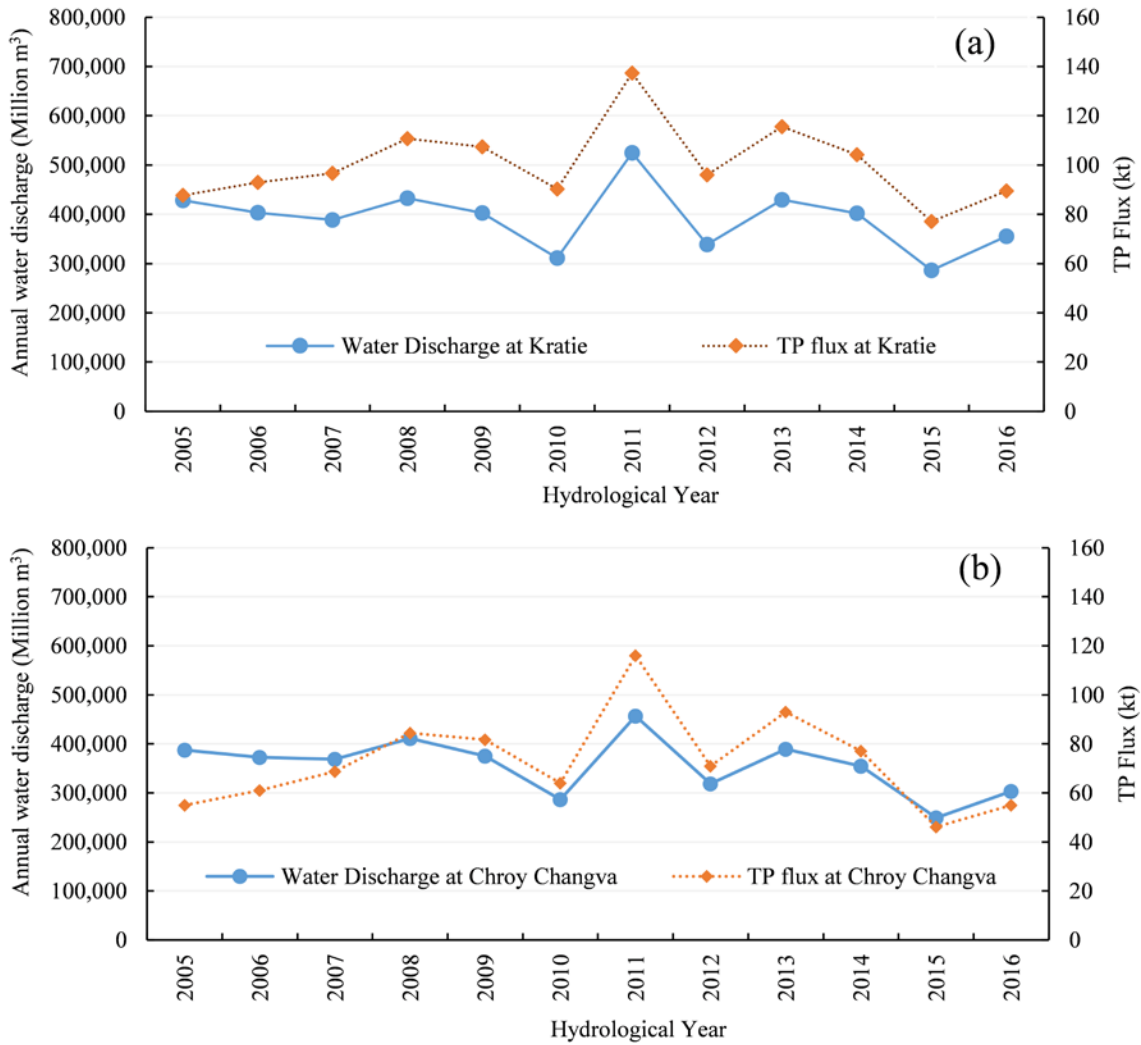


352

353 **Figure 7.** Annual NO_3^- flux dynamics in the Mekong River for the period of 1995 to 2016 (a)

354

at Kratie and (b) at Chroy Changva.



355

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

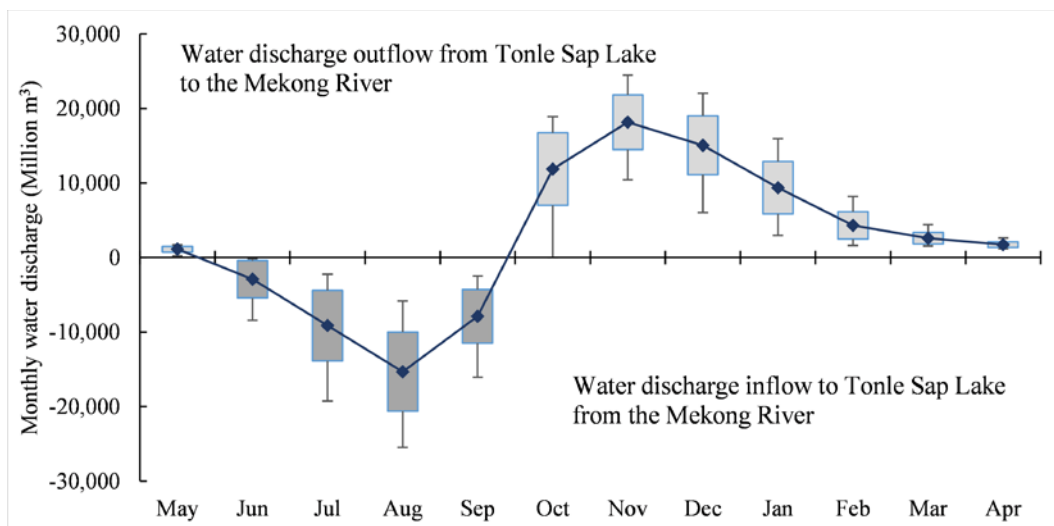
358 **Table 4.** Annual NO_3^- and TP flux dynamics in the Mekong River for the period of 1995 to
 359 2016 at Kratie and Chroy Changva

