Dams on Mekong Tributaries as significant contributors of hydrological alterations to the Tonle Sap Floodplain in Cambodia

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Abstract

River tributaries have a key role in the biophysical functioning of the Mekong Basin. Of particular attention are the Sesan, Srepok, and Sekong (3S) rivers, which contribute nearly a quarter of the total Mekong discharge. Forty two dams are proposed in the 3S, and once completed they will exceed the active storage of China's large dam cascade in the upper Mekong. Given their proximity to the lower Mekong floodplains, the 3S dams could alter the flood-pulse hydrology driving the productivity of downstream ecosystems. Therefore, the main objective of this study was to quantify how hydropower development in the 3S together with definite plans for infrastructure development through the basin would alter the hydrology of the Tonle Sap floodplain, the largest wetland in the Mekong and home to one of the most productive inland fisheries in the world. We coupled results from four numerical models representing the basin's surface hydrology, water resources development, and floodplain hydrodynamics. The scale of alterations caused by hydropower in the 3S was compared with the basin's definite future development scenario (DF) driven by the upper Mekong dam cascade. The DF or the 3S development scenarios could independently increase Tonle Sap's 30-day minimum water levels by 30 ± 5 cm and decrease annual water level fall rates by 0.30 ± 0.05 cm d^{-1}. When analyzed together (DF + 3S), these scenarios are likely to eliminate all baseline conditions (1986-2000) of extreme low water levels, a particularly important component of Tonle Sap's environmental flows. Given the ongoing trends and large economic incentives in the hydropower business in the region, there is a high possibility that most of the 3S hydropower potential will actually be exploited and that dams would be built even in locations where there is a high risk of ecological disruptions. Hence, retrofitting current designs and operations to promote sustainable hydropower practices that optimize multiple river services –rather than just maximize hydropower generation– appear to be the most feasible alternative to mitigate hydropower-related disruptions in the Mekong.

1 Introduction

More than half of the world's greatest rivers have been altered by dams (Nilsson et al., 2005) and there is worldwide evidence showing that hydropower development causes significant hydrological and ecological disruptions to downstream freshwater ecosystems (Poff and Zimmermann, 2010). Understanding the cumulative impact of water resources infrastructure is important for sustainable development of river basins, and although hydrological alterations from dams have basin-wide implications, impact assessments typically concentrate on river segments directly upstream and downstream of single dam projects (Nilsson and Berggren, 2000). Impact assessments, however, become more challenging when critical ecosystems occur further downstream under the influence of multiple dams as well as other water infrastructure components (e.g., irrigation, water supply, and flood control). The situation becomes even more complex in large rivers where the interests of upstream stakeholders differ from those downstream. Such is the case of the Mekong, a transboundary basin with a historically low levels of hydrological regulation (i.e., fraction of annual water discharge that can be stored in reservoirs) that is comparable to other large tropical basins such as the Amazon and Congo (Lehner et al., 2011; Nilsson et al., 2005). Aggressive plans for multiple large hydropower schemes throughout the Mekong Basin for economic development, however, are expected to bring significant disruptions to the hydrological regime (Lauri et al., 2012; Piman et al., 2013b), compromising the geomorphology (Kummu et al., 2010; Walling, 2009), fish ecology (Ziv et al., 2012), and productivity of downstream floodplain ecosystems (Arias et al., 2014) that sustain the food security of millions of people.

The Mekong is the largest river and basin in Southeast Asia, covering an extension of 795,000 km^2 shared by six different countries: China, Myanmar, Thailand, Laos, Cambodia, and Vietnam (Figure 1). Mean annual discharge in the Mekong at Kratie in Cambodia is 475

$km^3 yr^{-1}$ or 14,500 m^3/s, varying from an average of less than 3,000 m^3/s during March-April, to nearly 40,000 m^3/s during August-September (Adamson et al., 2009). The Sesan, Srepok, and Sekong basins (collectively known as the 3S) cover an area of 78,650 km^2 distributed among Cambodia (33%), Laos (29%), and Vietnam (38%). Due to its relatively high rainfall precipitation (1100-3800 mm yr^{-1}), the 3S provides the largest flow contribution among Mekong tributaries, with an average discharge of 510 m^3/s during March-April and 6,133 m^3/s during September. In general, the 3S contributes 23% of the annual Mekong discharge, compared to 16% generated in the upper Mekong in China (Adamson et al., 2009).

