

1 **Historical impact of water infrastructure on water levels of** 2 **the Mekong River and the Tonle Sap System.**

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13 **Abstract**

14 The rapid rate of water infrastructure development in the Mekong basin is a cause for concern
15 due to its potential impact on fisheries and downstream natural ecosystems. In this paper we
16 analyse the historical water levels of the Mekong River and Tonle Sap system by comparing
17 pre and post 1991 daily observations from six stations along the Mekong mainstream from
18 Chiang Sean (northern Laos), to Stung Treng (Cambodia), and the Prek Kdam station on the
19 Tonle Sap River. Observed alterations in water level patterns along the Mekong are linked to
20 temporal and spatial trends in water infrastructure development from 1960 to 2010. We
21 argue that variations in historical climatic factors are important, but they are not the main
22 cause of observed changes in key hydrological indicators related to ecosystem productivity.
23 Our analysis shows that the development of mainstream dams in the upper Mekong basin in
24 the post-1991 period may have resulted in a modest increase of 30-day minimum (+ 17%),
25 but significant increases in fall rates (+42 %) and the number of water level fluctuations
26 (+75) observed in Chiang Sean. This effect diminishes downstream until it becomes
27 negligible at Mukdahan (northeast Thailand), which represents a drainage area of over 50%
28 of the total Mekong Basin. Further downstream at Pakse (southern Laos), alterations to the

29 number of fluctuations and rise rate became strongly significant after 1991. The observed
30 alterations slowly decrease downstream, but modified rise rates, fall rates, and dry season
31 water levels were still quantifiable and significant as far as Prek Kdam. This paper provides
32 the first set of evidence of hydrological alterations in the Mekong beyond the Chinese dam
33 cascade in the upper Mekong. Given the evident alterations at Pakse and downstream, post-
34 1991 changes can also be directly attributed to water infrastructure development in the Chi
35 and Mun basins of Thailand. A reduction of 23% and 11% in the water raising and fall rates
36 respectively at Prek Kdam provides evidence of a diminished Tonle Sap flood pulse in the
37 post-1991 period. Given the observed water level alterations from 1991 to 2010 as a result of
38 water infrastructure development, we can extrapolate that future development in the
39 mainstream and the key transboundary Srepok, Sesan and Sekong subbasins will have an
40 even greater effect on the Tonle Sap flood regime, the lower Mekong floodplain, and the
41 delta.

42

43 **1 Introduction**

44 The Mekong River is one of the great rivers in the world, originating in the Tibetan highlands
45 and draining into the South China Sea where it forms the Vietnam delta. It has a length of
46 over 4,180 km, drains an area of 795,000 km², and has a mean annual discharge flow of
47 14,500 m³/s (MRC, 2005). The Mekong's hydrology is driven by the Southeast Asian
48 monsoons, causing the river to have a distinct seasonal flood pulse. A unique feature of the
49 Mekong River is its interaction with Southeast Asia's largest lake, the Tonle Sap in
50 Cambodia. The Mekong River receives discharge water from the Tonle Sap Lake during the
51 dry season (November to May) via the Tonle Sap River; during the wet season (June to
52 October), the floodwaters of the Mekong reverse the direction of the Tonle Sap River and
53 flow into the lake, causing its surface area to expand from 2,600 km² to approximately 15,000

54 km². The Tonle Sap system, along with the Mekong River and its tributaries, are also
55 considered one of the world's most productive freshwater fisheries (Baran and Myschowoda,
56 2009). Fish catch in the Mekong and Tonle Sap provides over 50% of the protein consumed
57 by humans in the lower Mekong (Hortle, 2007). The natural seasonal flood pulse and
58 hydrological water level patterns of the Mekong are attributed as being principal features for
59 maintaining the system's high ecosystem productivity (Holtgrieve et al., 2013).

60 While the boom for hydropower development peaked in the 1970s around the world (WCD,
61 2000), civil conflict and political instability maintained the Mekong Basin untapped for
62 several decades. The lower Mekong has been recently described as an unregulated river near
63 natural conditions (Kummu et al., 2010; Grumbine and Xu, 2011; Piman et al. 2013a) and
64 global assessments show that the Mekong has low to moderate levels of fragmentation and
65 regulation comparable to large rivers such as the Amazon and Congo (Nilsson et al. 2005;
66 Lehner et al. 2011). This general perception of a *pristine Mekong* has been rapidly changing
67 as water infrastructure projects have materialized throughout the basin in recent years. Much
68 attention has focused on mainstream dams in China and proposed/under construction dams in
69 Laos. There are, however, a large number of dams in the Mekong tributaries that have been
70 built since the early 1990s with undocumented hydrological alterations and environmental
71 impacts. Furthermore, there are over a hundred dams being proposed for development
72 throughout the basin, most of which are planned in the tributaries (MRC, 2014); thus,
73 quantifying and understanding the level of hydrological alterations from historical
74 development is critical information needed in the Mekong to be able to know what to expect
75 in upcoming decades.

76 Evidence of how dams and irrigation affect natural river regimes have been widely
77 documented throughout the world (Nilsson et al. 2005; Lehner et al. 2011). Dam operations,
78 for example, can affect rivers by redistributing and homogenizing flows, which is reflected in

79 decreased seasonal and inter-annual variability (Poff et al. 2007). These temporal trends,
80 however, can also be affected by other factors such as climate, making the distinction of dam-
81 driven vs. climate-driven alterations troublesome at times. To overcome this issue, it is
82 necessary to identify specific hydrological parameters that are solely associated to water
83 infrastructure development.

84 Ritcher et al. (1996) proposed the use of 32 hydrological parameters as indicators of
85 hydrological alteration. These indicators are broadly grouped into five classes: (1) Mean
86 monthly values, (2) magnitude and duration of extreme water conditions, (3) timing of
87 extreme water conditions, (4) frequency and duration of high/low pulses, and (5) rate and
88 frequency of water condition changes (Ritcher et al., 1996). Even though some indicators in
89 the first two classes have also been used to assess alterations associated with climate change
90 (e.g., Döll and Zhang, 2010), the cumulative alteration to multiple of these classes have been
91 primarily associated with river regulation by dams (Poff et al. 1997; Ritcher et al. 1997, Gao
92 et al. 2009).

93 Localized evidence of dam-related hydrological alterations has been documented in the
94 Mekong, but it is generally accepted that system-wide disruptions are not yet readily evident
95 (Adamson et al., 2009). For the Yali Falls dam in Sesan River in Vietnam, significant
96 downstream water level fluctuations and increases in dry season water levels have been
97 directly attributed to the operation of the dam, which have caused adverse ecological and
98 social impacts including bank erosion, adverse effects on sand bar nesting birds, disruptions
99 on fishing, shellfish collection and others (Wyatt and Baird, 2007). A number of studies have
100 analysed the localized impact of the Lancang-Jiang hydropower cascade in the upper Mekong
101 in China. For instance, Li and He (2008) studied linear trends in multiyear mean water levels
102 and concluded that no major alterations occurred as a result of the first two dams in China's
103 cascade. On the other hand, Lu and Siew (2006) found a significant decrease in dry season

104 water levels and an increase in water level fluctuations in 1993-2000 at Chiang Sean,
105 immediately downstream of the Chinese dam cascade. More recently, Lu et al. (2014)
106 assessed alterations to monthly water discharge at that same station up to 2010 and found
107 moderate alterations during March and April. The effect of the Chinese dams has also been
108 investigated through modelling studies by Räsänen et al. (2012) and Piman et al. (2013a) who
109 reported potential increases in dry season water discharge as far downstream as Kratie in
110 Central Cambodia. To the best of our knowledge, no study has documented hydrological
111 alterations in the Mekong caused by dams or other water infrastructure beyond the Chinese
112 dam cascade.

113 Contemporary basin-wide hydrological shifts have been documented in the Mekong, but they
114 have been primarily attributed to climatic patterns and not water infrastructure development.
115 In particular, a strong link between El Niño-Southern Oscillation (ENSO) and inter-decadal
116 patterns in wet season precipitation and river discharge of the Mekong has been suggested
117 (Delgado et al. 2012; Räsänen and Kummu, 2013). As 80-90% of the Mekong's discharge
118 occurs from May to October (Delgado et al. 2012), most of the research linking climate and
119 river discharge has focused on the distinct wet season months (typically June to October). In
120 general, strong El Niño periods have corresponded to years of lower than normal wet season
121 floods in the Mekong, whereas La Niña periods have corresponded to years of higher than
122 normal floods. The strong shift in the North Pacific was also detectable in the Lower Mekong
123 wet season discharge (Delgado et al., 2012), and overall, interannual variability in flood
124 levels have significantly increased during the Twentieth Century (Delgado et al., 2010;
125 Räsänen et al. 2013). With regards to the dry season, Cook et al. (2012) studied relationships
126 between lower Mekong water discharge during March-May with snow cover and local
127 precipitation. With opposite trends in snow cover (decrease) and precipitation (increase),
128 Cook et al. (2012) estimated negligible effects of these two factors in the lower Mekong

129 discharge during contemporary decades. How climate-driven shifts have interacted with
130 historical water infrastructure development has not been studied, although modelling studies
131 of the Mekong's future indicate that dam-driven alterations could be more noticeable and less
132 uncertain than climate change alterations (Lauri et al., 2012).

