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

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Abstract

The rapid rate of water infrastructure development in the Mekong basin is a cause for concern due to its potential impact on fisheries and downstream natural ecosystems. In this paper we analyse the historical water levels of the Mekong River and Tonle Sap system by comparing pre and post 1991 daily observations from six stations along the Mekong mainstream from Chiang Sean (northern Laos), to Stung Treng (Cambodia), and the Prek Kdam station on the Tonle Sap River. Observed alterations in water level patterns along the Mekong are linked to temporal and spatial trends in water infrastructure development from 1960 to 2010. We argue that variations in historical climatic factors are important, but they are not the main cause of observed changes in key hydrological indicators related to ecosystem productivity. Our analysis shows that the development of mainstream dams in the upper Mekong basin in the post-1991 period have resulted in a significant increase of 7-day minimum (+ 91.6%), fall rates (+42 %), and the number of water level fluctuations (+75) observed in Chiang Sean. This effect diminishes downstream until it becomes negligible at Mukdahan (northeast Thailand), which represents a drainage area of over 50% of the total Mekong Basin. Further downstream at Pakse (southern Laos), alterations to the number of fluctuations and rise rate became strongly significant after 1991. The observed alterations slowly decrease downstream, but modified rise rates, fall rates, and dry season water levels were still quantifiable and significant as far as Prek Kdam. This paper provides the first set of evidence of hydrological alterations in the Mekong beyond the Chinese dam cascade in the upper Mekong. Given the evident alterations at Pakse and downstream, post-1991 changes can also be directly attributed to water infrastructure development in the Chi and Mun basins of Thailand. A reduction of 23% and 11% in the water raising and fall rates respectively at Prek Kdam provides evidence of a diminished Tonle Sap flood pulse in the post-1991 period. Given the observed water level alterations from 1991 to 2010 as a result of water infrastructure development, we can extrapolate that future development in the mainstream and the key transboundary Srepok, Sesan and Sekong subbasins will have an even greater effect on the Tonle Sap flood regime, the lower Mekong floodplain, and the delta.

1 Introduction

The Mekong River is one of the great rivers in the world, originating in the Tibetan highlands and draining into the South China Sea where it forms the Vietnam delta. It has a length of over 4,180 km, drains an area of 795,000 km^2, and has a mean annual discharge flow of 14,500 m^3/s (MRC, 2005). The Mekong's hydrology is driven by the Southeast Asian monsoons, causing the river to have a distinct seasonal flood pulse. A unique feature of the Mekong River is its interaction with Southeast Asia's largest lake, the Tonle Sap in Cambodia. The Mekong River receives discharge water from the Tonle Sap Lake during the dry season (November to May) via the Tonle Sap River; during the wet season (June to October), the floodwaters of the Mekong reverse the direction of the Tonle Sap River and flow into the lake, causing its surface area to expand from 2,600 km^2 to approximately 15,000 km^2. The Tonle Sap system, along with the Mekong River and its tributaries, are also considered one of the world's most productive freshwater fisheries (Baran and Myschowoda, 2009). Fish catch in the Mekong and Tonle Sap provides over 50% of the protein consumed by humans in the lower Mekong (Hortle, 2007). The natural seasonal flood pulse and hydrological water level patterns of the Mekong are attributed as being principal features for maintaining the system's high ecosystem productivity (Holtgrieve et al., 2013).

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

Evidence of how dams and irrigation affect natural river regimes have been widely documented throughout the world (Nilsson et al. 2005; Lehner et al. 2011). Dam operations, for example, can affect rivers by redistributing and homogenizing flows, which is reflected in decreased seasonal and inter-annual variability (Poff et al. 2007). These temporal trends, however, can also be affected by other factors such as climate, making the distinction of dam-driven vs. climate-driven alterations troublesome at times. To overcome this issue, it is necessary to identify specific hydrological parameters that are solely associated to water infrastructure development.

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

Localized evidence of dam-related hydrological alterations has been documented in the Mekong, but it is generally accepted that system-wide disruptions are not yet readily evident (Adamson et al., 2009). For the Yali Falls dam in Sesan River in Vietnam, significant downstream water level fluctuations and increases in dry season water levels have been directly attributed to the operation of the dam, which have causes adverse ecological and social impacts including bank erosion, adverse effects on sand bar nesting birds, disruptions on fishing, shellfish collection and others (Wyatt and Baird, 2007). A number of studies have analysed the localized impact of the Lancang-Jiang hydropower cascade in the upper Mekong in China. For instance, Li and He (2008) studied linear trends in multiyear mean water levels and concluded that no major alterations occurred as a result of the first two dams in China's cascade. On the other hand, Lu and Siew (2006) found a significant decrease in dry season water levels and an increase in water level fluctuations in 1993-2000 at Chiang Sean, immediately downstream of the Chinese dam cascade. More recently, Lu et al. (2014) assessed alterations to monthly water discharge at that same station up to 2010 and found moderate alterations during March and April. The effect of the Chinese dams has also been investigated through modelling studies by Räsänen et al. (2012) and Piman et al. (2013a) who reported potential increases in dry season water discharge as far downstream as Kratie in Central Cambodia. To the best of our knowledge, no study has documented hydrological alterations in the Mekong caused by dams or other water infrastructure beyond the Chinese dam cascade.

Contemporary basin-wide hydrological shifts have been documented in the Mekong, but they have been primarily attributed to climatic patterns and not water infrastructure development. In particular, a strong link between El Niño-Southern Oscillation (ENSO) and inter-decadal patterns in wet season precipitation and river discharge of the Mekong has been suggested (Delgado et al. 2012; Räsänen and Kummu, 2013). As 80-90% of the Mekong's discharge occurs from May to October (Delgado et al. 2012), most of the research linking climate and river discharge has focused on the distinct wet season months (typically June to October). In general, strong El Niño periods have corresponded to years of lower than normal wet season floods in the Mekong, whereas La Niña periods have corresponded to years of higher than normal floods. The strong shift in the North Pacific was also detectable in the Lower Mekong wet season discharge (Delgado et al., 2012), and overall, interannual variability in flood levels have significantly increased during the Twentieth Century (Delgado et al., 2010; Räsänen et al. 2013). With regards to the dry season, Cook et al. (2012) studied relationships between lower Mekong water discharge during March-May with snow cover and local precipitation. With opposite trends in snow cover (decrease) and precipitation (increase), Cook et al. (2012) estimated negligible effects of these two factors in the lower Mekong discharge during contemporary decades. How climate-driven shifts have interacted with historical water infrastructure development has not been studied, although modelling studies of the Mekong's future indicate that dam-driven alterations could be more noticeable and less uncertain than climate change alterations (Lauri et al., 2012).