The Mekong River meets the Tonle Sap 300 km downstream from Stung Treng at the Cambodian capital, Phnom Penh. From October to May, water flows from the Tonle Sap River to the Mekong at a maximum daily discharge rate of 8,300 m^3/s; when the wet monsoon reaches the basin in May, the Mekong River rises to a higher level than the Tonle Sap, forcing the later to reverse its flow towards the Tonle Sap Lake. This phenomenon creates a floodplain that extends over 15,000 km^2 and stores up to 76.1 km^3 of Mekong's annual flood-pulse (Kummu et al., 2014). Overall, 53.5% of the water entering the Tonle Sap system comes from the Mekong, 34% from 11 tributaries in the Tonle Sap catchment, and 12.5% directly from rainfall (Kummu et al., 2014).

Hydropower development in the Mekong is occurring in three distinct regions. The first is the Lancang-Jiang cascade in the upper Mekong (Figure 1), a series of 6 dams (5 already built) with downstream hydrological alterations expected as far down as Kratie (Räsänen et al., 2012). The second focus of development is a series of 11 dams along the mainstream channel in the lower Mekong, only one of which is under construction, the Xayaburi dam in Lao. The lower Mekong mainstream dams have become very controversial due to their potential impacts on fisheries (Ziv et al., 2012) and their role in political affairs among the basin's countries (Grumbine et al., 2012; Grumbine and Xu, 2011; Stone, 2011). Of greater concern in terms of hydrological alterations is the third region of development occurring in the Mekong tributaries, in particular the 3S, where at least 42 dams are at some stage of development without much regional coordination or stakeholder consultation. Because of its proximity to the Tonle Sap and the rest of the lower Mekong floodplains, flow regulation in the 3S will most likely affect the floodplain's hydrological seasonality. Should the Tonle Sap hydrology be altered, however, serious consequences could happen to the ecological productivity that this floodplain wetland supports (Arias et al., 2014).

Thus far, existing dams are believed to have caused very little hydrological alterations in the lower Mekong (Adamson et al., 2009). There has been alterations to the frequency of extreme events beginning in the mid-1970s, but this is probably linked to changes to El Niño-Southern Oscillation (Delgado et al., 2012; Räsänen and Kummu, 2013). Several efforts and modeling tools have been developed to evaluate ongoing and future hydrological alterations in the Mekong (Johnston and Kummu, 2011). The primary focus of these studies have been the cumulative impact of multiple water infrastructure development plans for the basin (Lauri et al., 2012; Piman et al., 2013b; WB, 2004). Other studies have scrutinized alterations in particular regions of development such as the dam cascade in the upper Mekong River (Räsänen et al., 2012) and the 3S (Piman et al., 2013a; Ty et al., 2011), but linkages between development in these regions and impacts to the lower Mekong floodplains have not been assessed. Impact assessments of basin-wide alterations to the Tonle Sap, however, do exist and provide a good understanding of the general trends of future changes in the floodplain. Kummu and Sarkkula (2008) initially pointed out that the upstream development scenario from WB (2004) could increase Tonle Sap's dry season water levels by 15 cm and decrease wet season water levels by 36 cm, leading to a large reduction of seasonally inundated areas. Arias et al. (2012, 2013, 2014) demonstrated that hydropower-related alterations to the Tonle

Sap's hydrology could cause major disruptions to existing floodplain habitats and their contribution to aquatic primary production.

Impacts of hydrological alterations in rivers and floodplains have been well documented for decades (Petts, 1980). Hundreds of studies provide evidence that hydrological alterations cause ecological disruptions in river and riparian systems (Poff and Zimmermann, 2010), but most of these studies have been carried out in single river reaches in North America and Europe, where more than three quarters of rivers' discharge is regulated (Dynesius and Nilsson, 1994), and where sufficient time series exist to make statistical inference on pre-/post-dam alterations (FitzHugh, 2013; Poff et al., 2007). Studies in these regions have evaluated impacts of dam development based on the scale of alterations to the magnitude, frequency, duration, timing, and rate of change of natural flow regimes required for the integrity of river and floodplain ecosystems (Poff et al., 1997). Based on these properties, a method to assess the impacts of hydrological alternations (IHA) to environmental flows was developed (Richter et al., 1996, 1997). This method defines 32 hydrological parameters and environmental flow components (EFC) and assesses the magnitude and statistical significance of alterations caused by flow regulation. Recent developments have been proposed to the IHA method, including the analysis of multivariate components among indicators of alterations (Gao et al., 2009) and ranking of alteration levels for specific EFCs (FitzHugh, 2013).