	Kratie			Chroy Changva		
	Water Discharge (Million m ³ /year)	NO_3^- Flux (kt/year)	TP Flux (kt/year)	Water Discharge (Million m ³ /year)	NO_3^- Flux (kt/year)	TP Flux (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

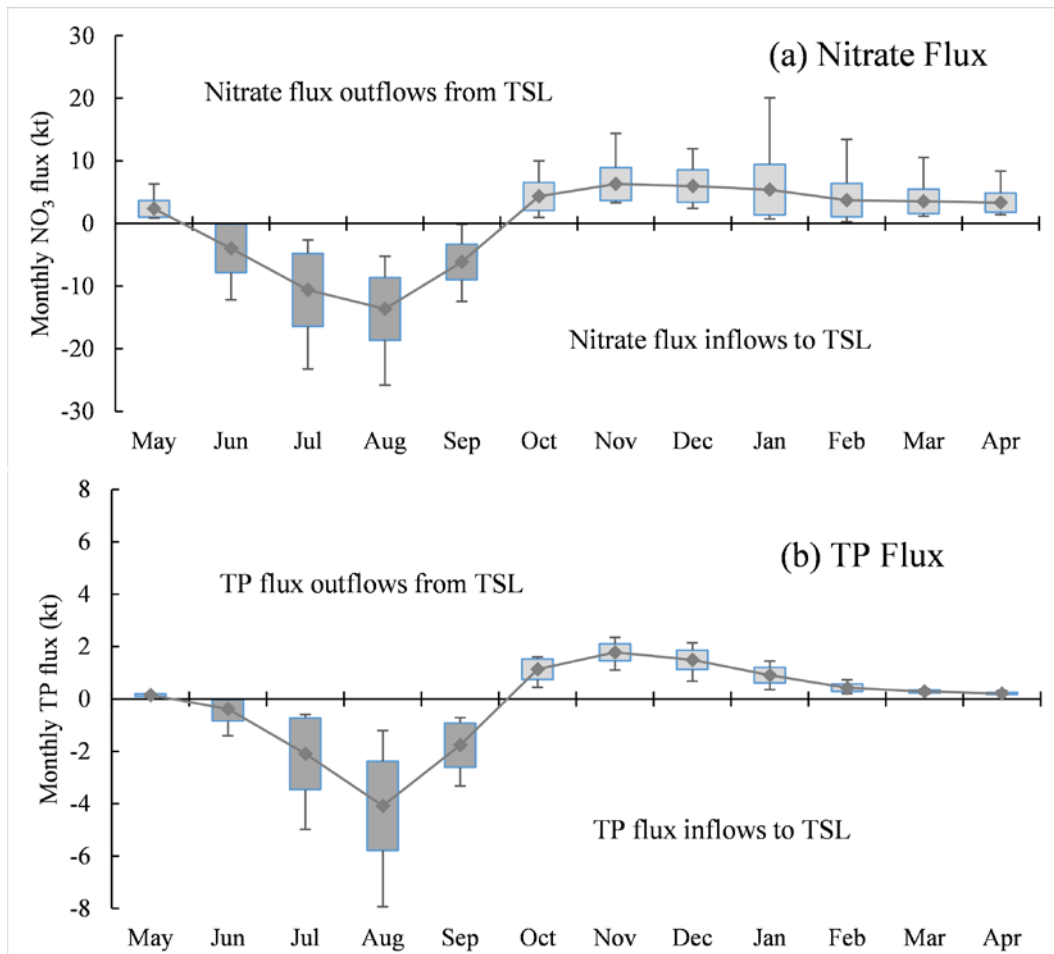
360

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

363 To assess the temporal variations in the exchange of nutrients between Tonle Sap Lake and the
364 Mekong River, it is very important to understand the inflow and outflow of lake water to the
365 Mekong River. In general, with the timing and magnitude of flow, the Mekong River provides
366 less water to Tonle Sap Lake than it receives. Inflow to the lake from the Mekong River starts
367 in May or very early June, whereas flow reversal occurs in October (Figure 9). The seasonal
368 variations in the fluxes of NO_3^- and TP from the Tonle Sap River were calculated to represent
369 opposite flow directions; from Tonle Sap Lake towards the Mekong River and from the
370 Mekong River towards Tonle Sap Lake (Figure 10). Generally, nutrient fluxes into Tonle Sap
371 Lake were observed during the rainy season (May–October), corresponding to flow discharge
372 from the Mekong River to the lake, while the reverse flux was observed in the dry season
373 (October–May). The estimated monthly fluxes of NO_3^- 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
375 observed in August. The estimated monthly fluxes of NO_3^- and TP from the Mekong River to
376 the lake were 0.88–1.72 kt and 0.04–1.14 kt, respectively. Thus, the TP flux from the Mekong
377 River into Tonle Sap Lake reached considerably higher values than that from the lake to the
378 Mekong River.



379
380 **Figure 9.** Monthly variation in water discharge between the Mekong River and Tonle Sap
381 Lake at Prek Kdam from 1997 to 2017 (mean, standard deviation, minimum, and maximum)