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

2 Materials and methods

Recorded daily water levels from 1960 to 2010 were obtained for monitoring stations in Chiang Sean, Luang Prabang, Vientiane, Mukdahan, Pakse, and Prek Kdam (Figure 1 and Table 1) from the Mekong River Commission (MRC). These stations provide the longest and most accurate records of water levels in the Mekong. An extended series of records from 1910 to 2010 was obtained for the Stung Treng monitoring station in Cambodia. The data were quality checked by the MRC for consistency and accuracy (MRC, 2014). Changes in monitoring location throughout the study period were accounted for, resulting in a consistent and continuous water level data set (MRC, 2014). Parts of this same data set have been reported in multiple publications featuring climate change, sediment analyses, and water infrastructure development in the Mekong (e.g., Arias et al., 2012; Delgado et al., 2010; Delgado et al., 2012; Lu and Siew, 2006; Räsänen and Kummu, 2012, Räsänen et al. 2013; Lu et al. 2014).

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

Daily water level records for each station were analysed using the Indicators of Hydrologic Alternation (IHA) software (The Nature Conservancy, 2009), which permits the calculation of up to 32 statistical hydrological parameters and the level of alteration in post-development scenarios. A detail analysis of all parameters is presented at Chiang Sean in order to compare our analysis with previous ones at this station (Lu and Siew, 2006; Lu et al. 2014). The analysis at the further downstream stations, however, focused on a selected set of parameters that have been demonstrated to be most related to hydropower operations in the Mekong (Kummu and Sarkkula, 2008; Lauri et al., 2012; Lu and Siew, 2006; Piman et al., 2013b; Lu et al., 2014; Wyatt and Baird, 2007), namely daily water level fluctuations, rise rates, fall rates, and 7 day minimum water levels (Figure 1). To our knowledge, none of these four indicators have been significantly associated with other factors of hydrological alterations in the lower Mekong.

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

3 Results

3.1 Hydropower and irrigation development in the Mekong basin

The locations and commissioning period of hydropower dams in the Mekong Basin up to the end of 2010 is presented inFigure 2, and a time series of the cumulative active storage at Pakse is presented in Figure 3. Reservoir active storage, total storage, and the number of dams commissioned before 1991 and in 5 year intervals between 1991 and 2010 above each monitoring station are presented in Table 2. Total and active storage in the basin before the end of 1991 was 11,609 and 7,854 Mm^3 respectively, with a total of 9 dams, three of which have active storage larger than 1,000 Mm^3 (Table S1 in supplementary material). There were no dams in the mainstream of the Mekong prior to 1991. A significant increase in hydropower development in the upper Mekong basin above Chiang Sean occurred after 1991, which can be quantified in terms of reservoir volume (18,216 Mm^3) and active storage

(10,773 Mm^3) of the 4 dams developed on the mainstream in China. Between the end of 1991 and 2010 there was minimal development between Chiang Sean and Vientiane with only 3 small dams being built in tributaries (Table S1); however, a significant increase in development occurred in tributaries between Vientiane and Mukdahan resulting in a near doubling of both active (23,117 Mm^3) and total storage (37,624 Mm^3) above Mukdahan by 2010. A number of tributary dams were also built between Mukdahan and Stung Treng resulting in a total basin active storage of 29,913 Mm^3 and total reservoir volume of 48,700 Mm^3. After 1991 hydropower development in the upper tributaries of the Sesan, Srepok, and Sekong (3S) basin in Vietnam and Lao PDR accounted for an increase in 3,374 Mm^3 of the total active storage. Seventeen out of the 39 dams in the Mekong basin became operational between 2006 and 2010, accounting for a 65 % of the total active storage and 67 % of the total reservoir volume in the Mekong basin up to 2010.

The largest irrigation scheme in the Mekong basin is located in the Chi–Mun subbasin in Thailand. The Chi-Mun subbasin is the largest tributary to the Mekong in terms of area, with the Mun and Chi River basins covering 67,000 km^2 and 49,477 km^2, respectively. The combined Chi and Mun Rivers contribute an average annual flow of 32,280 Mm^3 which discharges immediately above Pakse (MRC, 2005). These subbasins are highly developed, low-relief, with low runoff potential and significant reservoir storage for dry season irrigation, supporting a population of over 18 million people. The irrigated area is close to 1,266,000 ha with an annual water demand of 8,963 Mm^3 and a foreseeable demand of over 12,000 Mm^3 (Floch and Molle, 2007). The basins also include numerous flood prevention works, and most reservoirs are actually managed for joint irrigation, hydropower, and flood control. A summary of the largest multi-use reservoirs in the basin is provided in Table S2. The two largest reservoirs in the basin are Ubol Rattana (2,263 Mm^3) and Sirindhorn (Lam Dom Noi; 1966 Mm^3) located in the upper watershed areas. However, the most influential reservoir in terms of controlling flows out of the basin is the Pak Mun dam. Although this reservoir is small (225 Mm^3), it was built in 1994 close to the outlet of the basin and controls the flow from 117,000 km^2 of drainage area. Further development of hydropower and reservoirs is highly unlikely in the basin, but construction of additional electricity generating plants in current multi-user reservoirs is possible (Floch and Molle, 2007).

3.2 Parametric statistical analysis of hydrological alterations

A parametric statistical analysis of multiple hydrological alteration indicators was done for each site. Detailed results of the analysis are first provided for the Chiang Sean site (Table 3), which is the main monitoring station below the four upper Mekong mainstream dams developed in China after 1991; thus, we assume there are a number of parameters with significant alterations at this station which are strongly linked to water infrastructure development, although some may be linked to climatic variability. Pre- and post- 1991 mean monthly and extreme water levels, coefficients of variation, RVA low and high boundaries (representing 1 standard deviation from the mean), hydrological alteration factors (that is, the fraction of years in the post-development period in which a parameter falls out of a pre-development range of variability), and ANOVA significance levels ($p \leq 0.001$, 0.01, or 0.1) are shown for 32 hydrological alteration indicators. Results show high hydrological alteration factors (> -0.7) and statistically significant ($p \leq 0.001$) increases in water levels during the dry season months (January to May), the 7 to 90 day minimum levels, low pulse counts, fall rates, and fluctuations. Analyses from other sites also show significant differences in rise rates. Given these findings we focus our reporting on the analysis of multiple stations on seasonal water levels, 7-day minimum levels, rise rates, fall rates, and water level fluctuations.