Most of the current construction of hydropower projects is happening in the (sub-) tropics in South America, Africa and Asia (Kareiva, 2012), where hydrological and ecological monitoring has not been carried out to the temporal span and resolution needed to comprehensively use the IHA method (which typically requires time series with at least 20 years of daily measurements; The Nature Conservancy, 2009). Perhaps the only exceptions to this regional limitation include the Murray-Darling Basin in Australia (Kingsford, 2000) and the Paraná in Brazil (Agostinho et al., 2009), where hydrological alterations and corresponding ecological disruptions have been well documented. Despite the obvious limitations, applying the IHA method to tropical rivers under development brings interesting challenges and benefits. First, IHA can be used as *a priori* impact assessment tool to be applied on simulated scenarios of hydropower development in order to plan optimal and sustainable dam locations and operations. Furthermore, the tool can be used to compare the level of alterations between different projects and/or cascades, thus helping prioritize where sustainable hydropower and basin management strategies are most needed. Moreover, the IHA tool could be used to evaluate the cumulative impacts of dam cascades at critical downstream river reaches and high-value ecosystems, instead of just focusing on nearby downstream impacts of a single dam. With these particular applications in mind, an assessment of hydrological alterations in the Mekong would be an informative case study not only for researchers and managers in the basin but also to others in (sub-)tropical rivers undergoing similar development and biophysical transitions.

The main objective of this study is to quantify how proposed hydropower dams in the tributaries of the lower Mekong together with definite plans for infrastructure development through the basin would alter the hydrology of the Tonle Sap floodplain. This was carried out by first validating a 2D hydrodynamic model of the lower Mekong floodplains with historical water levels at the Tonle Sap. We then compared the expected hydrological alterations on the Tonle Sap caused by scenarios of 3S hydropower development and the most likely (definite) development scenario for the rest of the Mekong Basin by 2015. Once these two scenarios were analyzed separately, their cumulative impact on hydrological parameters and environmental flows at the Tonle Sap floodplain were estimated. We conclude with a discussion of major implications of our findings as well as feasible alternatives to mitigate expected hydrological alteration and consequent ecological disruptions.

2 Methods

2.1 Modelling Approach

This study integrates the results of four different sets of numerical models (Figure 2). Basin hydrology and daily runoff flows were simulated in a daily time step using the Soil and Water Assessment Tool (SWAT) as described by Piman et al. (2013a). This SWAT model was calibrated for 28 different gauges upstream of Kratie. Subbasin runoff flows were then used as inputs to two different models of water resources development impacts. The first set of results came from simulations using the Integrated Quantity and Quality Model (IQQM) that Piman et al. (2013b) applied to assess the impact of water regulation and abstraction in the Mekong. The second set of results were generated with the HEC-ResSim model presented by Piman et al. (2013a), which simulated the impact of hydropower development and operations in the 3S. Results from both IQQM and HEC-ResSim were used to compute daily river discharges in the Mekong at Kratie south of the 3S confluence (see location in Figure 1). Water movement from this location down through the lower Mekong floodplains (including the Tonle Sap) was simulated with the 2D EIA, a hydrodynamic model that solves the simplified Navier-Stokes and continuity equations numerically using a finite difference method (Koponen et al., 2010). The 2D EIA lower Mekong application covers an area of 430 km by 570 km from Kratie to the Mekong Delta at a grid resolution of 1 km^2. An earlier version of this application was presented by Västilä et al (2010). Daily water levels from the 2D EIA model were extracted and validated at K. Luong where the main water gauge on the Tonle Sap is located (see Figure 1). Simulated water levels were validated against historical measurements for the entire simulation period (1986-2000). Validation results were evaluated according to the linear correlation coefficient (r) between observed and simulated results, as well as the Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe, 1970).