133 The purpose of this study is to quantify and reveal observed alterations to water levels along
134 the Mekong River and Tonle Sap system and determine their link to spatial and temporal
135 patterns of water infrastructure development in the basin. We analysed historical records of
136 daily water levels in seven stations along the Mekong and Tonle Sap and compute indicators
137 of hydrological alterations that have been shown to respond most strongly to water
138 infrastructure development (Ritcher et al., 1996). We also use of the most comprehensive and
139 up to date database of dam development in the Mekong to determine when and where dams
140 were built and how that could have affected water levels in the Mekong and Tonle Sap
141 mainstreams. We hypothesised that although decadal and multi-year climatic variability is
142 responsible for some of the observed wet season changes in past decades, there has been
143 sufficient development through the basin since the 1990s to have caused observable
144 hydrological alterations along the Mekong and Tonle Sap.

145

146 **2 Materials and methods**

147 Recorded daily water levels from 1960 to 2010 were obtained for monitoring stations in
148 Chiang Sean, Luang Prabang, Vientiane, Mukdahan, Pakse, and Prek Kdam (Figure 1 and
149 Table 1) from the Mekong River Commission (MRC). These stations provide the longest and
150 most accurate records of water levels in the Mekong. An extended series of records from
151 1910 to 2010 was obtained for the Stung Treng monitoring station in Cambodia. The data
152 were quality checked by the MRC for consistency and accuracy (MRC, 2014). Changes in
153 monitoring location throughout the study period were accounted for, resulting in a consistent

154 and continuous water level data set (MRC, 2014). Parts of this same data set have been
155 reported in multiple publications featuring climate change, sediment analyses, and water
156 infrastructure development in the Mekong (e.g., Arias et al., 2012; Delgado et al., 2010;
157 Delgado et al., 2012; Lu and Siew, 2006; Räsänen and Kummu, 2012, Räsänen et al. 2013;
158 Lu et al. 2014). Of particular importance was the correction of water level data for the
159 Chiang Sean station, which underwent a change in location in Dec 15, 1993. Water level
160 values subsequent to that date were corrected by 0.62 m in order to compare with the water
161 level before the date (Lu et al., 2014).

162 Hydropower reservoir volumes and dates of initial operation were gathered from MRC's
163 hydropower database (MRC, 2014). This is an active database that was initially compiled in
164 2009 and the version used for this study was updated in 2013. This database has also been
165 reported in recent publications (Xue et al., 2011, Kummu, et al., 2010; Lauri et al., 2012;
166 Piman et al., 2013b). Irrigation schemes and related reservoir information were obtained
167 from MRC's Irrigation database (MRC, 2014) and from information provided by the Royal
168 Irrigation Department (Thailand), Electricity Generating Authority of Thailand (EGAT), and
169 Department of Energy Development and Promotion (DEDP) for the Chi-Mun River Basin as
170 compiled by Floch and Molle (2007).

171 Daily water level records for each station were analysed using the Indicators of Hydrologic
172 Alternation (IHA) software (The Nature Conservancy, 2009), which permits the calculation
173 of up to 32 statistical hydrological parameters and the level of alteration in post-development
174 scenarios. A detail analysis of all parameters is presented at Chiang Sean in order to compare
175 our analysis with previous ones at this station (Lu and Siew, 2006; Lu et al. 2014). The
176 analysis at the further downstream stations, however, focused on a selected set of parameters
177 that have been demonstrated to be most related to hydropower operations in the Mekong
178 (Kummu and Sarkkula, 2008; Lauri et al., 2012; Lu and Siew, 2006; Piman et al., 2013b; Lu

179 et al., 2014; Wyatt and Baird, 2007), namely daily water level fluctuations, rise rates, fall
180 rates, and 7 day minimum water levels (Figure 1). To our knowledge, none of these four
181 indicators have been significantly associated with other factors of hydrological alterations in
182 the lower Mekong.

183 To analyse the effect of water resources development on temporal and spatial water levels in
184 the Mekong River, the time series were divided into two periods and compared using a
185 parametric analysis of deviation from means, deviations of the coefficient of variation, a
186 range of variability approach (RVA; Ritcher et al., 1997), and analysis of variance
187 (ANOVA). The division of the datasets had to represent a period of low water infrastructure
188 development and a period of accelerated development in the basin. Furthermore, the division
189 had to ensure that an adequate number of hydrological years were available for each period to
190 enable statistical comparisons. Given these criteria, the data sets were divided into pre- and
191 post- 31 December 1990. A similar timeframe has also been used by other researchers in
192 defining the period where water infrastructure development in the Mekong gained significant
193 importance initiated by the construction of the first dam in the Chinese cascade, Manwan (Lu
194 and Siew, 2006; Räsänen et al., 2012; Lu et al. 2014).

195

196 **3 Results**

197 **3.1 Hydropower and irrigation development in the Mekong basin**

198 The locations and commissioning period of hydropower dams in the Mekong Basin up to the
199 end of 2010 is presented in Figure 2, and a time series of the cumulative active storage at
200 Pakse is presented in Figure 3. Reservoir active storage, total storage, and the number of
201 dams commissioned before 1991 and in 5 year intervals between 1991 and 2010 above each
202 monitoring station are presented in Table 2. Total and active storage in the basin before the
203 end of 1991 was 11,609 and 7,854 Mm³ respectively, with a total of 9 dams, three of which

204 have active storage larger than 1,000 Mm³ (Table S1 in supplementary material). There were
205 no dams in the mainstream of the Mekong prior to 1991. A significant increase in
206 hydropower development in the upper Mekong basin above Chiang Sean occurred after 1991,
207 which can be quantified in terms of reservoir volume (18,216 Mm³) and active storage
208 (10,773 Mm³) of the 4 dams developed on the mainstream in China. Between the end of
209 1991 and 2010 there was minimal development between Chiang Sean and Vientiane with
210 only 3 small dams being built in tributaries (Table S1); however, a significant increase in
211 development occurred in tributaries between Vientiane and Mukdahan resulting in a near
212 doubling of both active (23,117 Mm³) and total storage (37,624 Mm³) above Mukdahan by
213 2010. A number of tributary dams were also built between Mukdahan and Stung Treng
214 resulting in a total basin active storage of 29,913 Mm³ and total reservoir volume of 48,700
215 Mm³. After 1991 hydropower development in the upper tributaries of the Sesan, Srepok, and
216 Sekong (3S) basin in Vietnam and Lao PDR accounted for an increase in 3,374 Mm³ of the
217 total active storage. Seventeen out of the 39 dams in the Mekong basin became operational
218 between 2006 and 2010, accounting for a 65 % of the total active storage and 67 % of the
219 total reservoir volume in the Mekong basin up to 2010.

220 The largest irrigation scheme in the Mekong basin is located in the Chi–Mun subbasin in
221 Thailand. The Chi-Mun subbasin is the largest tributary to the Mekong in terms of area, with
222 the Mun and Chi River basins covering 67,000 km² and 49,477 km², respectively. The
223 combined Chi and Mun Rivers contribute an average annual flow of 32,280 Mm³ which
224 discharges immediately above Pakse (MRC, 2005). These subbasins are highly developed,
225 low-relief, with low runoff potential and significant reservoir storage for dry season
226 irrigation, supporting a population of over 18 million people. The irrigated area is close to
227 1,266,000 ha with an annual water demand of 8,963 Mm³ and a foreseeable demand of over
228 12,000 Mm³ (Floch and Molle, 2007). The basins also include numerous flood prevention

229 works, and most reservoirs are actually managed for joint irrigation, hydropower, and flood
230 control. A summary of the largest multi-use reservoirs in the basin is provided in Table S2.
231 The two largest reservoirs in the basin are Ubol Rattana (2,263 Mm³) and Sirindhorn (Lam
232 Dom Noi; 1966 Mm³) located in the upper watershed areas. However, the most influential
233 reservoir in terms of controlling flows out of the basin is the Pak Mun dam. Although this
234 reservoir is small (225 Mm³), it was built in 1994 close to the outlet of the basin and controls
235 the flow from 117,000 km² of drainage area. Further development of hydropower and
236 reservoirs is highly unlikely in the basin, but construction of additional electricity generating
237 plants in current multi-user reservoirs is possible (Floch and Molle, 2007).

238

239 **3.2 Parametric statistical analysis of hydrological alterations**

240 A parametric statistical analysis of multiple hydrological alteration indicators was done for
241 each site. Detailed results of the analysis are first provided for the Chiang Sean site (Table 3),
242 which is the main monitoring station below the four upper Mekong mainstream dams
243 developed in China after 1991; thus, we assume there are a number of parameters with
244 significant alterations at this station which are strongly linked to water infrastructure
245 development, although some may be linked to climatic variability. Pre- and post- 1991 mean
246 monthly and extreme water levels, coefficients of variation, RVA low and high boundaries
247 (representing 1 standard deviation from the mean), hydrological alteration factors (that is, the
248 fraction of years in the post-development period in which a parameter falls out of a pre-
249 development range of variability), and ANOVA significance levels ($p \leq 0.001$, 0.01, or 0.1)
250 are shown for 32 hydrological alteration indicators. Results show moderate hydrological
251 alteration factors (> -0.33) and statistically significant ($p \leq 0.05$) increases in water levels
252 during the dry season months (February to May), the 30 to 90 day minimum levels, low
253 pulse counts, fall rates, and fluctuations. Analyses from other sites also show significant

254 differences in rise rates. Given these findings we focus our reporting on the analysis of
255 multiple stations on seasonal water levels, 30-day minimum levels, rise rates, fall rates, and
256 water level fluctuations.