3.3 Seasonal changes in water levels

An analysis of pre- and post- 1991 water levels for Chiang Sean from 1960 to 2010 indicates that a significant increase ($p \leq 0.001$) in mean water levels has occurred for the dry season month of April and a non-significant increase is observed for the wet season month of October (Figure 4). A similar analysis was conducted for the Stung Treng station in the Lower Mekong using an extended data set between 1910 and 2010 (Figure 4). Results indicate an increase of 2 standard deviations in the April (dry season) mean monthly water levels post-1991, but no significant alterations for the month of October (wet season). A comparison of percent mean monthly alterations between pre- and post-1991 water levels for the Chiang Sean, Vientiane, Pakse, and Prek Kdam monitoring stations is presented in Figure 5. Results indicate that mean water levels for Chiang Sean have increased in excess of 80% for the dry season months of March and April, but monthly increases between June and November were less than 20 %. Monthly mean water levels for Vientiane have increased by 40 % for the month of April, but alterations between June and December were lower than 10%. For Pakse there was an increase of 30 % in April, but relatively no alterations in the months from June to January. For the Prek Kdam water level station in the Tonle Sap, there is an observed mean water level increase of 10-20 % for the months from November to May and a decrease in June and July of ~10 % or under. Changes in percent standard deviations were within the same magnitudes as observed changes in mean water levels for most data sets.

3.4 Minimum water levels

Seven-day minimum water levels were used to characterize alterations to extreme low water conditions. In general, greatest and most significant alterations were observed in the stations furthest upstream and downstream (Table 4). Changes to this parameter were large and significant at Chiang Sean (+91.6%, $p \leq 0.001$), but became negligible at Luang Prabang and Mukdahan. Alterations became again significant at Stung Treng (+11.6%, $p \leq 0.001$) and Prek Kdam (+19.5%, $p \leq 0.01$).

3.5 Water level rise and fall rate changes

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

3.6 Number of water level fluctuations

The difference in the number of water level changes (fluctuations) was calculated for each site. Water level fluctuations represent the number of times per year water levels have reversed from rising to falling or from falling to rising. Mean yearly values and coefficients of variations are reported for pre- and post-1991 periods for each of the monitoring sites (Table 4). Results indicate a significant increase in the number of fluctuations for all stations along the Mekong in the post-1991 period. The percent increase in the mean number of yearly fluctuations in Chiang Sean is 75.3 %, but this value decreases steadily downstream to 16.5 % at Mukdahan. An increase in the mean number of fluctuations was observed at Pakse with a mean increase of 26 fluctuations per year representing a 48.8 % increase after 1991. The percent increase in post-1991 fluctuations decreases in the downstream Stung Treng and Prek Kdam stations to 26 and 4 %, respectively.

Changes in the number of fluctuations per year between pre- and post-1991 for all stations are presented in Figure **6**. The number of fluctuations per year increase steadily after 1991 for all stations, but at different rates. An abrupt increase in yearly fluctuations after 1991 is evident between Mukdahan and Pakse, as well as a diminishing rate of post-1991 increases in fluctuations downstream of Chiang Sean to Mukdahan and from Pakse to Prek Kdam.

4 Discussion

Understanding and quantifying historical alterations influenced by water infrastructure development is important as a benchmark for monitoring and to analyse the impacts of future water infrastructure development in terms of ecological, economic, and social effects. Alterations to all reported hydrological parameters are important as they are indicators of wetland and river ecosystem habitat disruption, fish life histories, bank erosion, and sediment redistribution. Rise/fall water level rates and water level fluctuations influence drought stress on aquatic vegetation, entrapment of organisms on waterway islands or floodplains as well as desiccation stress on low-mobility stream edge organisms (Poff et al. 1997). Above all, changes to these hydrological factors could have subsequent impact on ecosystem productivity in the Tonle Sap (Arias et al. 2014a), the major driver of fish production and catches that are the largest source of protein consumed in the region (Hortle, 2007).

4.1 Impacts of reservoir and irrigation operations on downstream water levels

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

Dry Season Water Levels

To optimize electricity generation throughout the year, hydropower operations aim to fill reservoirs during the wet monsoon season and release water at higher volumes than natural flows in the dry season to extend the generation capacity. Operations of large reservoirs in the Mekong basin were thus expected to increase downstream dry season water levels and marginally reduce wet season water levels (e.g. Lu et al, 2014). The development of the four mainstream hydropower dams in the upper Mekong in China was observed to have an impact on seasonal water level changes, resulting in a large increase in dry season water levels in the stations closer to the dams, but with diminishing effects further downstream. Irrigation operations, on the other hand, would likely result in a reduction of downstream water levels or the rise rate during the dry season as water demand for agriculture increases (Floch and Molle, 2007).

Water Level Rise and Fall Rates

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

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

Water Level Fluctuations

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

We suggest that the post-1991 regulation of water in the Chi-Mun basin as a result of reservoir and irrigation schemes is a major cause of the large number of water level fluctuations observed at Pakse. The individual upstream dams in Chi-Mun may have limited impact on water levels at the outlet; however, irrigation operations during the growing (dry) season and the small (225 Mm^3) Pak Mun dam at the basin outlet, which controls hourly/daily flows to the greater Mekong, can directly alter downstream water level fluctuations. Although this subbasin only contributes 5-10% of the total Mekong's discharge at Pakse (MRC, 2005), it is not the quantity of water over the year, but rather the intensity and frequency of water management operations that is reflected in the large increase of water fluctuations at Pakse. In a similar manner, albeit at a lesser magnitude, the current regulation of waters in the 3S may have contributed to water level fluctuations in Stung Treng. The impact of the 3S tributary dams has been small up to 2010 because the dams are located in the highlands of these subbasins (Piman et al. 2013b). The Chi-Mun basin, however, will not experience further significant hydropower development, whereas the 3S basin has the potential for large reservoir storage projects in the near future (Piman et al. 2013b). Thus, we expect hydrological alterations (fluctuations, fall/rise rates, and seasonality) to increase beyond levels observed currently in Pakse and as far down as the Tonle Sap floodplain as it has been predicted to some extent with numerical models (Arias et al. 2014b). Water infrastructure development for agriculture and hydropower is accelerating in other tributaries throughout Laos, and this could further impact water levels in Mukdahan and downstream in the near future. Furthermore, the development and operations of other dams in the mainstream of the lower Mekong, such as the Xayabury dam in Laos, will undoubtedly have an immediate effect on rise/fall rates and fluctuations, potentially affecting critical fisheries and habitats in the lower Mekong.