2.2 Modeling Scenarios

A total of four scenarios were considered for this study (Table 1). A baseline scenario (BL) represented recent historical conditions (1986-2000) before major hydropower projects were built in the upper Mekong and the 3S. We were limited to this 15 year time series because no continuous and reliable water level data exist for the Tonle Sap before this and because large dams began to be built after 2000. Two of the wettest and five of the driest years in the past seven centuries occurred during this baseline period (Räsänen et al., 2013), and therefore it was considered a good representation of the range of historical hydrological conditions and variability in the basin. Although 17 dams were already operational by the end of this period (including the Manwan dam in China built in 1993), they were generally small and only accounted for 9.1 km^3 of active storage, in contrast to the approximately 38 km^3 that have been built since year 2000 (MRC, 2009). The first scenario of water resources development that was analyzed resembles the Definite Future (DF) scenario proposed by the Mekong River Commission (MRC; Piman et al., 2013b), which represents existing and on-going water resources infrastructure development up to the year of 2015. The DF scenario is primarily driven by the six dams in the Lancang-Jiang dam cascade in the upper Mekong in China, which provide an additional 23.2 km^3 of active storage from baseline (Räsänen et al., 2012). The DF scenario in our study does not consider any proposed dams in the 3S. The second scenario of water resources development was based on the simulations of dams operations in the 3S presented by Piman et al. (2013a). This scenario represents a total of 42 dams at different development stages (existing, under construction, and proposed) in the 3S tributaries and sub-tributaries with 26.3 km^3 of active storage. The last scenario analyzed represents the cumulative impact of both DF and 3S (DF + 3S) with an additional 49.5 km^3 of active storage from baseline. All simulations were carried out on daily time steps for a period of 15 years from January 1st of 1986 to December 31st of 2000.

2.3 Data Analysis

Simulated water levels were used to calculate 30 hydrological parameters and corresponding alterations using the IHA Tool (The Nature Conservancy 2009). This tool computes hydrologic parameters that are relevant to ecosystem processes and it calculates the level of alteration between baseline and post-alteration periods. Analyses were carried out by combining the BL scenario time series with each of the water development scenarios so that the first 15 years defined the pre-alteration period and the second 15 years represented the post-development period, as if all dams were built at once in Jan 1st of 2001. Three different sets of analyses were carried out: DF scenario, 3S scenario, and DF + 3S. All analyses were carried out using non-parametric statistics. Data were analyzed according to calendar years (Jan 1 to December 31). Environmental flow components were set according to commonly used parameters. The 75th percentile of water levels for each year was defined as the threshold between periods of low flow and high flow pulses. Small floods were defined as those with a peak above the 2 year return period flood, whereas large flood events were defined as those with a peak above the 10 year flood. Extreme low flows were defined as those with an initial low flow below the 10th percentile from daily records for each period.

Annual summary statistics were used to compare the magnitude of alterations between scenarios. All hydrologic parameters were analyzed with the Kruskal-Wallis test (Kruskal and Wallis, 1952) to determine if differences among the BL, DF, and 3S scenarios were significant to the 95th level. Once individual scenarios were compared, hydrological alterations were calculated for the DF and for the DF + 3S scenarios. Environmental flow components were estimated, exceedance probability charts plotted, and hydrological alteration factors were computed for all parameters according to the Range of Variability

Approach (RVA; Richter et al. 1997). This approach consists on dividing the data into 3 different categories (bounded by the 33rd and 67th percentiles), estimating the frequency at which values are expected to occur within each category, and then estimating the percent difference between the expected frequency and the simulated frequency for the impact scenarios.

In addition to the IHA analysis, changes in spatial flooding patterns were analyzed. Rasters representing cumulative flood duration were generated from the 2D EIA model at the geographical extend of the Tonle Sap floodplain (15,000 km^2 approximately), and these were transformed into flood frequency rasters by normalizing flood duration according to the simulation's total length. Outputs from the impact scenarios were overlaid on the baseline raster in order to calculate and visualize spatial changes in flood regime.