257 **3.3 Seasonal changes in water levels**

258 An analysis of pre- and post- 1991 water levels for Chiang Sean from 1960 to 2010 indicates
259 that a significant increase ($p \leq 0.01$) in mean water levels has occurred for the dry season
260 month of April and a non-significant increase is observed for the wet season month of
261 October (Figure 4). A similar analysis was conducted for the Stung Treng station in the
262 Lower Mekong using an extended data set between 1910 and 2010 (Figure 4). Results
263 indicate an increase of 2 standard deviations in the April (dry season) mean monthly water
264 levels post-1991, but no significant alterations for the month of October (wet season).

265 A comparison of percent mean monthly alterations between pre- and post-1991 water levels
266 for the Chiang Sean, Vientiane, Pakse, and Prek Kdam monitoring stations is presented in
267 Figure 5. Results indicate that mean water levels for Chiang Sean have modestly increased in
268 excess 30% for the dry season months of March and April, but monthly increases between
269 June and December were mostly less than 5 %. Monthly mean water levels for Vientiane
270 have increased by 40 % for the month of April, but alterations between June and December
271 were lower than 10%. For Pakse there was an increase of 30 % in April, but relatively no
272 alterations in the months from June to January. For the Prek Kdam water level station in the
273 Tonle Sap, there is an observed mean water level increase of 10-20 % for the months from
274 November to May and a decrease in June and July of ~10 % or under. Changes in percent
275 standard deviations were within the same magnitudes as observed changes in mean water
276 levels for most data sets.

277

278 **3.4 Minimum water levels**

279 Thirty-day minimum water levels were used to characterize alterations to low water
280 conditions. In general, greatest and most significant alterations were observed in the stations
281 furthest upstream and downstream (Table 4). Changes to this parameter were modest, but
282 significant at Chiang Sean (+21%, $p \leq 0.03$), but became negligible at Luang Prabang and
283 Mukdahan. Alterations became again significant at Stung Treng (+12%, $p \leq 0.001$) and Prek
284 Kdam (+20%, $p \leq 0.01$).

285

286 **3.5 Water level rise and fall rate changes**

287 Water level variations were quantified by calculating the rise and fall rate. Rise rates are
288 defined as the mean of all positive differences between consecutive daily water level values
289 and fall rates are the mean of all negative differences between consecutive daily water level
290 values. Water level rise and fall rates (m/day) for pre- and post-1991 for all stations are
291 presented in Table 4. At the Chiang Sean, Luang Prabang, Vientiane, and Mukdahan
292 monitoring stations, the mean differences between pre- and post-1991 rise rates were less
293 than +/- 10%. The mean rise rate at Pakse changed by -21% and then fell again to under -8 %
294 at Stung Treng. The mean fall rate changes, however, ranged from over 42% at Chiang Sean
295 to just over 5% in Pakse. At Stung Treng, mean fall rates increase by over 12% ($p \leq 0.01$).
296 At Prek Kdam in the Tonle Sap, rise and fall rates changed significantly by approximately -
297 23 % ($p \leq 0.001$) and -11 % ($p \leq 0.01$), respectively.

298

299 **3.6 Number of water level fluctuations**

300 The difference in the number of water level changes (fluctuations) was calculated for each
301 site. Water level fluctuations represent the number of times per year water levels have

302 reversed from rising to falling or from falling to rising. Mean yearly values and coefficients
303 of variations are reported for pre- and post-1991 periods for each of the monitoring sites
304 (Table 4). Results indicate a significant increase in the number of fluctuations for all stations
305 along the Mekong in the post-1991 period. The percent increase in the mean number of
306 yearly fluctuations in Chiang Sean is 75 %, but this value decreases steadily downstream to
307 17 % at Mukdahan. An increase in the mean number of fluctuations was observed at Pakse
308 with a mean increase of 26 fluctuations per year representing a 49 % increase after 1991.
309 The percent increase in post-1991 fluctuations decreases in the downstream Stung Treng and
310 Prek Kdam stations to 26 and 4 %, respectively.
311 Changes in the number of fluctuations per year between pre- and post-1991 for all stations
312 are presented in Figure 6. The number of fluctuations per year increase steadily after 1991
313 for all stations, but at different rates. An abrupt increase in yearly fluctuations after 1991 is
314 evident between Mukdahan and Pakse, as well as a diminishing rate of post-1991 increases in
315 fluctuations downstream of Chiang Sean to Mukdahan and from Pakse to Prek Kdam.

316 **4 Discussion**

317 Understanding and quantifying historical alterations influenced by water infrastructure
318 development is important as a benchmark for monitoring and to analyse the impacts of future
319 water infrastructure development in terms of ecological, economic, and social effects.
320 Alterations to all reported hydrological parameters are important as they are indicators of
321 wetland and river ecosystem habitat disruption, fish life histories, bank erosion, and sediment
322 redistribution. Rise/fall water level rates and water level fluctuations influence drought stress
323 on aquatic vegetation, entrapment of organisms on waterway islands or floodplains as well as
324 desiccation stress on low-mobility stream edge organisms (Poff et al. 1997). Above all,
325 changes to these hydrological factors could have subsequent impact on ecosystem

326 productivity in the Tonle Sap (Arias et al. 2014a), the major driver of fish production and
327 catches that are the largest source of protein consumed in the region (Hortle, 2007).

328

329 **4.1 Impacts of reservoir and irrigation operations on downstream water levels**

330 The hydrological alterations observed in the post-1991 period have a rational explanation
331 within the context of water infrastructure development in the Mekong. The key hydrological
332 alteration indicators (dry season, rise/fall rates, and fluctuations) quantified in the analysis of
333 pre- and post-1991 water level monitoring data can be linked to temporal and spatial patterns
334 of water resources development in the basin.

335

336 **Dry Season Water Levels**

337 To optimize electricity generation throughout the year, hydropower operations aim to fill
338 reservoirs during the wet monsoon season and release water at higher volumes than natural
339 flows in the dry season to extend the generation capacity. Operations of large reservoirs in the
340 Mekong basin were thus expected to increase downstream dry season water levels and
341 marginally reduce wet season water levels (e.g. Lu et al, 2014). An analysis of historical
342 rainfall patterns by Lu et al. (2014) upstream of Chiang Sean demonstrated that there has
343 been little variation in precipitation patterns pre and post 1991, although slight increases in
344 temperature were noted. The development of the four mainstream hydropower dams in the
345 upper Mekong in China is thus likely to have had a minor impact on the observed seasonal
346 water level changes since 1991, resulting in a modest increase in dry season water levels in
347 the stations closer to the dams, but with diminishing effects further downstream. However, it
348 has to be noted that the two largest dams were operational only after 2008 and thus their
349 mean effect on the pre and post 1991 historical analysis of dry season water levels is
350 relatively small, but it is expected to be observably larger in years to come. The difference

351 between pre and post 1991 thirty day dry levels only become significant further downstream
352 in Stung Treng and Prek Kdam, which can likely be attributed to development in the 3S
353 basin. Irrigation operations, on the other hand, would likely result in a reduction of
354 downstream water levels or the rise rate during the dry season as water demand for
355 agriculture increases (Floch and Molle, 2007).

356

357 **Water Level Rise and Fall Rates**

358 Irrigation will decrease downstream rise rates because water is abstracted during the growing
359 season, preventing downstream river water levels from rising at their normal rates.

360 Hydropower operations were not expected to increase downstream water level rise rates
361 during normal operations; however, during reservoir flood control operations, rise rates
362 would be reduced as water is held in reservoirs and slowly released thereafter. A significant
363 change of -21% water level rise rate was observed at Pakse post 1991, which can be
364 attributed to the level of irrigation in the Chi Mun basin during the growing (dry) season and
365 flood control operations (wet and dry) in the basin. A post-1991 near doubling of total
366 reservoir storage in the upper tributaries between Vientiane and Mukdahan (Table 2) can also
367 help explain an increase in rise rates downstream from Mukdahan due to increased irrigation
368 operations and flood control.

369 Retention of water in reservoirs during regular filling operations would increase water level
370 fall rates downstream. Observed post-1991 high fall rates with minimal alterations in rise
371 rates are indicative of hydropower reservoir filling and storage operations in the upper
372 Mekong up to Vientiane. On the other hand, downstream water retention would decrease fall
373 rates. For example, higher water levels in the Mekong River during the dry season will result
374 in lower water level fall rates in the Tonle Sap as water is discharged slower into the Mekong.

375

376 **Water Level Fluctuations**

377 Arguably the most evident indicator of hydrological alteration related to hydropower
378 reservoir operations is the number of downstream water level fluctuations (Wyatt and Baird,
379 2007). Even though this indicator is not a reflection of the volume of water being regulated, it
380 is indeed indicative of the frequency and intensity of water regulation along a river. In a
381 pristine large river water level fluctuations are minimal and typically reflect seasonal
382 changes; thus, an increase of this indicator in a large river is most likely a direct function of
383 reservoir fill and release operations. Lu and Siew (2006) had already shown had this indicator
384 increased at Chiang Sean once the Marwan dam was built. We have shown that this trend has
385 continued to increase not only at Chiang Sean but at stations further downstream.