Impact on Water Levels of the Tonle Sap

Because of the flow reversal phenomena in the Tonle Sap River, fall rates, rise rates, and fluctuations for the Prek Kdam station are affected both by Mekong river inflows/outflows and by contributing flows from the Tonle Sap catchment, which accounts for approximately 34% of yearly flows (Kummu, et al., 2014). Alterations to rise and fall rates can affect the reversal of water flows in the Tonle Sap River. Of significant importance is that Prek Kdam exhibited a post 1991 decrease of 23 and 11 % of rise and fall rates, respectively, and a decrease of 65 and 71 % in the deviation of the coefficient of variation. The decrease in rise rates in the Tonle Sap river (Table 4) is likely a result of the increase in dry season water levels in the Mekong resulting in a milder slope in the water level rise rate during the filling phase of the Tonle Sap. Rise and fall rates, as well as a significant decrease in the coefficient of variation for both parameters, indicates a modified flood pulse regime and more stable water levels in the Tonle Sap system as a result of upstream water infrastructure development. Most impact assessments of hydropower on the Tonle Sap have focused on seasonal water levels and spatial inundations patterns (see Kummu and Sarkkula, 2008; Arias et al., 2012; Arias et al., 2014a; Piman et al., 2013a), but alterations to the magnitude of fall/rise rates have been dismissed for the most part. Given the strong synchronicity between water flows, fish migrations, and fish catches in the Tonle Sap, it is probable that such hydrological alterations had an undocumented effect on the fish ecology of this important ecosystem. To the extent of our knowledge, however, there are no reliable fish catch records or any ecological information pre-1991 that could be used to prove and quantify ecological shifts in past decades.

4.2 Climate versus water infrastructure development

The impacts of climate change are temporally complex and spatially varied and there is no consensus as to what the potential climate-driven water level alterations might be throughout the Mekong basin despite multiple discussions on the subject (e.g., Kingston et al. 2011, Lauri et al., 2012, Thompson et al., 2013). Specific climate change factors, such as an increase in glacial melting, could theoretically contribute to increased water levels during the dry season as it has ocurred in other large rivers with headwater in the Himalayas (Xu et al. 2009); however, to date there is no concensus at to the extent of alterations in Mekong flows might be associated with the Himalaya's melting (Xu et al. 2009). Cook et al. (2012) found a significant relationship between Himalaya's snow cover and dry season flows as far south as Kratie, but they concluded that contemporary and future changes in lower Mekong flows between March and May are negligible as a result of the conflicting effect of melting snow cover and increasing local precipitation . To our knowledge, there is no evidence of climate induced alterations to indicators other than interannual and wet season extremes; besides, most of the previous studies highlighting the correlation between climate and river discharge patterns have only demonstrated contemporary alterations during the wet season months (Delgado et al., 2010; Räsänen and Kummu, 2013; Räsänen et al., 2013). The link between infrastructure development and water levels presented in this paper have largely excluded those indicators representing alterations during the wet season; thus, we argue that it is more likely that the increased number of water level fluctuations, 7-day minimum levels, as well as alterations to rise/fall rates observed in the post-1991 measurements at the various monitoring stations are evidence of the increasing impact of infrastructure development through the Mekong basin. Furthermore, hydropower simulations in the 3S basin demonstrate that changes to downstream water levels from various scenarios of climate change are minimal compared to the ability of hydropower operations to alter water levels (Piman et al., 2014).

5 Conclusions

This paper clarifies that the perception of a *Pristine Mekong* may have been outdated for over two decades. We have shown that hydropower operations and irrigation development in the Mekong may have already caused observable alterations to natural water levels along the Mekong mainstream and the Tonle Sap river beginning as early as 1991. Significant increases in water levels during the dry season (March, April and May) of 80% to 20% post-1991 in Chiang Sean downstream to StungTreng were documented, and such alterations are most likely caused by water infrastructure development in the basin. The effect of the upper Mekong hydropower development tributary operations is clearly observable up to Mukdahan station in terms of water level fluctuations and fall rates. Alterations observed in Pakse and downstream are likely a result of irrigation development, flood control, and hydropower hourly/daily operations (at Pak Mun dam in particular) in the Chi-Mun basin. Alterations observed downstream from Stung Treng will be exacerbated by the ongoing development in the 3S basin. Previous studies have highlighted climate shifts occurring downstream of Pakse as the factor responsible for long term hydrological alterations to wet season floods; however, alterations to extreme dry season levels, water level rise/fall rates and fluctuations has not been related to climate variability, and as we have demonstrated in this paper they were most likely caused by water infrastructure development in China and Thailand during the 1990s and 2000s.

Ongoing and proposed hydropower development will continue to increase the magnitude of water level alterations throughout the Mekong. Given the numerous water infrastructure development proposals which will significantly increase the basin's total active storage, drastic alterations to the hydrological pulse and subsequent ecological features in the Tonle Sap (Kummu and Sarkkula, 2008, Arias et al. 2012; Arias et al. 2014a) and the rest of the

Mekong floodplains do not seem unrealistic. In particular, development in catchments such as the 3S basin is occurring at a fast pace in a poorly coordinated fashion. Recent estimates with detail modelling of the 3S dams have shown considerably higher levels of alterations in the Tonle Sap than what has been observed or simulated before (Arias et al. 2014b), which highlights the potentially confounding impacts of these dams. Moreover, indicators of hydrological alterations in the Mekong highlighted in this paper, in particular rise rates, fall rates, and water level fluctuations, have been dismissed for the most part from modelling studies. Future research should explicitly simulate and analyse daily and even hourly water levels in order to capture these key indicators of change. Given the historical alterations we have documented and the expected future development in the Mekong, research is also necessary to examine ecological indicators linked to the system’s hydrology in order to quantify past, current, and future alterations before they become a threat to the integrity, biodiversity, and food security of the Mekong.

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Table 1. Catchment areas and average historical seasonal flows (1960-2004) above each 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%)**

Table 2. Hydropower reservoir active and total storage (Mm^3) above monitoring stations in 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**