3 Results

3.1 Baseline Scenario Validation

Prior to the analysis and comparison among scenarios, the simulated daily water levels at K. Luong were validated against historical measurements for the entire simulation period (1986-2000). Overall, simulations of the baseline scenario show a tendency to overestimate historical records of daily water levels at low water levels, but this discrepancy disappears at water levels above approximately 7 m (Figure 3). The linear correlation coefficient between the observed and simulated daily water levels was 0.97 and the Nash-Sutcliffe efficiency coefficient was 0.91.

3.2 Comparison between BL, DF, and 3S Scenarios

Overall, similar scales and alteration trends between the DF and the 3S scenarios were found. Of the 30 hydrological parameters analyzed, 9 appeared to be significantly different ($p \leq 0.05$) in either the DF or the 3S scenario when compared to the BL scenario (Table 2): April and May monthly water levels, water fall rate (that is, the difference between the annual minimum and maximum water levels divided by the duration between them), base flow index (that is, the 7-day minimum over the mean annual water level), and 1-, 3-, 7-, 30-, and 90-day minima. None of the parameters, however, appeared to be significantly different between the DF and the 3S scenario. Boxplots of some of the most representative parameters were prepared in order to demonstrate the general trends encountered in this comparison (Figure 4). For instance, the 30-day minimum water level median was 1.52 m (range from 1.22 to 2.18 m) for the BL scenario, which is significantly different from 1.84 m (1.51 - 2.48) and 1.80 m (1.50 – 2.46 m) for the DF and 3S scenarios, respectively (Figure 4a). Water level fall rate for the BL (median of 3.2 cm d^{-1}, range 3.0-3.6 cm d^{-1}) was also significantly different from DF (median of 2.8 cm d^{-1}, range 2.7 - 3.4 cm d^{-1}) and 3S (median of 2.9 cm d^{-1}, range 2.7-3.4 cm d^{-1}; Fig 4c). In contrast, maximum annual water level from BL (median of 8.58 m, range of 7.42 - 9.67 m) was not found to be significantly different from either development scenarios (Figure 4b).

3.3 Cumulative Hydrological Alteration from the DF + 3S Scenario

The results of the simulations with the cumulative effects from the DF + 3S scenarios suggest that there could be significant impacts to the overall Tonle Sap flood regime. In terms of environmental flows, the cumulative impact of the DF + 3S scenario virtually eliminates all baseline extreme low flow conditions (Figure 5); the frequency of these events is reduced from 11 to just 1 event in 15 years. Moreover, the BL scenario shows that high flow pulses and floods occur every single year, but the frequency of these events decreases to 2 in every 3 years.

Changes in the flood regime of the Tonle Sap will also be reflected in the probability of water level exceedance (Figure 6). Greatest deviations occur at exceeding levels above 70%; for instance, 2.36 m corresponds to the 80% exceeding level in BL, but this increases to 2.62 m and 2.80 m for the DF and the DF + 3S cases, respectively. Mild declines occur at the 20% exceedance level, but much milder changes were found for greatest (and less frequent) events.

Hydropower development through the Mekong and tributaries would alter multiple seasonal and annual hydrological parameters. Primarily, greatest alteration factors are expected during the dry season months, with large alteration factors for monthly water levels during April and May, as well as other parameters including the 1-day, 3-day, 7-day, 30-day, and 90-day minima (Table 3). The DF scenario decreases the frequency of occurrence of the baseline dry season parameters by 40-60%), but the addition of the 3S hydropower network (DF + 3S) results in alteration factors of –100% for all of these parameters (meaning that they are expected to be altered every year). Factors of alteration in annual rates of water rise/fall change by –33/–20% for the DF scenario, but the magnitude of alteration factors increase to –83 and –60% for the DF + 3S scenario (Table 4).