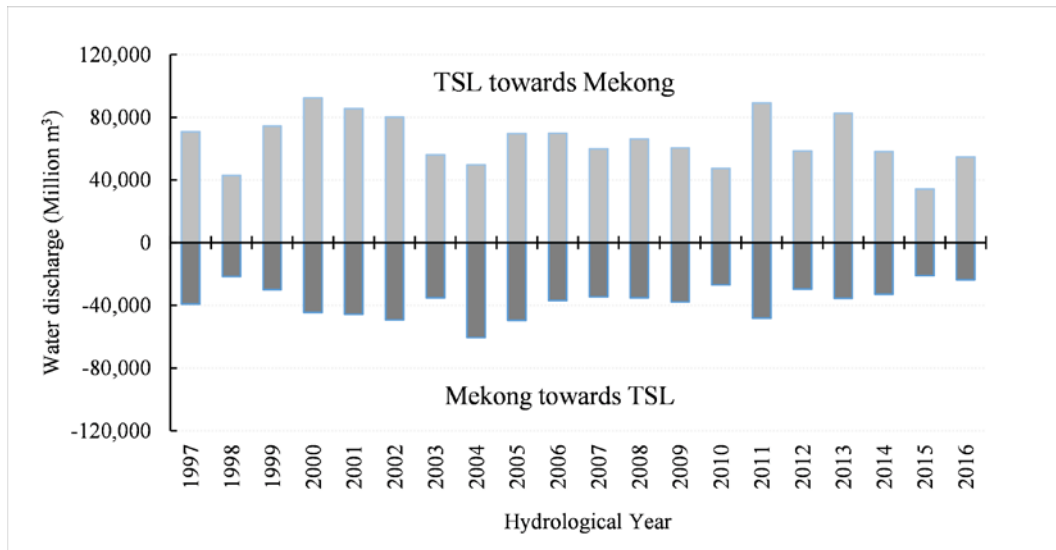


382

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

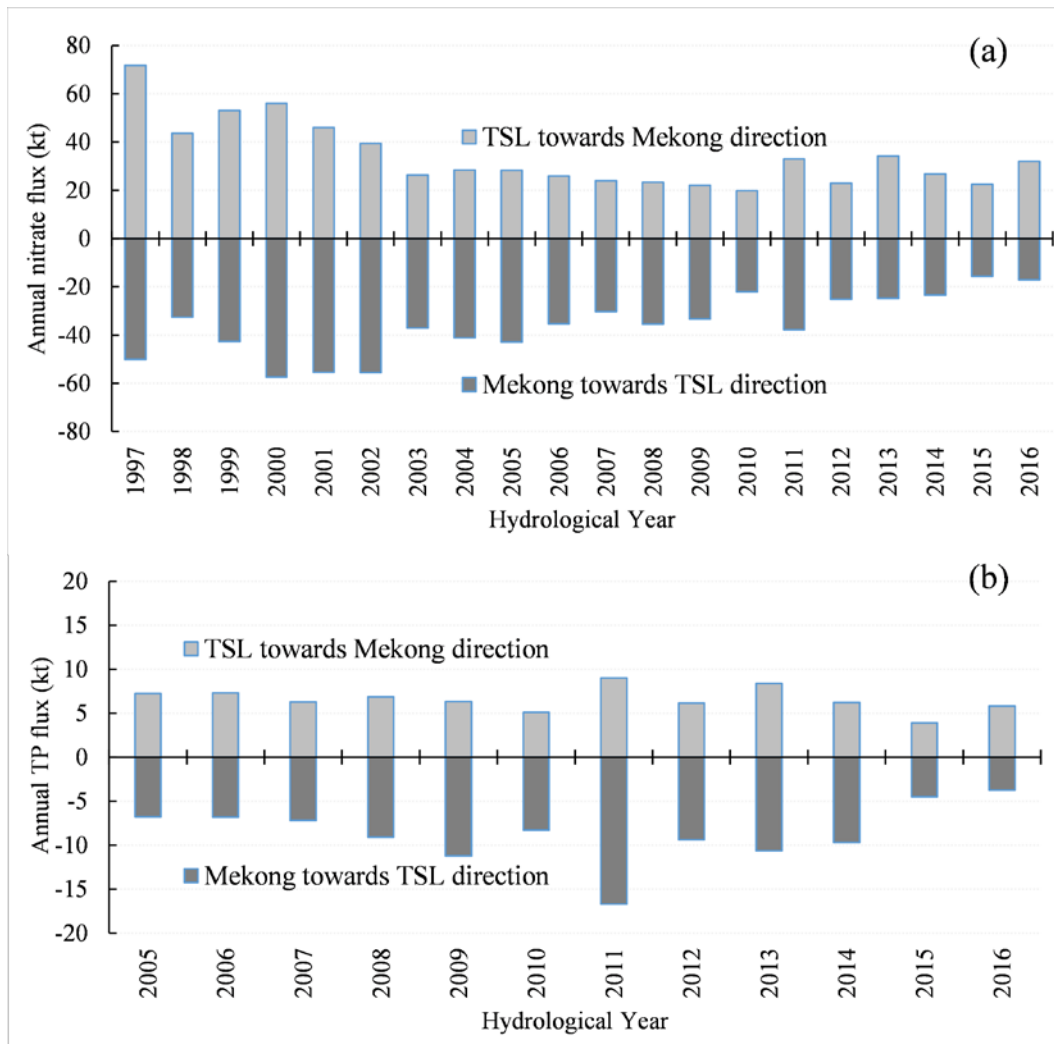
385 The results of the annual water balance revealed that Tonle Sap Lake contributed ~36 000 Mm³
 386 of water to the Mekong River during the low-flow season from October to May. The cumulative
 387 seasonal water volumes are presented in Figure 11, whereby negative values indicate a reverse
 388 flow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