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

	Pre-impact period: 1960-1990				Post-impact period: 1991-2010			
Indicators of			RVA Boundaries[a]				Hydrologic	ANOVA
hydrological alterations	Means	Coeff. of var.	Low	High	Means	Coeff of var.	alteration factor[b]	Signif. level[c]
Mean monthly values (m)								
January	1.396	0.206	1.108	1.683	2.047	0.181	-0.857	***
February	1.010	0.215	0.794	1.227	1.683	0.200	-0.857	***
March	0.796	0.262	0.587	1.004	1.565	0.214	-0.833	***
April	0.954	0.237	0.728	1.180	1.712	0.242	-0.786	***
May	1.557	0.300	1.090	2.025	2.426	0.233	-0.727	***
June	2.948	0.201	2.357	3.539	3.477	0.228	-0.348	**
July	4.639	0.168	3.860	5.417	5.445	0.176	-0.250	**
August	5.912	0.160	4.969	6.855	6.238	0.166	-0.045	
September	5.262	0.158	4.430	6.094	5.828	0.161	-0.340	*
October	4.180	0.126	3.652	4.708	4.642	0.113	-0.357	**
November	3.023	0.163	2.530	3.515	3.502	0.187	-0.250	**
December	1.998	0.178	1.644	2.353	2.571	0.148	-0.714	***
Extreme water conditions (m)								
1-day minimum	0.623	0.315	0.427	0.819	1.114	0.356	-0.929	***
3-day minimum	0.631	0.313	0.434	0.829	1.164	0.361	-0.929	***
7-day minimum	0.650	0.304	0.452	0.847	1.245	0.293	-0.850	***
30-day minimum	0.734	0.274	0.533	0.935	1.410	0.229	-0.850	***
90-day minimum	0.895	0.230	0.689	1.102	1.623	0.193	-0.850	***
1-day maximum	8.204	0.179	6.733	9.675	8.486	0.166	-0.152	
3-day maximum	8.000	0.186	6.514	9.486	8.265	0.167	-0.063	
7-day maximum	7.556	0.194	6.091	9.020	7.827	0.164	-0.125	
30-day maximum	6.376	0.160	5.355	7.397	6.773	0.154	-0.217	
90-day maximum	5.430	0.118	4.787	6.072	5.953	0.139	-0.520	*
Timing of extreme water conditions								
Date of minimum	87.2	0.039	72.8	101.5	91.9	0.065	-0.217	
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	0.6	2.382	-0.9	***
Low pulse duration	26.5	0.863	10.4	49.3	7.4	0.630	-0.9	
High pulse count	5.3	0.407	3.2	7.5	5.2	0.317	0.2	
High pulse duration	15.7	0.692	4.8	26.6	20.1	0.575	-0.1	
Water condition changes								
Rise rate (m/day)	0.186	0.155	0.157	0.214	0.189	0.157	-0.143	
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	129.5	0.186	-0.929	***

[a] Range of Variability Approach Boundaries represent the values within one standard deviation from the pre-impact period mean

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

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

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

		Pre-impact (1960-1990)		Post-impact (1991-2010)		
Monitoring station	Indicators of hydrological alteration	mean	coeff. of var.	mean (% diff.)	coeff. of var. (% diff.)	ANOVA signif. level[a]
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)	-0.2023 (+58)	***
	Number of fluctuations	73.9	0.115	129.5 (+75)	0.186 (+61)	***
	7-day minimum	0.6	0.304	1.25 (+92)	0.293 (-4)	***
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)	***
	7-day minimum	3.1	0.068	3.025 (-2)	0.111 (+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)	-0.1301 (13)	***
	Number of fluctuations	56.1	0.135	69.4 (+24)	0.137 (+1)	***
	7-day minimum	0.4	0.467	0.558 (+28)	0.531 (+14)	.
Mukdahan	Rise rate (m/day)	0.171	0.138	0.157 (-8)	0.131 (-5)	*
	Fall rate (m/day)	-0.091	-0.086	-0.0951 (+5)	-0.112 (+31)	.
	Number of fluctuations	45.6	0.159	53.2 (+17)	0.149 (-6)	**
	7-day minimum	1.1	0.097	1.16 (+2)	0.173 (+79)	
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)	-0.0924 (-28)	
	Number of fluctuations	54.6	0.148	81.3 (+49)	0.197 (+33)	***
	7-day minimum	0.6	0.220	0.666 (+16)	0.313 (+42)	.
Stung Treng	Rise rate (m/day)	0.156	0.189	0.144 (-8)	0.167 (-11)	
	Fall rate (m/day)	-0.078	-0.131	-0.0871 (+12)	-0.136 (+4)	**
	Number of fluctuations	57.7	0.140	72.7 (+26)	0.144 (+3)	***
	7-day minimum	1.8	0.090	2.04 (+12)	0.103 (+14)	***
Prek Kdam	Rise rate (m/day)	0.104	0.265	0.0800 (-23)	0.119 (-55)	***
	Fall rate (m/day)	-0.060	-0.183	-0.0536 (-11)	-0.0696 (-62)	*
	Number of fluctuations	47.7	0.186	50 (+5)	0.178 (-4)	
	7-day minimum	0.7	0.172	0.862 (+20)	0.186 (+8)	**

[a] Significance level codes: ***: $p \leq 0.001$; **: $p \leq 0.01$; *: $p \leq 0.05$; . : $p \leq 0.1$

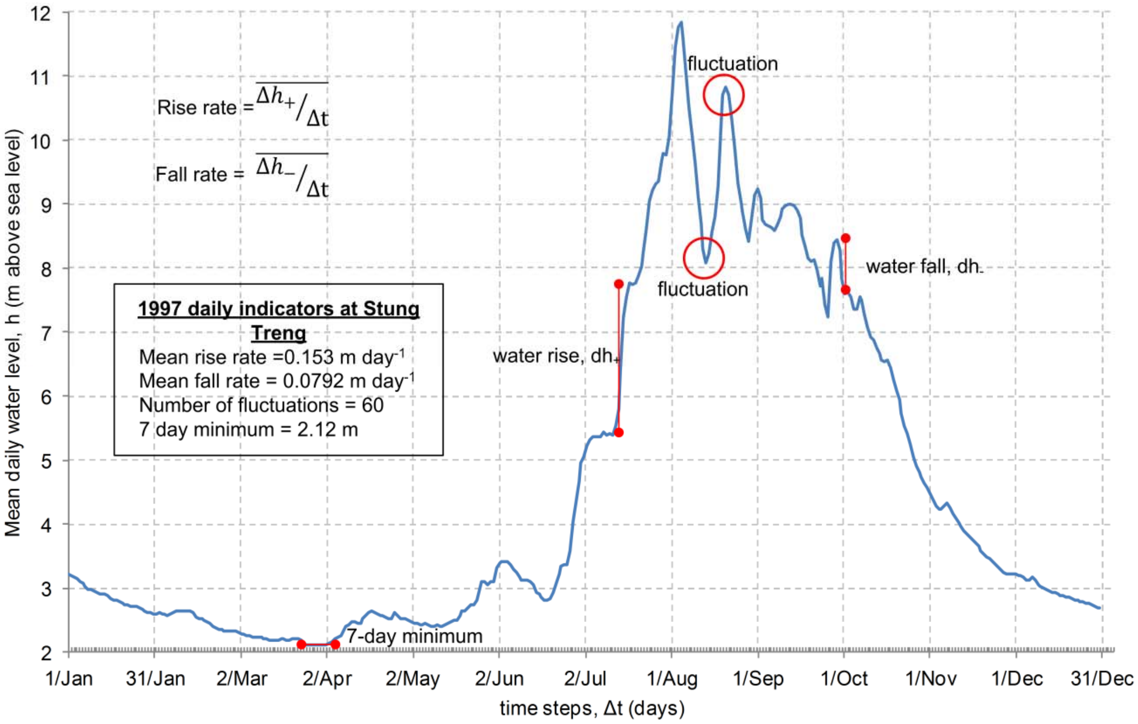


Figure 1. Illustration of hydrological alteration indicators most sensitive to reservoir operations. Hydrograph represents mean daily water levels during 1997 at Stung Treng.