386 We suggest that the post-1991 regulation of water in the Chi-Mun basin as a result of
387 reservoir and irrigation schemes is a major cause of the large number of water level
388 fluctuations observed at Pakse. The individual upstream dams in Chi-Mun may have limited
389 impact on water levels at the outlet; however, irrigation operations during the growing (dry)
390 season and the small (225 Mm³) Pak Mun dam at the basin outlet, which controls
391 hourly/daily flows to the greater Mekong, can directly alter downstream water level
392 fluctuations. Although this subbasin only contributes 5-10% of the total Mekong's discharge
393 at Pakse (MRC, 2005), it is not the quantity of water over the year, but rather the intensity
394 and frequency of water management operations that is reflected in the large increase of water
395 fluctuations at Pakse. In a similar manner, albeit at a lesser magnitude, the current regulation
396 of waters in the 3S may have contributed to water level fluctuations in Stung Treng. The
397 impact of the 3S tributary dams has been small up to 2010 because the dams are located in
398 the highlands of these subbasins (Piman et al. 2013b). The Chi-Mun basin, however, will not
399 experience further significant hydropower development, whereas the 3S basin has the
400 potential for large reservoir storage projects in the near future (Piman et al. 2013b). Thus, we

401 expect hydrological alterations (fluctuations, fall/rise rates, and seasonality) to increase
402 beyond levels observed currently in Pakse and as far down as the Tonle Sap floodplain as it
403 has been predicted to some extent with numerical models (Arias et al. 2014b). Water
404 infrastructure development for agriculture and hydropower is accelerating in other tributaries
405 throughout Laos, and this could further impact water levels in Mukdahan and downstream in
406 the near future. Furthermore, the development and operations of other dams in the
407 mainstream of the lower Mekong, such as the Xayabury dam in Laos, will undoubtedly have
408 an immediate effect on rise/fall rates and fluctuations, potentially affecting critical fisheries
409 and habitats in the lower Mekong.

410

411 **Impact on Water Levels of the Tonle Sap**

412 Because of the flow reversal phenomena in the Tonle Sap River, fall rates, rise rates, and
413 fluctuations for the Prek Kdam station are affected both by Mekong river inflows/outflows
414 and by contributing flows from the Tonle Sap catchment, which accounts for approximately
415 34% of yearly flows (Kummu, et al., 2014). Alterations to rise and fall rates can affect the
416 reversal of water flows in the Tonle Sap River. Of significant importance is that Prek Kdam
417 exhibited a post 1991 decrease of 23 and 11 % of rise and fall rates, respectively, and a
418 decrease of 65 and 71 % in the deviation of the coefficient of variation. The decrease in rise
419 rates in the Tonle Sap River (Table 4) is likely a result of the increase in dry season water
420 levels in the Mekong resulting in a milder slope in the water level rise rate during the filling
421 phase of the Tonle Sap. Rise and fall rates, as well as a significant decrease in the coefficient
422 of variation for both parameters, indicates a modified flood pulse regime and more stable
423 water levels in the Tonle Sap system as a result of upstream water infrastructure
424 development. Most impact assessments of hydropower on the Tonle Sap have focused on
425 seasonal water levels and spatial inundations patterns (see Kummu and Sarkkula, 2008; Arias

426 et al., 2012; Arias et al., 2014a; Piman et al., 2013a), but alterations to the magnitude of
427 fall/rise rates have been dismissed for the most part. Given the strong synchronicity between
428 water flows, fish migrations, and fish catches in the Tonle Sap, it is probable that such
429 hydrological alterations had an undocumented effect on the fish ecology of this important
430 ecosystem. To the extent of our knowledge, however, there are no reliable fish catch records
431 or any ecological information pre-1991 that could be used to prove and quantify ecological
432 shifts in past decades.

433

434 **4.2 Climate versus water infrastructure development**

435 The impacts of climate change are temporally complex and spatially varied and there is no
436 consensus as to what the potential climate-driven water level alterations might be throughout
437 the Mekong basin despite multiple discussions on the subject (e.g., Kingston et al. 2011,
438 Lauri et al., 2012, Thompson et al., 2013). Specific climate change factors, such as an
439 increase in glacial melting, could theoretically contribute to increased water levels during the
440 dry season as it has occurred in other large rivers with headwater in the Himalayas (Xu et al.
441 2009); however, to date there is no consensus as to the extent of alterations in Mekong flows
442 might be associated with the Himalaya's melting (Xu et al. 2009). Cook et al. (2012) found a
443 significant relationship between Himalaya's snow cover and dry season flows as far south as
444 Kratie, but they concluded that contemporary and future changes in lower Mekong flows
445 between March and May are negligible as a result of the conflicting effect of melting snow
446 cover and increasing local precipitation . To our knowledge, there is no evidence of climate
447 induced alterations to indicators other than interannual and wet season extremes; besides,
448 most of the previous studies highlighting the correlation between climate and river discharge
449 patterns have only demonstrated contemporary alterations during the wet season months
450 (Delgado et al., 2010; Räsänen and Kummu, 2013; Räsänen et al., 2013). The link between

451 infrastructure development and water levels presented in this paper have largely excluded
452 those indicators representing alterations during the wet season; thus, we argue that it is more
453 likely that the increased number of water level fluctuations, as well as alterations to rise/fall
454 rates observed in the post-1991 measurements at the various monitoring stations are evidence
455 of the increasing impact of infrastructure development through the Mekong basin.
456 Furthermore, hydropower simulations in the 3S basin demonstrate that changes to
457 downstream water levels from various scenarios of climate change are minimal compared to
458 the ability of hydropower operations to alter water levels (Piman et al., 2014).

459

460 **5 Conclusions**

461 This paper clarifies that the perception of a *Pristine Mekong* may have been outdated for over
462 two decades. We have shown that hydropower operations and irrigation development in the
463 Mekong may have already caused observable alterations to natural water levels along the
464 Mekong mainstream and the Tonle Sap river beginning as early as 1991. Increases in water
465 levels during the dry season (March, April and May) of 35% to 20% post-1991 in Chiang
466 Sean downstream to Stung Treng were documented, and such alterations, although relatively
467 minor, are probably caused by water infrastructure development in the basin. The effect of
468 the upper Mekong hydropower development tributary operations is clearly observable up to
469 Mukdahan station in terms of water level fluctuations and fall rates. Alterations observed in
470 Pakse and downstream are likely a result of irrigation development, flood control, and
471 hydropower hourly/daily operations (at Pak Mun dam in particular) in the Chi-Mun basin.
472 Alterations observed downstream from Stung Treng will be exacerbated by the ongoing
473 development in the 3S basin. Previous studies have highlighted climate shifts occurring
474 downstream of Pakse as the factor responsible for long term hydrological alterations to wet
475 season floods; however, alterations to dry season levels, water level rise/fall rates and

476 fluctuations has not been related to climate variability, and as we have demonstrated in this
477 paper they were most likely caused by water infrastructure development in China and
478 Thailand during the 1990s and 2000s.

479 Ongoing and proposed hydropower development will continue to increase the magnitude of
480 water level alterations throughout the Mekong. Given the numerous water infrastructure
481 development proposals which will significantly increase the basin's total active storage,
482 drastic alterations to the hydrological pulse and subsequent ecological features in the Tonle
483 Sap (Kummu and Sarkkula, 2008, Arias et al. 2012; Arias et al. 2014a) and the rest of the
484 Mekong floodplains do not seem unrealistic. In particular, development in catchments such as
485 the 3S basin is occurring at a fast pace in a poorly coordinated fashion. Recent estimates with
486 detail modelling of the 3S dams have shown considerably higher levels of alterations in the
487 Tonle Sap than what has been observed or simulated before (Arias et al. 2014b), which
488 highlights the potentially confounding impacts of these dams. Moreover, indicators of
489 hydrological alterations in the Mekong highlighted in this paper, in particular rise rates, fall
490 rates, and water level fluctuations, have been dismissed for the most part from modelling
491 studies. Future research should explicitly simulate and analyse daily and even hourly water
492 levels in order to capture these key indicators of change. Given the historical alterations we
493 have documented and the expected future development in the Mekong, research is also
494 necessary to examine ecological indicators linked to the system's hydrology in order to
495 quantify past, current, and future alterations before they become a threat to the integrity,
496 biodiversity, and food security of the Mekong.

497

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684

685 Table 1. Catchment areas and average historical seasonal flows (1960-2004) above each
 686 monitoring station. Source: MRC (2010) and verified with flow records.

Monitoring station	Catchment area in km ²	Mean dry season (Dec. - May) flows in m ³ /s	Mean wet season (Jun. - Nov.) flows in m ³ /s	Mean annual flows in m ³ /s
Chiang Sean (CS)	189,000 (25%)	1,120 (5%)	4,250 (14%)	2,700 (19%)
Luang Prabang (LP)	268,000 (35%)	1,520 (6%)	6,330 (21%)	3,900 (27%)
Vientiane (VT)	299,000 (39%)	1,630 (7%)	7,190 (23%)	4,400 (30%)
Mukdahan (MH)	391,000 (51%)	2,200 (9%)	12,950 (43%)	7,600 (52%)
Pakse (PS)	545,000 (72%)	2,620 (10%)	16,850 (57%)	9,700 (67%)
Stung Treng (ST)	635,000 (84%)	3,310 (13%)	22,940 (77%)	13,100 (90%)
Total basin	760,000 (100%)			14,500 (100%)

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697 Table 2. Hydropower reservoir active and total storage (Mm³) above monitoring stations in
 698 operation by 2010.