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



402

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



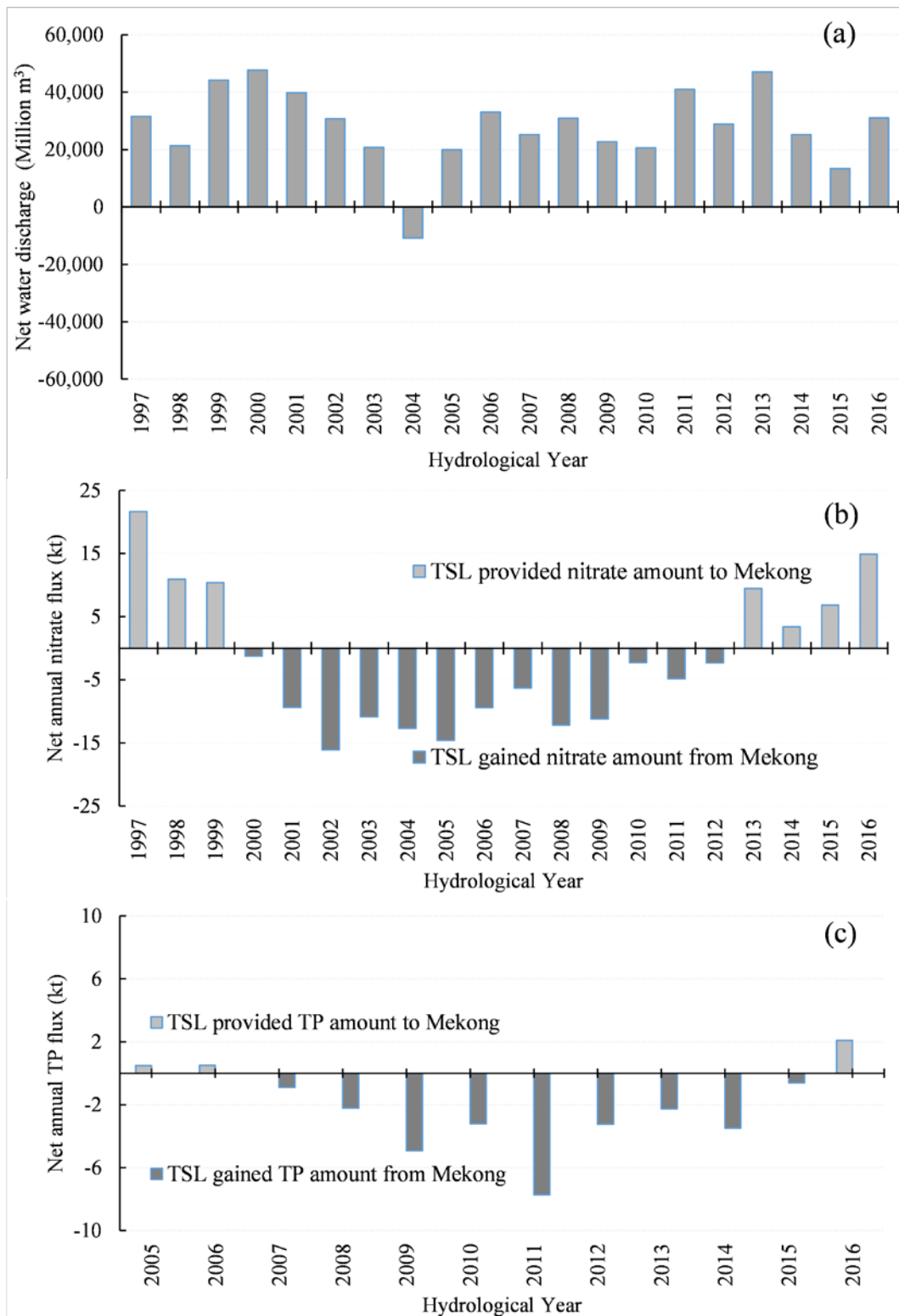
405

406 **Figure 12.** Seasonal NO_3^- and TP fluxes between Tonle Sap Lake and the Mekong River
 407 through the Tonle Sap River at Prek Kdam. (a) Seasonal NO_3^- flux from 1997 to 2016 and (b)
 408 seasonal TP flux from 2005 to 2016

409 **3.5 Changes in the nutrient exchange between Tonle Sap Lake and the Mekong River**

410 Tonle Sap Lake received less water than it contributed to the Mekong River system, except in
 411 2004. This was because the Mekong River at Chroy Changva reached its maximum discharge
 412 of 60 000 Mm^3 in 2004, while the mean discharge was 36 000 Mm^3 . The annual water balance
 413 showed that, during the low-flow season, Tonle Sap Lake generally contributed $\sim 65\,000\ \text{Mm}^3$
 414 (i.e., 18% of the total annual discharge of the Mekong River) of water to the Mekong River
 415 and Mekong Delta (Figure 13). Even though the Mekong River has been reported to provide
 416 water and a potential source of nutrients to the lake through overland flow during the peak flow
 417 period ($\sim 2500\ \text{Mm}^3$), the present study only investigated the amount of nutrients exchanged
 418 through the channel of the Tonle Sap River.

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



433

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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 NO_3^- 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.

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

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

441

442 **4. Discussion**

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

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

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

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

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

505 Nitrogen occurs in freshwater ecosystems in three forms: DIN (including ammonium ($\text{NH}_4\text{-N}$),
506 $\text{NO}_3\text{-N}$, and nitrite ($\text{NO}_2\text{-N}$)), dissolved organic N (DON, e.g., amino acids and
507 polypeptides), and particulate organic N (PON) (Allan and Castillo, 2007). In addition, N
508 occurs in gaseous forms, such as dinitrogen gas (N_2) and nitrous oxide (N_2O), which is a potent
509 greenhouse gas. Among these, DIN is biologically available for aquatic primary producers and
510 microorganisms, with $\text{NH}_4\text{-N}$ being taken up more readily by aquatic organisms because of
511 the lower physiological costs (Burgin and Hamilton, 2007). The mean DIN concentration may
512 comprise 0.1 mg/L of $\text{NO}_3\text{-N}$, 0.015 mg/L of $\text{NH}_4\text{-N}$, and 0.001 mg/L of $\text{NO}_2\text{-N}$ (Allan et al.,
513 2020). It has been estimated that DON accounts for 40%–90% of the total N concentration;
514 thus, it often constitutes a major component of the nutrients within an ecosystem (Weigelhofer
515 et al., 2018). Therefore, NO_3^- represents a relatively small portion of the total N flux in an
516 ecosystem. This study investigated the dynamic flux of NO_3^- based on the available data for
517 the study area. Although NO_3^- is not the dominant constituent of the total N pool, it is a basic
518 form of DIN required by primary producers and microorganisms in the aquatic ecosystem.
519 When data on DIN and total N data are not available, NO_3^- is often assessed in nutrient studies.
520 For example, Bussi et al. (2017) investigated the impact of land use and climate on the nutrients
521 in the Thames River in the United Kingdom, whereby NO_3^- and P were the target parameters.
522 Trang et al. (2017) also used NO_3^- as an indicator to study the impacts of climate and land use
523 changes on nutrient yields in the 3S basin of the lower part of the Mekong River basin, while
524 Oeurng et al. (2016) used NO_3^- as an indicator to investigate the variation in riverine nutrients.
525 The upper part of the Mekong River basin is characterized by fissured rocks and karst aquifers.
526 In contrast, the Mekong Delta is extensively covered by nutrient-containing unconsolidated
527 alluvial sediments, which extend from the coast to the northwest in Cambodia, including Tonle
528 Sap Lake (Lee et al., 2018). Sinkholes, which may be connected to subterranean rivers, are
529 widely distributed in karst catchments (Li et al., 2010). During rainfall events, especially during
530 extreme storms, sediment-laden flows can drain out through sinkholes (Bai et al., 2013). Thus,