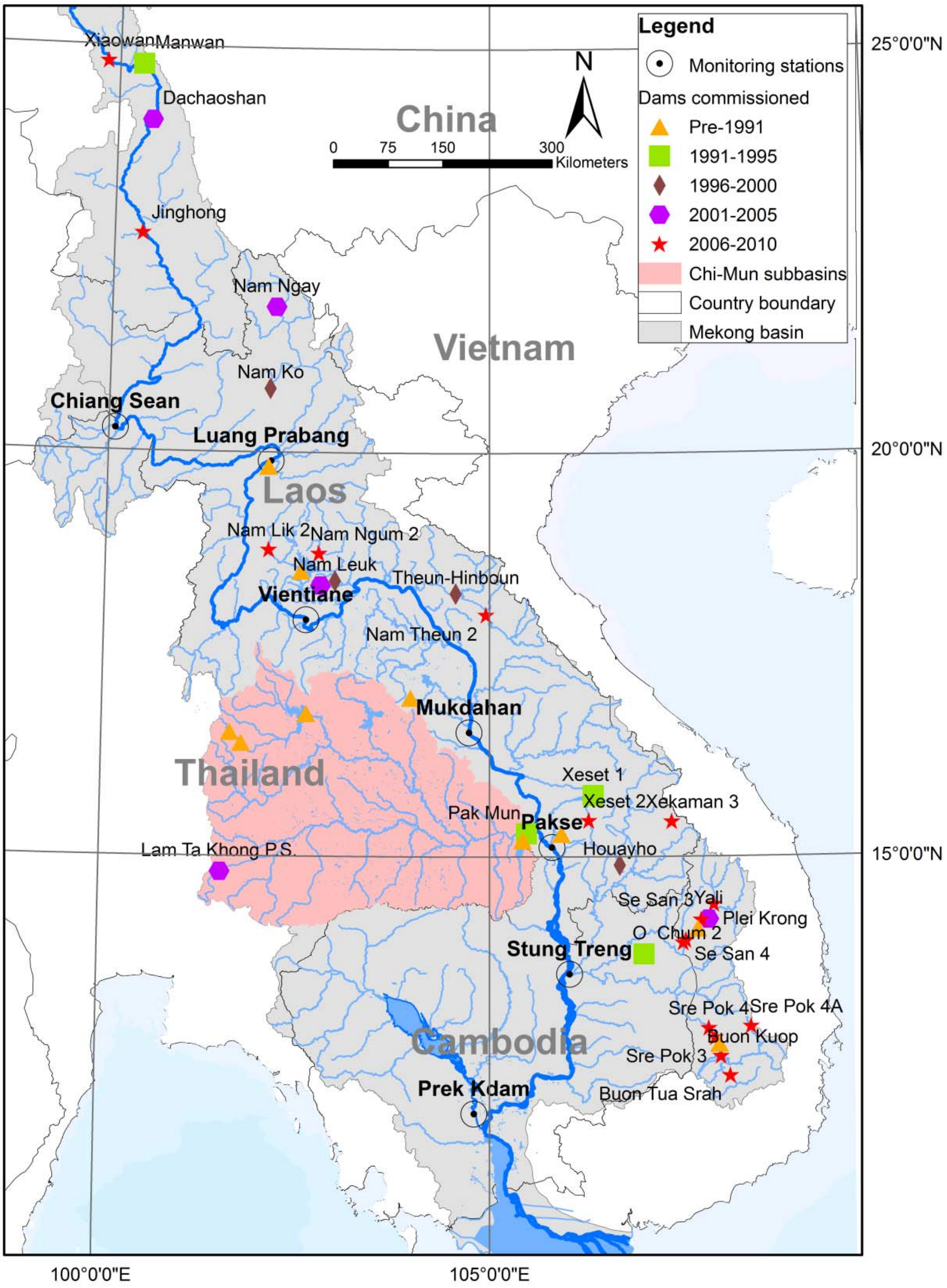


Figure 2. Operating dams and key hydrological monitoring stations in the Mekong Basin up to December 2010.

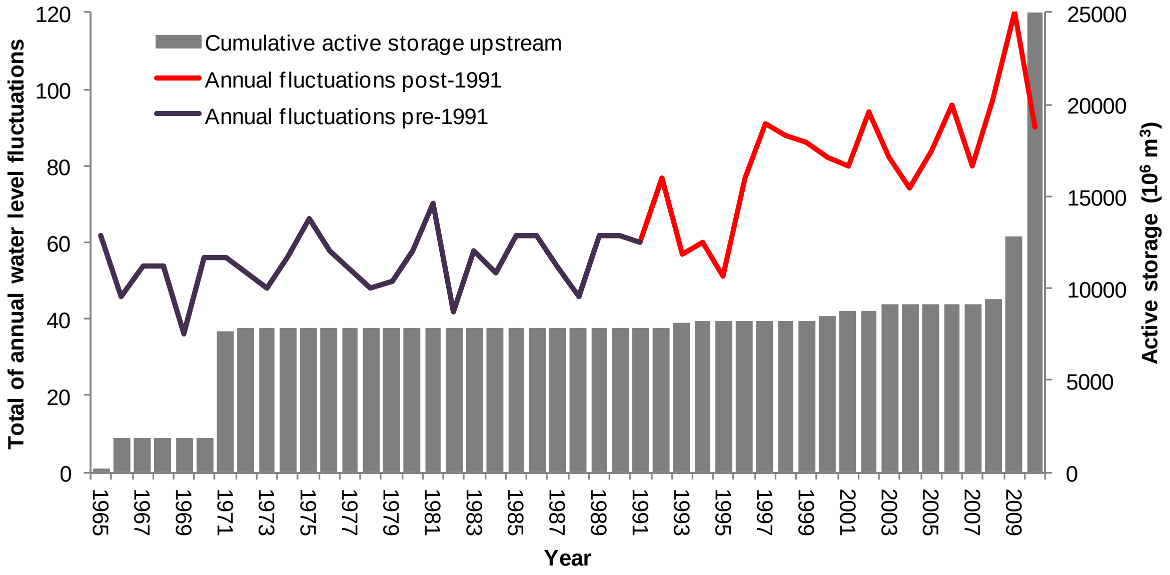
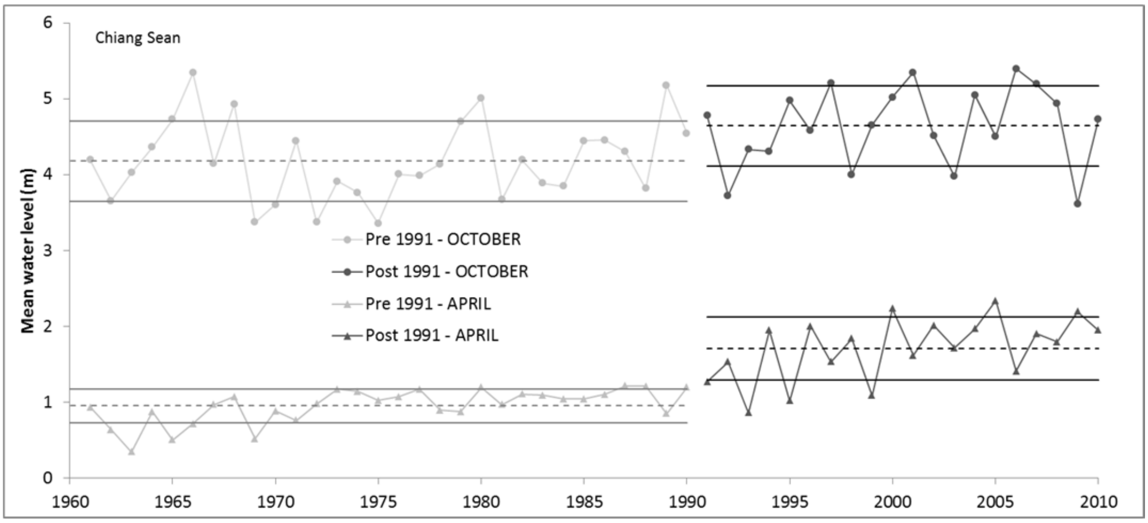