Year	Chiang Sean (CS)			Luang Prabang (LP)			Vientiane (VT)		
	No.	Active	Total	No.	Active	Total	No.	Active	Total
Pre-1991	0	0.00	0.00	0	0.00	0.00	1	0.02	0.03
1991-1995	1	257.00	920.00	2	257.00	920.01	2	257.00	920.01
1996-2000	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00
2001-2005	1	367.00	933.00	2	367.67	933.70	2	367.67	933.70
2006-2010	2	10,149.00	16,363.00	2	10,149.00	16,363.00	2	10,149.00	16,363.00
Total	4	10,773.00	18,216.00	6	10,773.68	18,216.71	7	10,773.69	18,216.73

Year	Mukdahan (MH)			Pakse (PS)			Stung Treng (ST)		
	No.	Active	Total	No.	Active	Total	No.	Active	Total
Pre-1991	3	4856.82	7165.53	8	7852.12	11,606.33	9	7853.62	11,609.23
1991-1995	2	257.00	920.01	4	382.30	1,147.34	5	382.42	1,147.49
1996-2000	2	243.20	375.40	2	243.20	375.40	3	892.20	1,049.50
2001-2005	3	412.67	1,038.43	4	702.67	1,348.43	5	1,481.69	2,387.14
2006-2010	5	17,347.40	28,124.99	6	17,356.70	28,134.86	17	19,302.83	32,476.44
Total	15	23,117.09	37,624.35	24	26,536.99	42,612.35	39	29,912.76	48,669.79

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702 Table 3. Indicators of hydrological alterations and alteration factors (within 1 standard
 703 deviation) at Chiang Sean.

Indicators of hydrological alterations	Pre-impact period: 1960-1990				Post-impact period: 1991-2010			
	Means	Coeff. of var.	RVA Boundaries ^a		Means	Coeff of var.	Hydrologic alteration factor ^b	ANOVA Signif. level ^c
			Low	High				
Mean monthly values (m)								
January	1.396	0.206	1.108	1.683	1.52	0.1939	0.143	
February	1.010	0.215	0.794	1.227	1.156	0.2401	-0.143	*
March	0.796	0.262	0.587	1.004	1.038	0.2551	-0.333	***
April	0.954	0.237	0.728	1.180	1.188	0.2949	-0.571	**
May	1.557	0.300	1.090	2.025	1.899	0.2329	-0.114	*
June	2.948	0.201	2.357	3.539	2.95	0.2358	-0.152	
July	4.639	0.168	3.860	5.417	4.918	0.1799	0.050	
August	5.912	0.160	4.969	6.855	5.711	0.1716	-0.182	
September	5.262	0.158	4.430	6.094	5.301	0.1642	-0.100	
October	4.180	0.126	3.652	4.708	4.115	0.1228	0.000	
November	3.023	0.163	2.530	3.515	2.975	0.2128	-0.182	
December	1.998	0.178	1.644	2.353	2.028	0.1628	0.000	
Extreme water conditions (m)								
1-day minimum	0.623	0.315	0.427	0.819	0.599	0.546	-0.357	
3-day minimum	0.631	0.313	0.434	0.829	0.649	0.532	-0.357	
7-day minimum	0.650	0.304	0.452	0.847	0.728	0.424	-0.550	
30-day minimum	0.734	0.274	0.533	0.935	0.886	0.312	-0.325	*
90-day minimum	0.895	0.230	0.689	1.102	1.097	0.220	-0.325	**
1-day maximum	8.204	0.179	6.733	9.675	7.959	0.172	-0.152	
3-day maximum	8.000	0.186	6.514	9.486	7.738	0.173	-0.188	
7-day maximum	7.556	0.194	6.091	9.020	7.300	0.172	-0.188	
30-day maximum	6.376	0.160	5.355	7.397	6.246	0.158	-0.022	
90-day maximum	5.430	0.118	4.787	6.072	5.426	0.136	-0.280	
Timing of extreme water conditions								
Date of minimum	87.2	0.039	72.8	101.5	91.5	0.064	-0.152	
Date of maximum	233.1	0.069	207.6	258.5	242.8	0.063	-0.063	
Pulses Frequency/duration (days)								
Low pulse count	2.3	0.595	0.9	3.7	3.5	0.755	-0.5	***
Low pulse duration	26.5	0.863	10.4	49.3	6.4	0.691	-0.7	
High pulse count	5.3	0.407	3.2	7.5	5.4	0.280	0.3	
High pulse duration	15.7	0.692	4.8	26.6	13.5	0.602	0.0	
Water condition changes								
Rise rate (m/day)	0.186	0.155	0.157	0.214	0.189	0.157	-0.071	
Fall rate (m/day)	-0.102	-0.128	-0.115	-0.089	-0.145	-0.202	-0.850	***
Number of fluctuations	73.9	0.115	65.4	82.4	129.4	0.187	-0.929	***

704 ^a Range of Variability Approach Boundaries represent the values within one standard deviation from the pre-
 705 impact period mean

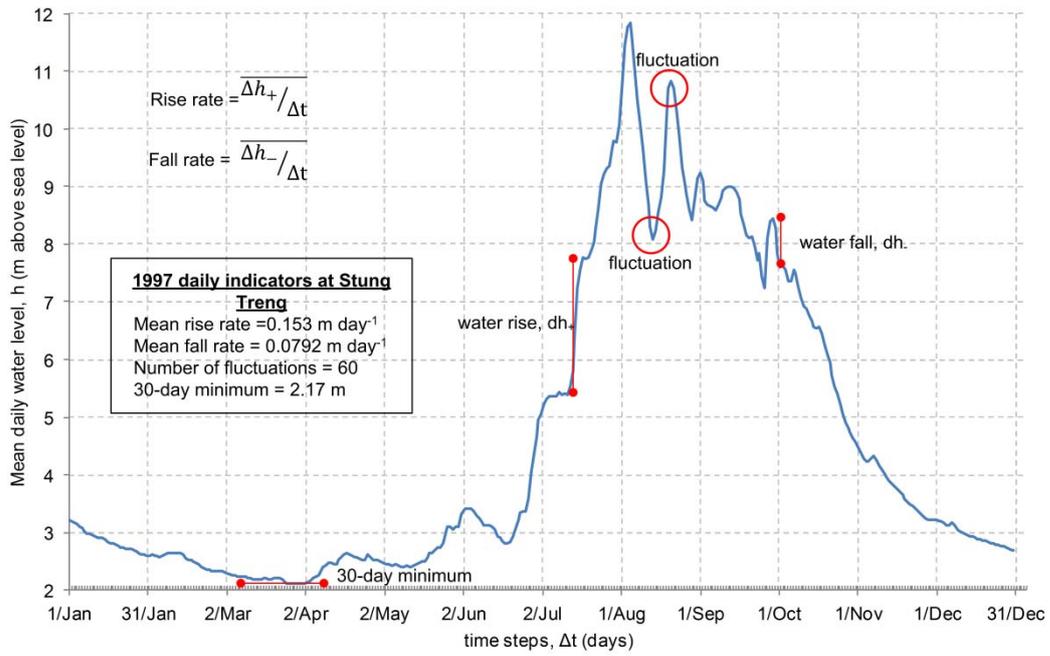
706 ^b Hydrological alternation factor represents the percentage of years in the post-impact period in which values fall
 707 outside the RVA boundaries

708 ^c Significance level codes: ***: $p \leq 0.001$; **: $p \leq 0.01$; *: $p \leq 0.05$; .: $p \leq 0.1$