531 large amounts of sediments and nutrients are lost from sinkholes to the underground drainage
532 system. Moreover, the effectiveness of vegetation cover in reducing soil erosion and nutrient
533 loss is considerably limited in karst areas. Seasonal changes in particulate nutrient exports from
534 intensive agricultural catchments have been found to be dominated by dry season surface runoff
535 in the Mekong River basin. Another study suggested that the nutrient export flux of runoff was
536 mainly controlled by the time and pattern of fertilization use, as well as ground cover (Li et al.,
537 2020). With the increasing demand for food, the application of chemical fertilizers in
538 agriculture has increased considerably in the Mekong River basin, while the efficiency of
539 nitrogen use for agricultural production has dramatically decreased in recent years. The change
540 in agricultural practices combined with the highly permeable characteristics of karst soils and
541 subsurface hydrological systems make these areas prone to NO_3^- pollution due to
542 anthropogenic activities (Yu et al., 2019; Yue et al., 2019; Yue et al., 2015). Excessive
543 fertilization results in a large export of nutrients from agricultural lands to rivers (Li et al.,
544 2020). High rainfall events can lead to the rapid transport of large amounts of nutrients to
545 drainage systems in karst regions (Wang et al., 2020). In karst and non-karst areas, dams can
546 significantly reduce the discharge amounts of sediment and nutrients in rivers, although the
547 magnitudes of such reductions vary between different rivers. In some rivers with high sediment
548 discharge, such as many rivers in Asia, the effectiveness of dams decreases over time as they
549 are progressively filled with deposited sediments (Wang et al., 2016).

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

564 increase the water depth and residence time compared with pre-dam conditions. Phosphorus,
 565 which is mainly attached to soil particles, is heavily influenced by the trapping of sediment in
 566 reservoirs (Oeurng et al., 2016). A study on the effects of dams on nutrients in the Huron and
 567 Raisin rivers demonstrated that dams can play a vital role in effectively removing excess
 568 nutrients (Bosch, 2008). Eight main rivers (the Yangtze, Huanghe, Liaohe, Haihe, Huaihe,
 569 Qiangtangjiang, Minjiang, and Zhujiang rivers) account for the majority of the discharge into
 570 the coastal waters of China. Nutrient fluxes have also been reported for other East Asian
 571 monsoon rivers, such as the Yangtze River (Shen and Liu, 2009) and the Red River (Li et al.,
 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 (10 ⁶ km ²)	River length (km)	Water Discharge (km ³ /y)	NO ₃ ⁻ flux (kt/y)	TP flux (kt/y)	Reference
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

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

588 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
590 the Mekong River provided an important source of nutrients to the lake and its floodplain. This
591 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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603 **Reference:**

- 604 Adamson, P.T., Rutherford, I.D., Peel, M.C., Conlan, I.A. (2009). The hydrology of the
605 Mekong River *The Mekong* (pp. 53-76): Elsevier.
- 606 Allan, J.D., Castillo, M.M., 2007. An introduction to fluvial ecosystems. *Stream Ecology:*
607 *Structure and function of running waters*, 1-12.
- 608 Allan, J.D., Castillo, M.M., Capps, K.A. (2020). *Stream ecology: structure and function of*
609 *running waters*: Springer Nature.
- 610 Arias, M., Piman, T., Lauri, H., Cochrane, T., Kummu, M., 2014. Dams on Mekong
611 tributaries as significant contributors of hydrological alterations to the Tonle Sap
612 Floodplain in Cambodia. *Hydrology and Earth System Sciences* 18, 5303.
- 613 Bai, X., Zhang, X., Long, Y., Liu, X., Siyu, Z., 2013. Use of ¹³⁷Cs and ²¹⁰Pbex
614 measurements on deposits in a karst depression to study the erosional response of a
615 small karst catchment in Southwest China to land-use change. *Hydrological Processes*
616 27, 822-829.
- 617 Bosch, N.S., 2008. The influence of impoundments on riverine nutrient transport: An
618 evaluation using the Soil and Water Assessment Tool. *Journal of Hydrology* 355, 131-
619 147.
- 620 Bouraoui, F., Grizzetti, B., 2011a. Long term change of nutrient concentrations of rivers
621 discharging in European seas. *Science of the Total Environment* 409, 4899-4916.
- 622 Bouraoui, F., Grizzetti, B.J.S.o.t.T.E., 2011b. Long term change of nutrient concentrations of
623 rivers discharging in European seas. 409, 4899-4916.
- 624 Burgin, A.J., Hamilton, S.K., 2007. Have we overemphasized the role of denitrification in
625 aquatic ecosystems? A review of nitrate removal pathways. *Frontiers in Ecology and*
626 *the Environment* 5, 89-96.

627 Bussi, G., Janes, V., Whitehead, P.G., Dadson, S.J., Holman, I.P., 2017. Dynamic response of
628 land use and river nutrient concentration to long-term climatic changes. *Science of the*
629 *Total Environment* 590, 818-831.

630 Campbell, I., 2007. Perceptions, data, and river management: Lessons from the Mekong
631 River. *Water Resources Research* 43.

632 Campbell, I. (2009). The challenges for Mekong River management *The Mekong* (pp. 403-
633 419): Elsevier.

634 Chai, C., Yu, Z., Shen, Z., Song, X., Cao, X., Yao, Y., 2009. Nutrient characteristics in the
635 Yangtze River Estuary and the adjacent East China Sea before and after impoundment
636 of the Three Gorges Dam. *Science of the Total Environment* 407, 4687-4695.

637 Chan, B., Ngor, P.B., So, N., Lek, S. (2017). *Spatial and temporal changes in fish yields and*
638 *fish communities in the largest tropical floodplain lake in Asia*. Paper presented at the
639 *Annales de Limnologie-International Journal of Limnology*.

640 Chang, C.C., Kendall, C., Silva, S.R., Battaglin, W.A., Campbell, D.H.J.C.J.o.F., Sciences,
641 A., 2002. Nitrate stable isotopes: tools for determining nitrate sources among different
642 land uses in the Mississippi River Basin. 59, 1874-1885.