Figure 3. Temporal trend in water level fluctuations and cumulative active storage upstream of Pakse.



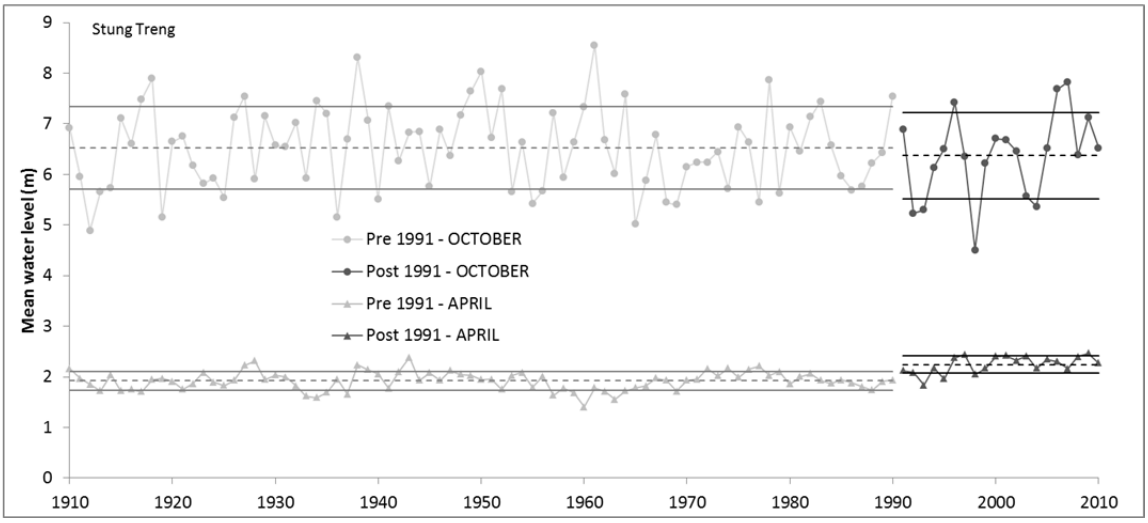


Figure 4. Mean measured water levels at Chiang Sean (1960-2010) and Stung Treng (1910 to 2010) for the months of April and October. Dashed lines indicate mean water levels for periods before and after 1991 and parallel solid lines indicate +/- 1 standard deviations around the mean for each period.