709 Table 4. Hydrological alterations of selected indicators for pre- and post- 1991 periods along
 710 the lower Mekong

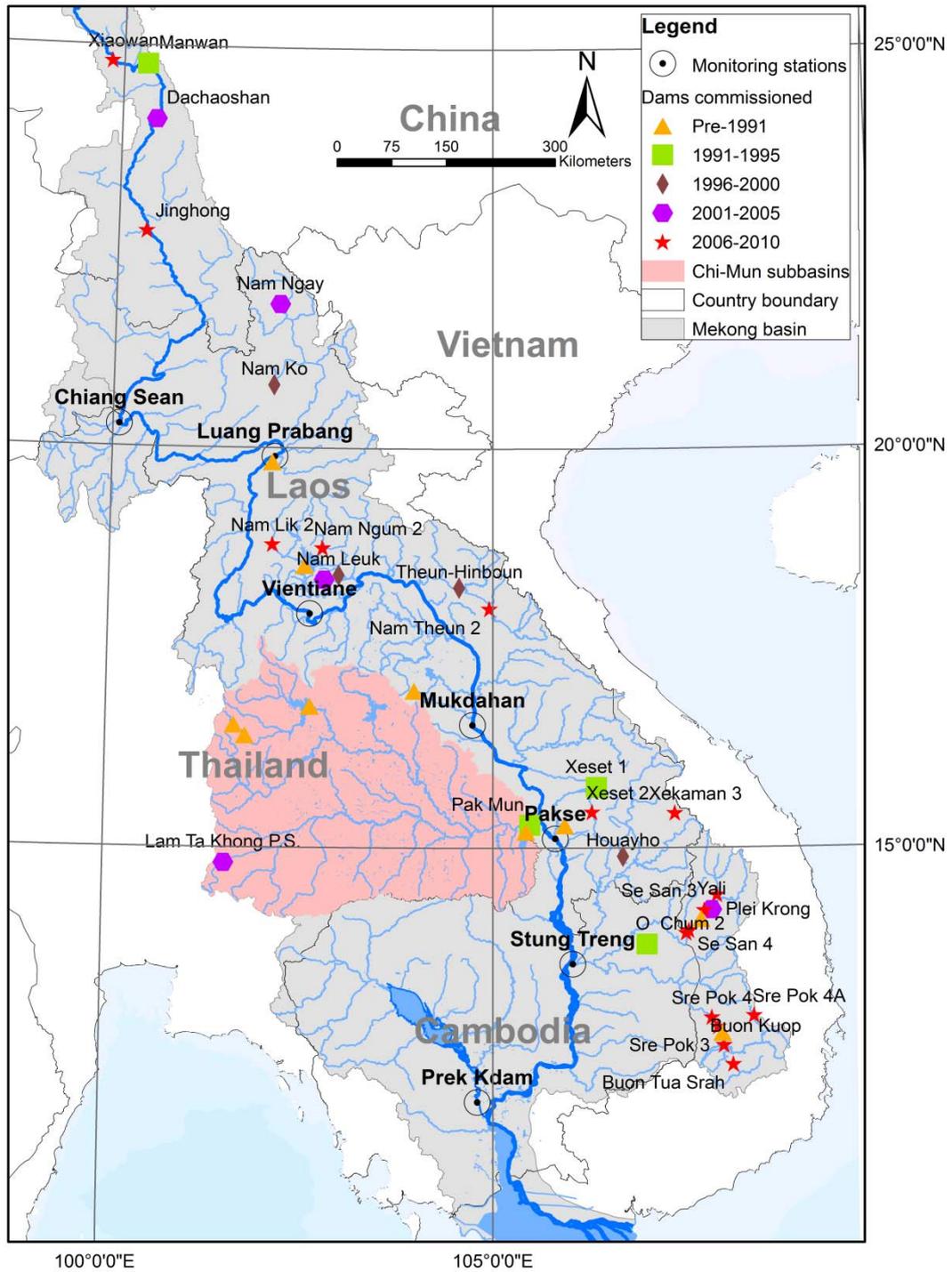
Monitoring station	Indicators of hydrological alteration	Pre-impact (1960-1990)		Post-impact (1991-2010)		ANOVA signif. level ^a
		mean	coeff. of var.	mean (% diff.)	coeff. of var. (% diff.)	
Chiang Sean	Rise rate (m/day)	0.186	0.155	0.189 (+2)	0.157 (+2)	
	Fall rate (m/day)	-0.102	-0.128	-0.145 (+42)	-0.202 (+58)	***
	Number of fluctuations	73.9	0.115	129.4 (+75)	0.187 (+62)	***
	30-day minimum	0.734	0.274	0.886 (+21)	0.312 (14)	*
Luang Prabang	Rise rate (m/day)	0.261	0.133	0.252 (-3)	0.174 (+31)	
	Fall rate (m/day)	-0.138	-0.114	-0.164 (+18)	-0.156 (+37)	***
	Number of fluctuations	66.8	0.123	92.8 (+39)	0.136 (+11)	***
	30-day minimum	3.189	0.067	3.217 (+1)	0.109 (+64)	
Vientiane	Rise rate (m/day)	0.196	0.103	0.190 (-3)	0.136 (+32)	
	Fall rate (m/day)	-0.104	-0.115	-0.120 (+15)	-0.130 (13)	***
	Number of fluctuations	56.1	0.135	69.4 (+24)	0.137 (+1)	***
	30-day minimum	0.530	0.4137	0.710 (+34)	0.437 (+6)	*
Mukdahan	Rise rate (m/day)	0.171	0.138	0.157 (-8)	0.131 (-5)	*
	Fall rate (m/day)	-0.091	-0.086	-0.095 (+5)	-0.112 (+31)	.
	Number of fluctuations	45.6	0.159	53.2 (+17)	0.149 (-6)	**
	30-day minimum	1.192	0.09492	1.231 (+3%)	0.1579 (+66)	
Pakse	Rise rate (m/day)	0.207	0.171	0.163 (-21)	0.124 (-28)	***
	Fall rate (m/day)	-0.100	-0.128	-0.105 (+5)	-0.092 (-28)	
	Number of fluctuations	54.6	0.148	81.3 (+49)	0.197 (+33)	***
	30-day minimum	0.615	0.205	0.734 (+19)	0.256 (+25)	*
Stung Treng	Rise rate (m/day)	0.156	0.189	0.144 (-8)	0.167 (-11)	
	Fall rate (m/day)	-0.078	-0.131	-0.087 (+12)	-0.136 (+4)	**
	Number of fluctuations	57.7	0.140	72.7 (+26)	0.144 (+3)	***
	30-day minimum	1.880	0.080	2.119 (+13)	0.092 (+15)	***
Prek Kdam	Rise rate (m/day)	0.104	0.265	0.080 (-23)	0.119 (-55)	***
	Fall rate (m/day)	-0.060	-0.183	-0.054 (-11)	-0.069 (-62)	*
	Number of fluctuations	47.7	0.186	50.0 (+5)	0.178 (-4)	
	30-day minimum	0.833	0.127	0.979 (+17)	0.155 (+22)	***

711 ^aSignificance level codes: ***: $p \leq 0.001$; **: $p \leq 0.01$; *: $p \leq 0.05$; .: $p \leq 0.1$



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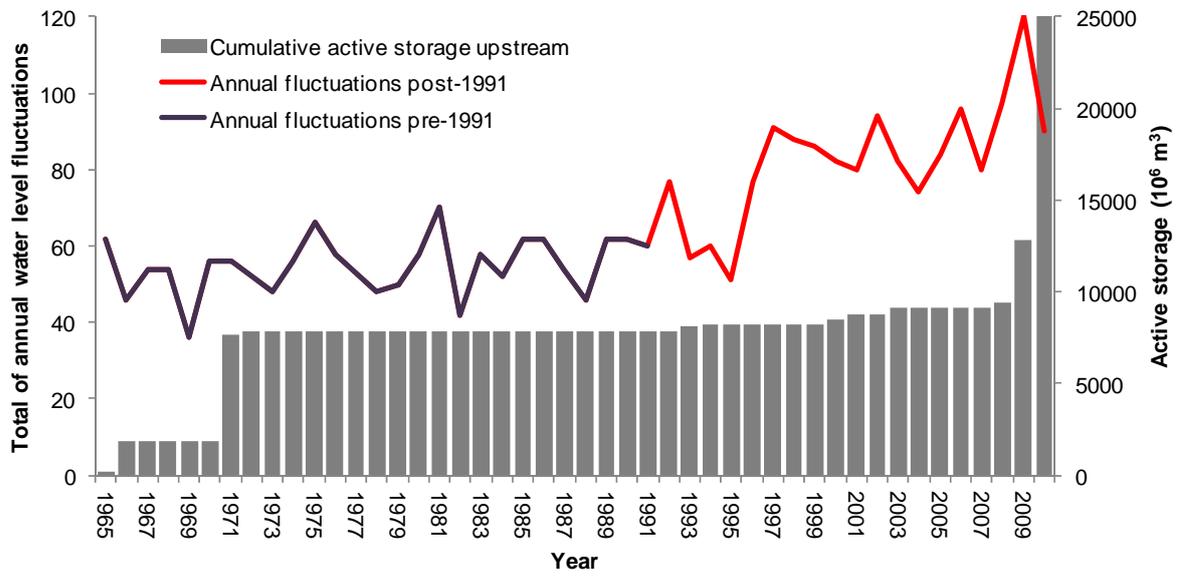
713 Figure 1. Illustration of hydrological alteration indicators most sensitive to reservoir
 714 operations. Hydrograph represents mean daily water levels during 1997 at Stung Treng.



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716 Figure 2. Operating dams and key hydrological monitoring stations in the Mekong Basin up
 717 to December 2010.

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720 Figure 3. Temporal trend in water level fluctuations and cumulative active storage upstream
721 of Pakse.