643 Chea, R., Grenouillet, G., Lek, S., 2016. Evidence of water quality degradation in lower
644 Mekong basin revealed by self-organizing map. *PloS one* 11.

645 Clesceri, L., Greenberg, A., Eaton, A.J.A., WEF, Monrovia, USA. 1998. Standard Methods
646 for the Examination of Water and Wastewater APHA.

647 Coates, D., Poeu, O., Suntornratnana, U., Nguyen, T., Viravong, S., 2005. Biodiversity and
648 fisheries in the Mekong River Basin. Mekong development series.

649 Croll, B., Hayes, C., 1988. Nitrate and water supplies in the United Kingdom. *Environmental*
650 *pollution* 50, 163-187.

651 Dippner, J.W., Nguyen, K.V., Hein, H., Ohde, T., Loick, N., 2007. Monsoon-induced
652 upwelling off the Vietnamese coast. *Ocean Dynamics* 57, 46-62.

653 Dudgeon, D., 2005. River rehabilitation for conservation of fish biodiversity in monsoonal
654 Asia. *Ecology and Society* 10.

655 Fenton, O., Mellander, P.-E., Daly, K., Wall, D., Jahangir, M., Jordan, P., Hennessey, D.,
656 Huebsch, M., Blum, P., Vero, S., 2017. Integrated assessment of agricultural nutrient
657 pressures and legacies in karst landscapes. *Agriculture, Ecosystems & Environment*
658 239, 246-256.

659 Froese, R., Pauly, D. (2010). FishBase: Fisheries Centre, University of British Columbia.

660 Fujii, H., Garsdal, H., Ward, P., Ishii, M., Morishita, K., Boivin, T., 2003. Hydrological roles
661 of the Cambodian floodplain of the Mekong River. *International Journal of River*
662 *Basin Management* 1, 253-266.

663 Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P.,
664 Asner, G.P., Cleveland, C.C., Green, P., Holland, E.A., 2004. Nitrogen cycles: past,
665 present, and future. *Biogeochemistry* 70, 153-226.

666 Gong, Y., Yu, Z., Yao, Q., Chen, H., Mi, T., Tan, J., 2015. Seasonal variation and sources of
667 dissolved nutrients in the Yellow River, China. *International journal of environmental*
668 *research and public health* 12, 9603-9622.

669 Gupta, A., Liew, S.C., 2007. The Mekong from satellite imagery: A quick look at a large
670 river. *Geomorphology* 85, 259-274.

671 Hanley, K.W., Wollheim, W.M., Salisbury, J., Huntington, T., Aiken, G., 2013. Controls on
672 dissolved organic carbon quantity and chemical character in temperate rivers of North
673 America. *Global biogeochemical cycles* 27, 492-504.

674 Hecht, J.S., Lacombe, G., Arias, M.E., Dang, T.D., Piman, T., 2019. Hydropower dams of the
675 Mekong River basin: A review of their hydrological impacts. *Journal of hydrology*
676 568, 285-300.

677 Hedlund, U., Manusthiparom, C., Jirayoot, K., Modeller, , Campbell, I.C., 2005. Water
678 Statistics in the Mekong River Basin. IWG-Env, International Work Session on Water
679 Statistics, Vienna.

680 Hirsch, R.M.J.J.o.t.A.W.R.A., 2014. Large biases in regression-based constituent flux
681 estimates: Causes and diagnostic tools. 50, 1401-1424.

682 Hu, J., Li, S., 2009. Modeling the mass fluxes and transformations of nutrients in the Pearl
683 River Delta, China. *Journal of Marine Systems* 78, 146-167.

684 Hua, W., Huaiyu, Y., Fengnian, Z., Bao, L., Wei, Z., Yeye, Y., 2019. Dynamics of nutrient
685 export from the Yangtze River to the East China sea. *Estuarine, Coastal and Shelf
686 Science* 229, 106415.

687 Iida, T., Inkhamseng, S., Yoshida, K., Tanji, H., 2011. Characterization of water quality
688 variation in the Mekong River at Vientiane by frequent observations. *Hydrological
689 Processes* 25, 3590-3601.

690 Jarvie, H., Whitton, B., Neal, C., 1998. Nitrogen and phosphorus in east coast British rivers:
691 speciation, sources and biological significance. *Science of the Total environment* 210,
692 79-109.

693 Johnston, S.E., Shorina, N., Bulygina, E., Vorobjeva, T., Chupakova, A., Klimov, S.I.,
694 Kellerman, A.M., Guillemette, F., Shiklomanov, A., Podgorski, D.C., 2018. Flux and
695 seasonality of dissolved organic matter from the Northern Dvina (Severnaya Dvina)
696 River, Russia. *Journal of Geophysical Research: Biogeosciences* 123, 1041-1056.

697 Kiernan, K., 2011. Challenges for environmentally sustainable development of natural
698 resources in the Nam Ou karst, northern Laos. *Acta Carsologica* 40.

699 Kiernan, K., 2015. Karst geomorphology along the Nam Ou, northern Lao PDR. *Cave and
700 Karst science* 42, 86-94.

701 Kondolf, G.M., Schmitt, R.J., Carling, P., Darby, S., Arias, M., Bizzi, S., Castelletti, A.,
702 Cochrane, T.A., Gibson, S., Kummu, M., 2018. Changing sediment budget of the
703 Mekong: Cumulative threats and management strategies for a large river basin.
704 *Science of the total environment* 625, 114-134.

705 Kongmeng, L., Larsen, H., 2014. Lower Mekong Regional water quality monitoring report.
706 MRC Technical Paper No 60.

707 Kongmeng, L., Larsen, H. (2016). Lower Mekong Regional water quality monitoring report:
708 Vientiane, Lao PDR: Mekong River Commission.

709 Kummu, M., Penny, D., Sarkkula, J., Koponen, J., 2008. Sediment: curse or blessing for
710 Tonle Sap Lake? *AMBIO: A Journal of the Human Environment* 37, 158-163.