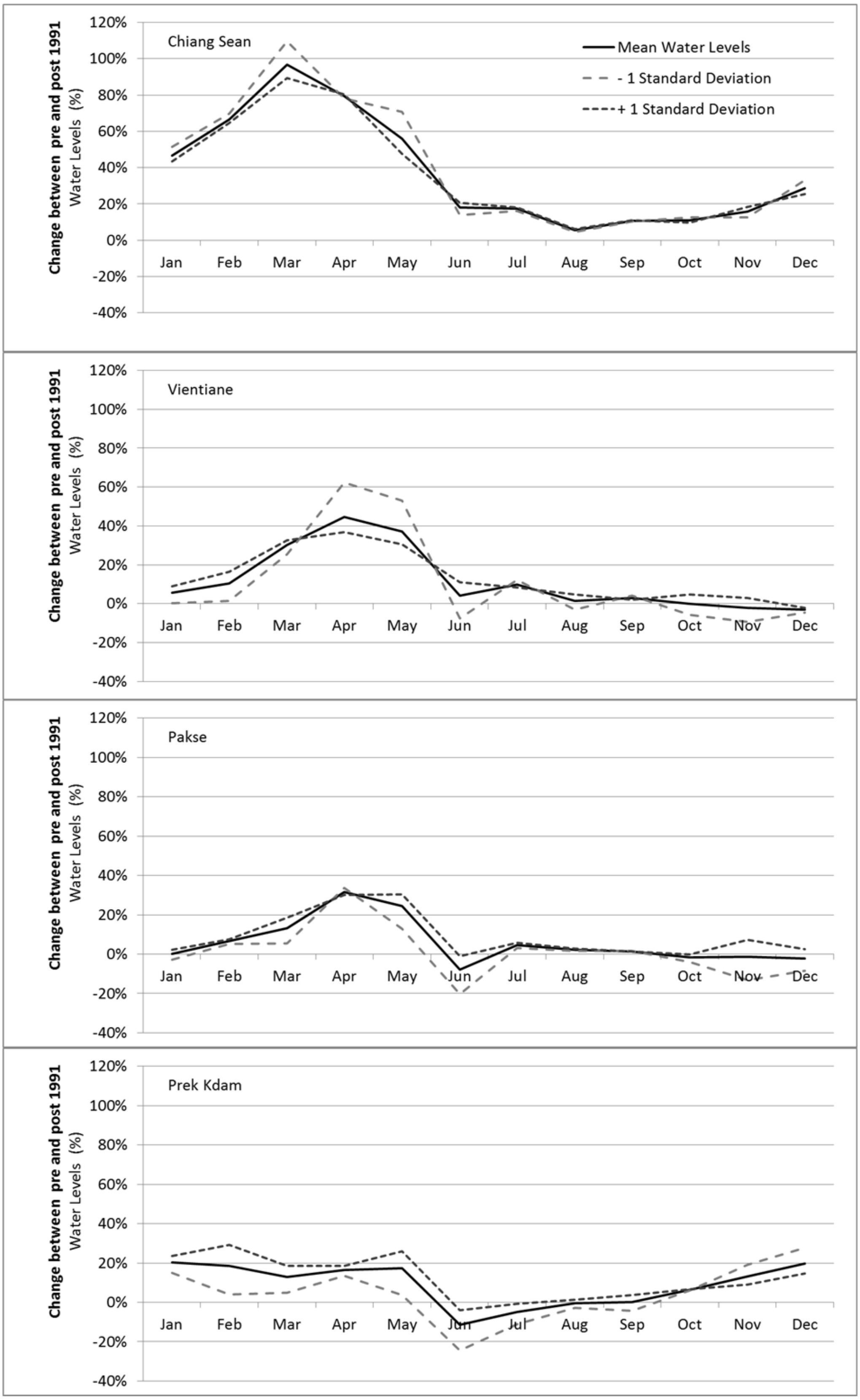
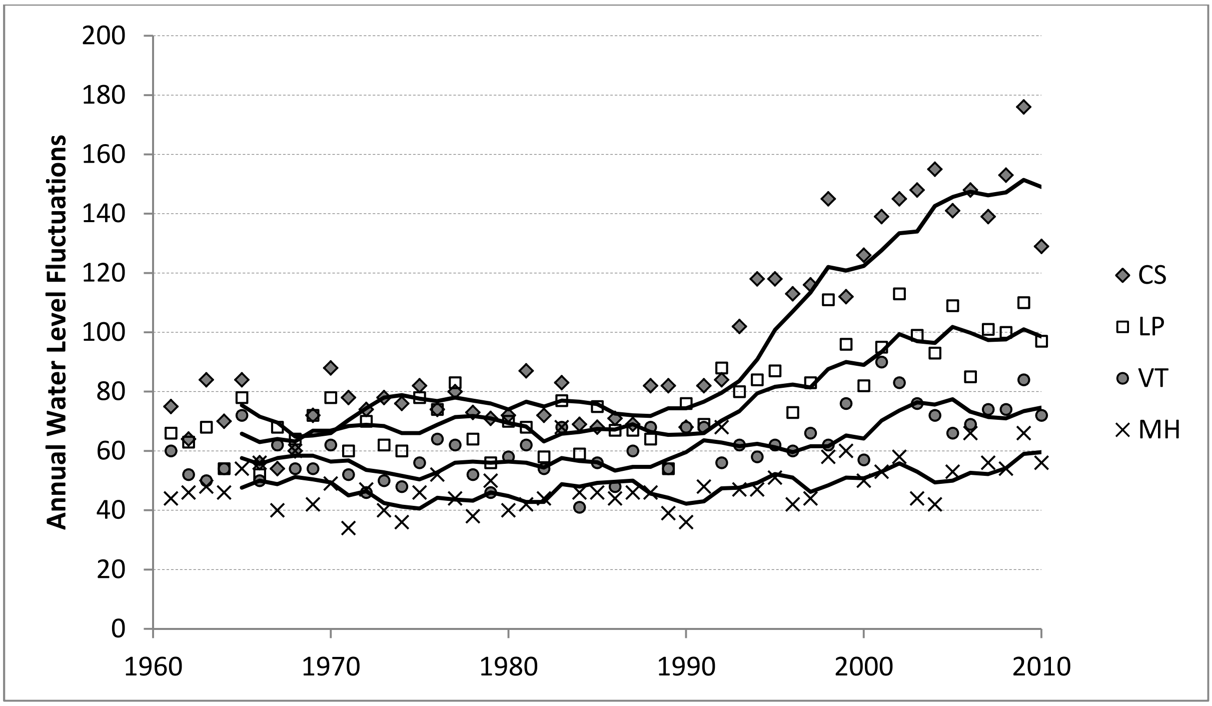


Figure 5. Change (%) in average mean and +/- 1 standard deviations for each month between pre and post 1991 water levels for Chiang Sean, Vientiane, Pakes, and Prek Kdam.



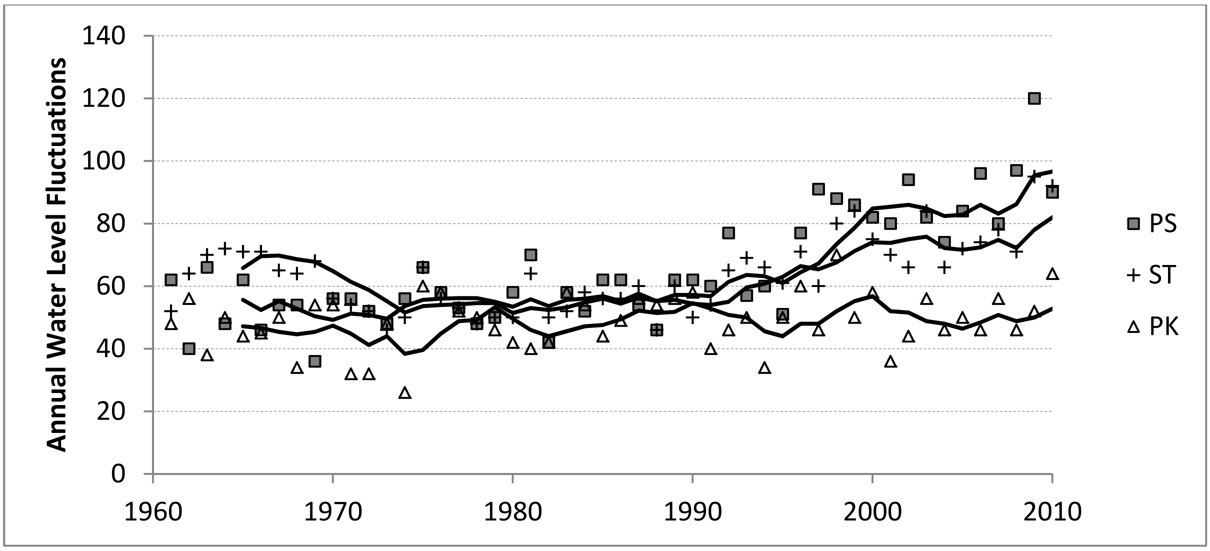


Figure 6. Number of annual water level fluctuations for each monitoring station between 1961 and 2010. Solid lines indicate a 5 year moving average for each station: Chiang Sean (CS), Luang Prabang (LP), Vientiane (VT), Mukdahan (MH), Pakse (PS), Stung Treng (ST), and Prek Kdam (PK).

Supplementary Material

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

Table S2. Multi-use reservoirs (hydropower and irrigation) in the Chi and Mun basins. Data 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

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