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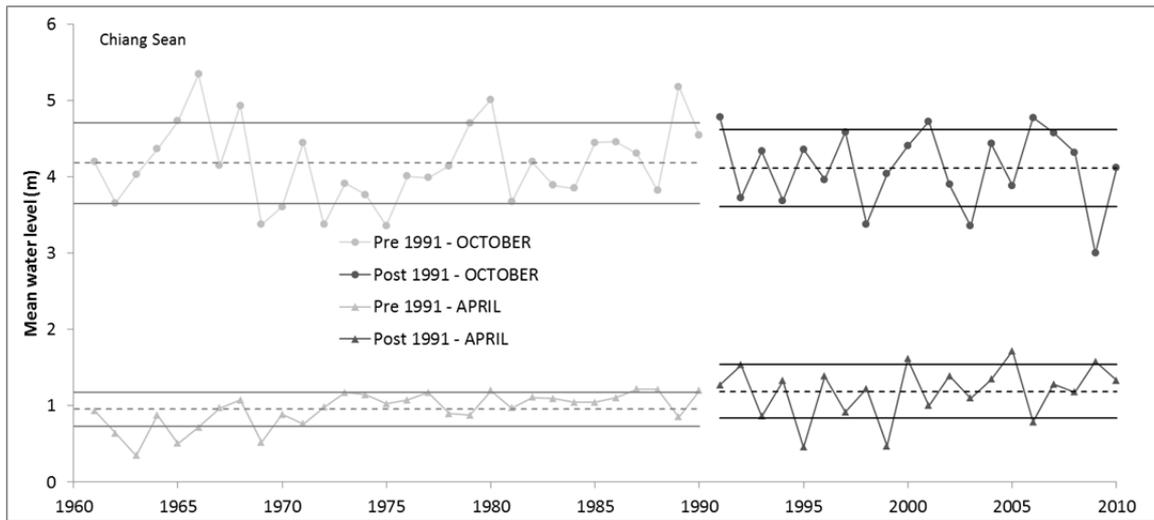
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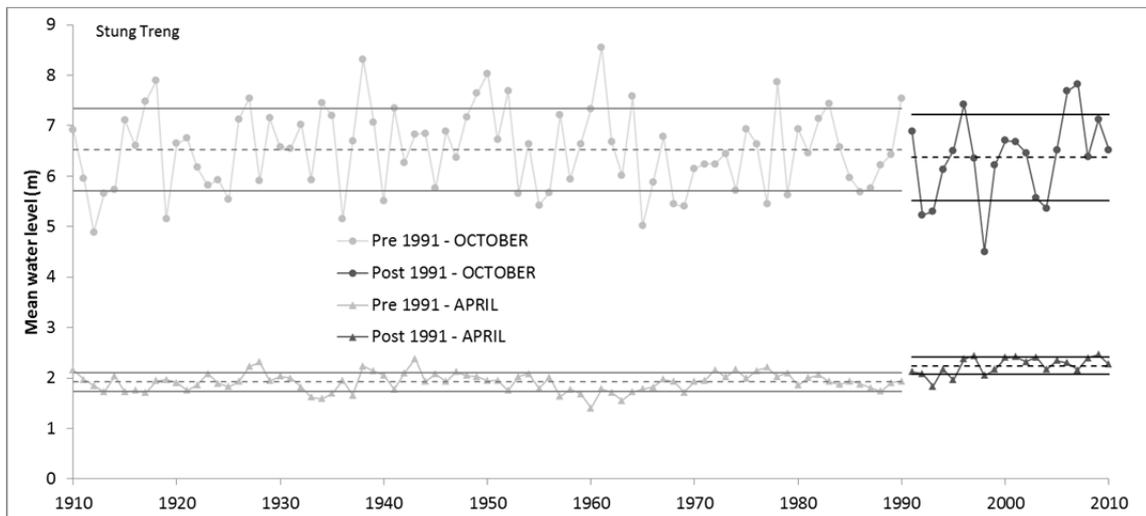
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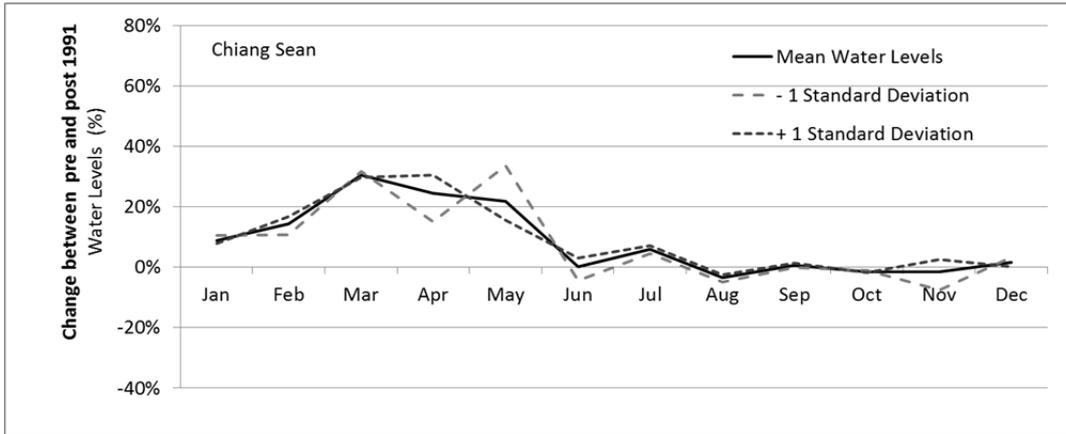
731 Figure 4. Mean measured water levels at Chiang Sean (1960-2010) and Stung Treng (1910 to
732 2010) for the months of April and October. Dashed lines indicate mean water levels for
733 periods before and after 1991 and parallel solid lines indicate ± 1 standard deviations
734 around the mean for each period.