711 Kummu, M., Sarkkula, J., 2008. Impact of the Mekong River flow alteration on the Tonle
712 Sap flood pulse. *AMBIO: A Journal of the Human Environment* 37, 185-192.

713 Kummu, M., Tes, S., Yin, S., Adamson, P., Józsa, J., Koponen, J., Richey, J., Sarkkula, J.,
714 2014. Water balance analysis for the Tonle Sap Lake–floodplain system. *Hydrological
715 Processes* 28, 1722-1733.

716 Kummu, M., Varis, O., 2007. Sediment-related impacts due to upstream reservoir trapping,
717 the Lower Mekong River. *Geomorphology* 85, 275-293.

718 Lamberts, D., 2006. The Tonle Sap Lake as a productive ecosystem. *International Journal of
719 Water Resources Development* 22, 481-495.

720 Le, T.P.Q., Billen, G., Garnier, J., 2015. Long-term biogeochemical functioning of the Red
721 River (Vietnam): past and present situations. *Regional Environmental Change* 15,
722 329-339.

723 Lee, E., Jayakumar, R., Shrestha, S., Han, Z., 2018. Assessment of transboundary aquifer
724 resources in Asia: Status and progress towards sustainable groundwater management.
725 *Journal of Hydrology: Regional Studies* 20, 103-115.

726 Li, Siyue, Bush, T. R., 2015. Rising flux of nutrients (C, N, P and Si) in the lower Mekong
727 River. *Journal of Hydrology* 530, 447-461.

728 Li, H., Zhang, X., Wang, K., Wen, A., 2010. Assessment of sediment deposition rates in a
729 karst depression of a small catchment in Huanjiang, Guangxi, southwest China, using
730 the cesium-137 technique. *Journal of soil and water conservation* 65, 223-232.

731 Li, S.-L., Xu, S., Wang, T.-J., Yue, F.-J., Peng, T., Zhong, J., Wang, L.-C., Chen, J.-A.,
732 Wang, S.-J., Chen, X., 2020. Effects of agricultural activities coupled with karst
733 structures on riverine biogeochemical cycles and environmental quality in the karst
734 region. *Agriculture, Ecosystems & Environment* 303, 107120.

735 Liljeström, I., Kummu, M., Varis, O., 2012. Nutrient Balance Assessment in the Mekong
736 Basin: nitrogen and phosphorus dynamics in a catchment scale. *International journal*
737 *of water resources development* 28, 373-391.

738 Liu, S., Hong, G.-H., Zhang, J., Ye, X., Jiang, X., 2009. Nutrient budgets for large Chinese
739 estuaries. *Biogeosciences* 6.

740 Lu, X., Kummu, M., Oeurng, C., 2014. Reappraisal of sediment dynamics in the Lower
741 Mekong River, Cambodia. *Earth Surface Processes and Landforms* 39, 1855-1865.

742 Lu, X., Siew, R., 2005. Water discharge and sediment flux changes in the Lower Mekong
743 River.

744 Malzahn, A.M., Aberle, N., Clemmesen, C., Boersma, M., 2007. Nutrient limitation of
745 primary producers affects planktivorous fish condition. *Limnology and Oceanography*
746 52, 2062-2071.

747 Masumoto, T., Kubota, T., Matsuda, S., 2001. Preliminary analysis of the 2000-flood in the
748 Lower Mekong River basin. *Annual Report of Japan Research Society of Practical*
749 *Hydrology System* 4, 103-122.

750 MRC. (2003). *State of the basin report*: Mekong River Commission.

751 MRC. (2010). *State of the basin report*: Mekong River Commission (MRC).

752 MRC. 2019. *State of the Basin Report*.

753 Ngor, P.B., McCann, K.S., Grenouillet, G., So, N., McMeans, B.C., Fraser, E., Lek, S., 2018.
754 Evidence of indiscriminate fishing effects in one of the world's largest inland
755 fisheries. *Scientific reports* 8, 1-12.

756 Noe, G.B., Hupp, C.R., Rybicki, N.B., 2013. Hydrogeomorphology influences soil nitrogen
757 and phosphorus mineralization in floodplain wetlands. *Ecosystems* 16, 75-94.

758 Oeurng, C., Cochrane, T.A., Arias, M.E., Shrestha, B., Piman, T., 2016. Assessment of
759 changes in riverine nitrate in the Sesan, Srepok and Sekong tributaries of the Lower
760 Mekong River Basin. *Journal of Hydrology: Regional Studies* 8, 95-111.

761 Paul, L., 2003. Nutrient elimination in pre-dams: results of long term studies. *Hydrobiologia*
762 504, 289-295.

763 Perrin, C., Michel, C., Andréassian, V., 2003. Improvement of a parsimonious model for
764 streamflow simulation. *Journal of hydrology* 279, 275-289.

765 Ribolzi, O., Cuny, J., Sengsoulichanh, P., Mousquès, C., Souleuth, B., Pierret, A., Huon, S.,
766 Sengtaheuanghong, O., 2011. Land use and water quality along a Mekong tributary
767 in Northern Lao PDR. *Environmental management* 47, 291-302.

768 Runkel, R.L., Crawford, C.G., Cohn, T.A. (2004). *Load Estimator (LOADEST): A FORTRAN*
769 *program for estimating constituent loads in streams and rivers (2328-7055)*

770 Seitzinger, S.P., Harrison, J.A., Dumont, E., Beusen, A.H., Bouwman, A., 2005. Sources and
771 delivery of carbon, nitrogen, and phosphorus to the coastal zone: An overview of
772 Global Nutrient Export from Watersheds (NEWS) models and their application.
773 *Global Biogeochemical Cycles* 19.

774 Shannon, E.E., Brezonik, P.L., 1972. Relations between lake trophic state and nitrogen and
775 phosphorus loading rates. *Environmental Science & Technology* 6, 719-725.

- 776 Shen, Z.-L., Liu, Q., 2009. Nutrients in the changjiang river. Environmental monitoring and
777 assessment 153, 27-44.
- 778 Sok, T., Oeurng, C., Kaing, V., Sauvage, S., Kondolf, G.M., Sánchez-Pérez, J.M., 2021.
779 Assessment of suspended sediment load variability in the Tonle Sap and Lower
780 Mekong Rivers, Cambodia. CATENA 202, 105291.
- 781 Sovannara, U., Kodikara, D., Kana, H., Theng, V., Mong, M., Siev, S., Sok, T., Try, S.,
782 Kaing, V., Khanal, R., Yang, H., Seav, T., Oeurng, C., Chihiro, Y. (2021). *Nutrient*
783 *availability and phosphorus dynamics. In Yoshimura C, Khanal R., Sovannara U.*
784 *(Ed.), Comparative Cognition: Water and Life in Tonle Sap Lake. Springer (to be*
785 *published, 30th August, 2021).*
- 786 Stueber, A.M., Criss, R.E., 2005. ORIGIN AND TRANSPORT OF DISSOLVED
787 CHEMICALS IN A KARST WATERSHED, SOUTHWESTERN ILLINOIS 1.
788 JAWRA Journal of the American Water Resources Association 41, 267-290.
- 789 Sun, C., Shen, Z., Liu, R., Xiong, M., Ma, F., Zhang, O., Li, Y., Chen, L., 2013. Historical
790 trend of nitrogen and phosphorus loads from the upper Yangtze River basin and their
791 responses to the Three Gorges Dam. Environmental Science and Pollution Research
792 20, 8871-8880.
- 793 Supit, C., Ohgushi, K., 2012. Dam construction impacts on stream flow and nutrient transport
794 in Kase River Basin. International Journal of Civil & Environmental Engineering 12,
795 1-5.
- 796 Szabo, S., Brondizio, E., Renaud, F.G., Hetrick, S., Nicholls, R.J., Matthews, Z., Tessler, Z.,
797 Tejedor, A., Sebesvari, Z., Foufoula-Georgiou, E., 2016. Population dynamics, delta
798 vulnerability and environmental change: comparison of the Mekong, Ganges–
799 Brahmaputra and Amazon delta regions. Sustainability science 11, 539-554.
- 800 Tamura, T., Saito, Y., Sieng, S., Ben, B., Kong, M., Choup, S., Tsukawaki, S., 2007.
801 Depositional facies and radiocarbon ages of a drill core from the Mekong River
802 lowland near Phnom Penh, Cambodia: evidence for tidal sedimentation at the time of
803 Holocene maximum flooding. Journal of Asian Earth Sciences 29, 585-592.
- 804 Tockner, K., Stanford, J.A., 2002. Riverine flood plains: present state and future trends.
805 Environmental conservation 29, 308-330.
- 806 Tong, Y., Bu, X., Chen, J., Zhou, F., Chen, L., Liu, M., Tan, X., Yu, T., Zhang, W., Mi, Z.,
807 2017. Estimation of nutrient discharge from the Yangtze River to the East China Sea
808 and the identification of nutrient sources. Journal of hazardous materials 321, 728-
809 736.
- 810 Trang, N.T.T., Shrestha, S., Shrestha, M., Datta, A., Kawasaki, A., 2017. Evaluating the
811 impacts of climate and land-use change on the hydrology and nutrient yield in a
812 transboundary river basin: A case study in the 3S River Basin (Sekong, Sesan, and
813 Srepok). Science of the Total Environment 576, 586-598.
- 814 Wang, S., Fu, B., Piao, S., Lü, Y., Ciais, P., Feng, X., Wang, Y., 2016. Reduced sediment
815 transport in the Yellow River due to anthropogenic changes. Nature Geoscience 9, 38-
816 41.
- 817 Wang, Z.-J., Li, S.-L., Yue, F.-J., Qin, C.-Q., Buckerfield, S., Zeng, J., 2020. Rainfall driven
818 nitrate transport in agricultural karst surface river system: Insight from high resolution
819 hydrochemistry and nitrate isotopes. Agriculture, Ecosystems & Environment 291,
820 106787.
- 821 Watanabe, T., Nagumo, T., Hung, N., 2003. Estimation of changes in nitrogen flow
822 accompanying agricultural development in Cantho Province, Vietnam predicted for
823 2010. Estimation of changes in nitrogen flow accompanying agricultural development
824 in Cantho Province, Vietnam predicted for 2010., 22-23.

825 Weigelhofer, G., Hein, T., Bondar-Kunze, E., 2018. Phosphorus and nitrogen dynamics in
826 riverine systems: Human impacts and management options. *Riverine Ecosystem*
827 *Management* 187.

828 Wu, G., Cao, W., Wang, F., Su, X., Yan, Y., Guan, Q., 2019. Riverine nutrient fluxes and
829 environmental effects on China's estuaries. *Science of The Total Environment* 661,
830 130-137.

831 XX Lu, X.X., Siew, R., 2006. Water discharge and sediment flux changes over the past
832 decades in the Lower Mekong River: possible impacts of the Chinese dams.

833 Yoshimura, C., Zhou, M., Kiem, A.S., Fukami, K., Prasantha, H.H., Ishidaira, H., Takeuchi,
834 K., 2009. 2020s scenario analysis of nutrient load in the Mekong River Basin using a
835 distributed hydrological model. *Science of the total Environment* 407, 5356-5366.

836 Yu, C., Huang, X., Chen, H., Godfray, H.C.J., Wright, J.S., Hall, J.W., Gong, P., Ni, S., Qiao,
837 S., Huang, G., 2019. Managing nitrogen to restore water quality in China. *Nature* 567,
838 516-520.

839 Yue, F.-J., Waldron, S., Li, S.-L., Wang, Z.-J., Zeng, J., Xu, S., Zhang, Z.-C., Oliver, D.M.,
840 2019. Land use interacts with changes in catchment hydrology to generate chronic
841 nitrate pollution in karst waters and strong seasonality in excess nitrate export.
842 *Science of the Total Environment* 696, 134062.

843 Yue, F.J., Li, S.L., Liu, C.Q., Lang, Y.C., Ding, H., 2015. Sources and transport of nitrate
844 constrained by the isotopic technique in a karst catchment: an example from
845 Southwest China. *Hydrological Processes* 29, 1883-1893.

846 Zhang, J., 1996. Nutrient elements in large Chinese estuaries. *Continental Shelf Research* 16,
847 1023-1045.

848