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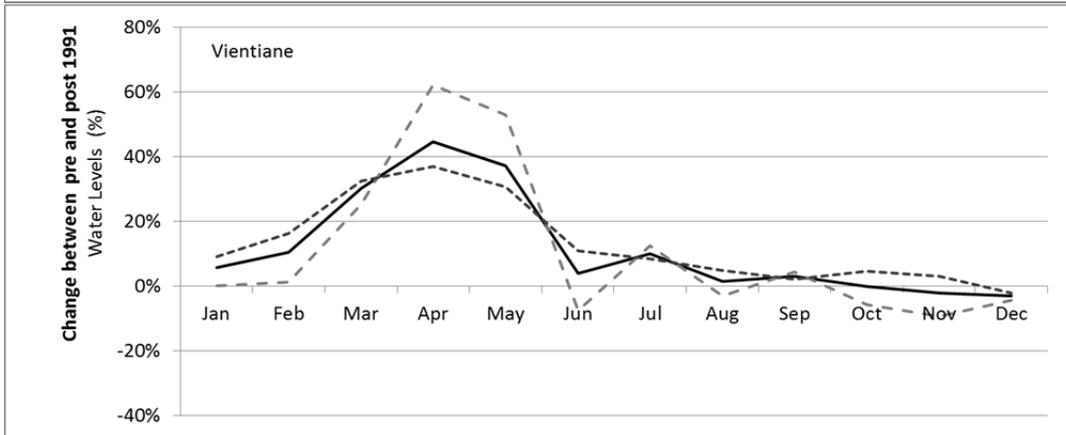
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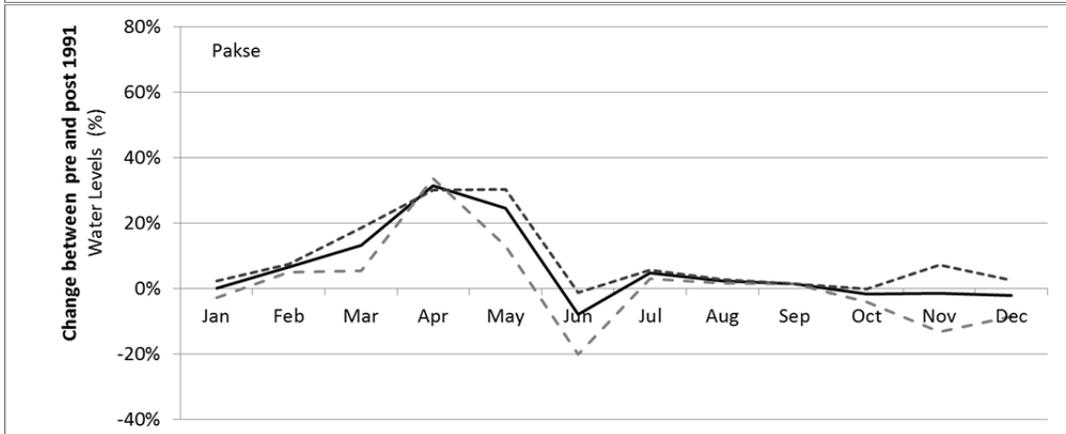
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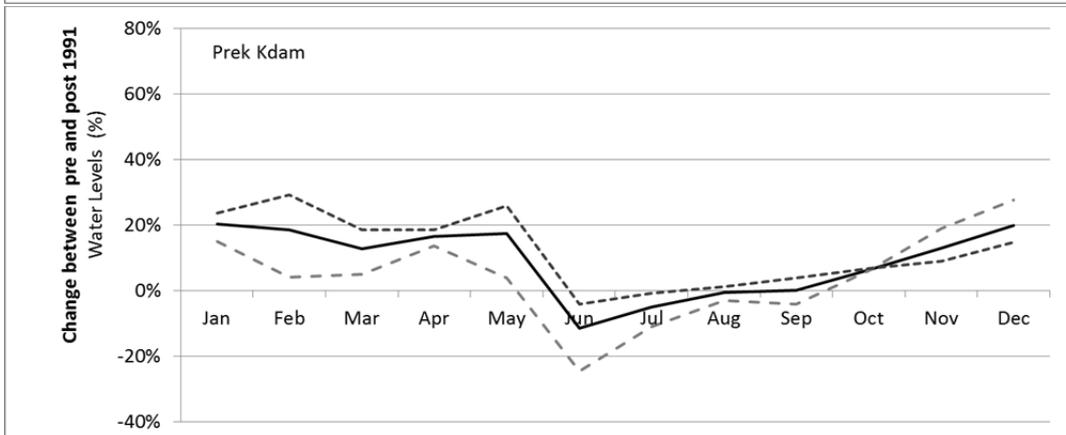
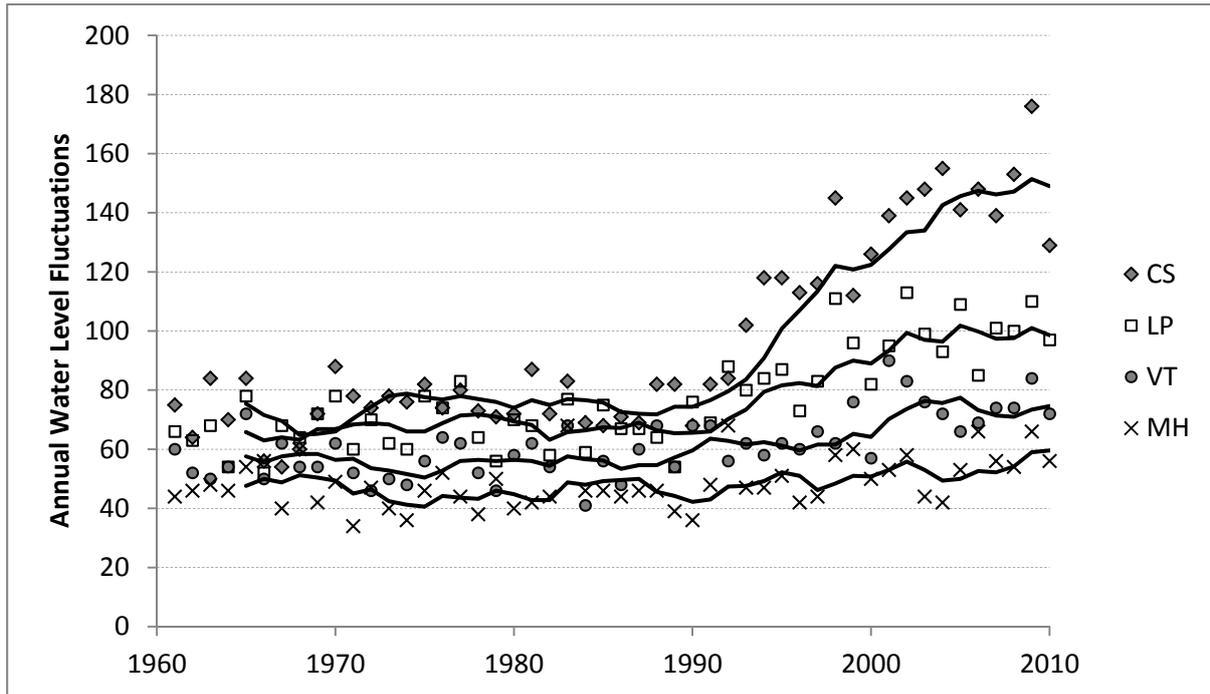
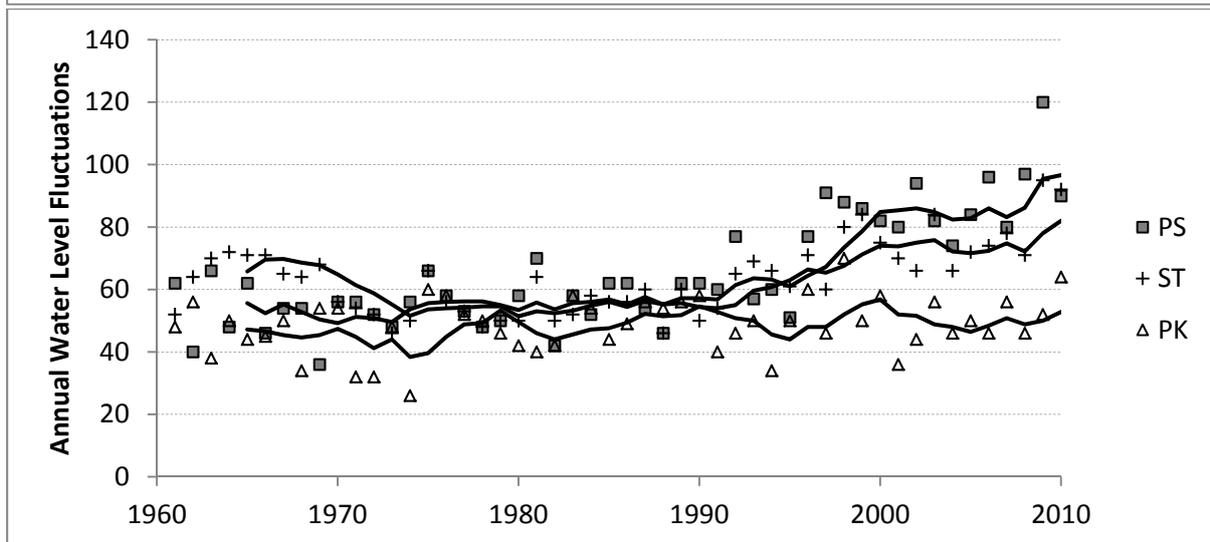


Figure 5. Change (%) in average mean and +/- 1 standard deviations for each month between pre and post 1991 water levels for Chiang Sean, Vientiane, Pakes, and Prek Kdam.

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Figure 6. Number of annual water level fluctuations for each monitoring station between

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1961 and 2010. Solid lines indicate a 5 year moving average for each station: Chiang Sean

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(CS), Luang Prabang (LP), Vientiane (VT), Mukdahan (MH), Pakse (PS), Stung Treng (ST),

751

and Prek Kdam (PK).

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755 **Supplementary Material**

756 Table S1. Existing dams up to 2010 in Mekong River Commission hydropower database

757 (MRC, 2014).

Location	MRC dam code	Dam Name	Year Completed	Active storage (M m ³)	Total storage (M m ³)
Above CS	C001	Manwan	1993	257.000	920.000
	C002	Dachaoshan	2003	367.000	933.000
	C003	Jinghong	2008	249.000	1,233.000
	C004	Xiaowan	2010	9,900.000	15,130.000
CS-LP	L009	Nam Ko	1996	0.005	0.007
	L010	Nam Ngay	2002	0.674	0.700
LP-VT	L002	Nam Dong	1970	0.015	0.025
VT-MH	T003	Nam Pung	1965	156.800	165.500
	L001	Nam Ngum 1	1971	4,700.000	7,000.000
	L005	Theun-Hinboun	1998	15.000	30.000
	L007	Nam Leuk	2000	228.200	345.400
	L008	Nam Mang 3	2004	45.000	104.730
	L011	Nam Theun 2	2009	3,378.400	3,680.190
	L014	Nam Ngum 2	2010	2,994.000	6,740.000
	L015	Nam Lik 2	2010	826.000	1,341.800
MH-PS	T006	Ubol Ratana	1966	1,695.000	2,263.000
	L003	Xelabam	1969	0.800	1.000
	T005	Sirindhorn	1971	1,135.000	1,966.000
	T001	Chulabhorn	1972	144.500	188.000
	T002	Huai Kum	1982	20.000	22.800
	T004	Pak Mun	1994	125.000	225.000
	L004	Xeset 1	1994	0.300	2.330
	T007	Lam Ta Khong P.S.	2001	290.000	310.000
	L013	Xeset 2	2009	9.300	9.870
PS-ST	V014	Dray Hlinh 1	1990	1.500	2.900
	C001	O Chum 2	1992	0.120	0.150
	L006	Houayho	1999	649.000	674.100
	V003	Yali	2001	779.020	1,038.710
	V004	Se San 3	2006	3.800	86.500
	V005	Se San 3A	2007	4.000	80.610
	V002	Plei Krong	2008	948.000	1,948.680
	V007	Se San 4A	2008	7.500	8.500
	L012	Xekaman 3	2009	108.540	163.860
	V006	Se San 4	2009	264.160	893.340
	V009	Buon Tua Srah	2009	522.600	752.280
	V010	Buon Kuop	2009	14.740	36.110
	V012	Sre Pok 3	2009	62.580	242.780
	V013	Sre Pok 4	2009	10.110	128.740
	V015	Sre Pok 4A	2009	0.100	0.180

758 Table S2. Multi-use reservoirs (hydropower and irrigation) in the Chi and Mun basins. Data
 759 from MRC (2014).

Project	Year completed	Agency	Location	Watershed area (km ²)	Storage capacity (10 ⁶ m ³)	Power generating capacity (MW)	Annual average power (GWh)
Ubol Rattana	1966	EGAT	Ubol Rattana District, Khon Kaen	12,000	2,263	25.2	54.73
Sirindhorn (Lam Dom Noi)	1971	EGAT	Piboon Mungsahan District, Ubon Ratchathani	2,097	1,966	36	90
Chulaphon	1972	EGAT	Konsan District, Chaiyaphum	545	188	40	94.84
Huey Koom	1982	EGAT	Kaset District, Chaiyaphum	262	22.8	1.06	2.91
Huey Patoa	1992	DEDE	Kang Kroh, Chaiyaphum	162	44 & 14.8	4.5	18.41
Pak Mun	1994	EGAT	Khong Jiem District, Ubon Ratchathani	117,000	225	136	280
Lam Takong	2001	EGAT	Sikiew District, Nakhon, Ratchasima	1,430	310	500	400

760 Source: Electricity Generating Authority of Thailand (EGAT), Department of Alternative
 761 Energy Development and Efficiency (DEDE)
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