3.4 Changes in Flood Duration

Both DF and DF+3S scenarios could bring changes to the long-term spatial patterns of inundation throughout 51-60% of the Tonle Sap Floodplain (Figure 7). In general, areas that are marginally inundated and areas that are permanently inundated are likely to expand, whereas areas that are seasonally inundated are likely to decrease. For instance, areas in the outermost class (inundated between 0.5-10% of the time) expand by 177 km^2 (10.1%) and 283 km^2 (16.1%) as a result of the DF and the DF + 3S scenarios, respectively (Table 5). Moreover, largest area shifts occur in areas inundated 90-100% of the time, which expand by 279 km^2 (5.7%) and 424 km^2 (8.6%) as a result of the DF and the DF + 3S scenarios, respectively. On the contrary, classes inundated 20-90% shrink by 600 km^2 and 994 km^2 as a result of the DF and the DF + 3S scenarios, respectively.

4 Discussion

This study presents an important contribution to the assessment of water resources management and development of the Mekong River Basin. We have combined multiple hydrological modeling tools –all of which have been previously validated for the basin– and simulated the specific and combined impact of water resources development in two regions of great hydrological contribution to the whole basin. Piman et al. (2013a) had already pointed out that the scale of hydropower development in the 3S was as large as the Lancang-Jiang dam cascade. In this study, we have taken a step further and shown that the corresponding hydrological alterations from the 3S hydropower projects are as large; more importantly, we have demonstrated that the cumulative effect of development in the upper Mekong and the 3S will cause significant disruptions to the inundation patterns of the lower Mekong floodplains, in particular through an increase in dry season water levels as well as a reduction in water level rise/fall rates.

Our study has assumed (intentionally) no changes in rainfall-runoff from one simulation to the other in order to solely explore the issue of water regulation in tributary dams. This assumption, however, is not a complete representation of changes to the basin's hydrological cycle, as there are other key factors such as climate change (Kingston et al., 2011; Lauri et al., 2012), new irrigation schemes (Piman et al., 2013b), and land use/land cover changes (Costa-Cabral et al., 2007; Ishidaira et al., 2008) that are altering rainfall-runoff characteristics and thus simultaneously affecting the role of the 3S on the Tonle Sap hydrology. As Ty et al., (2012) pointed out for one of the 3S rivers (Srepok), these other factors could also cause alterations, particularly as a decrease in water availability during the dry season. Räsänen et al. (2014) showed that for the Sesan dam cascade in Vietnam, however, irrigation water use during the dry season was relatively small compared to the increased in water flow caused by hydropower dams. In short, there is a great need for detailed modelling studies that take into account all of these major drivers of hydrological alterations.

This study demonstrated the use of IHA tools to assess the impact of future scenarios of water resources development. Although this tool has been previously used for simulated scenarios by Gao et al. (2009), their scenarios represented hypothetical reservoirs and dam operations, whereas our study represented existing and proposed projects based on actual design characteristics. IHA tools have been used in the Mekong by Ty et al. (2011) and Thompson et al. (2013), but their applications focused on climate change and excluded the Tonle Sap flooding characteristics. Our study has actually made a first attempt at quantifying environmental flows for the Tonle Sap using the simulations of baseline conditions, and our estimates could help guiding environmental flows criteria based on specific biological needs of this system. As the validation results showed, however, our model scheme had a slight tendency to overestimate historical dry season water levels; for that reason, the reported magnitude of water levels defining extreme low flows need to be read with caution as they might actually be marginally higher than historical observations. We recommend that a closer analysis using long term observed water level records is carried out in order to more accurately define environmental flows and monitor ongoing alterations to these parameters.

Previous studies (Arias et al., 2012, 2014) also assessed the impacts of water resources development on water levels and flood duration at the Tonle Sap. These previous studies used three representative hydrological years (dry, average, and wet) in order to characterize multiyear variability, and in general it was found that hydrological alterations increased from wet to dry years. While results from this study still support this trend in representative years, we found that over a longer time series only alterations on dry season water levels are expected to be recurrent. Furthermore, our estimates of dry season water level alterations for the DF scenario are consistent with values previously reported (Arias et al., 2012; MRC, 2010), whereas our estimates for the DF + 3S scenario (+ 47 cm and + 61 cm for April and May, respectively) are considerably larger than any of the MRC future development scenarios previously reported (maximum of + 33 cm in April and + 39 cm in May; MRC, 2010). This difference highlights the significance of tributary dams to the hydrology of the entire basin and the importance of modeling their dimensions and operations in detail. Difference between the DF + 3S scenario and previous estimates could also be partially attributed to water abstraction for irrigation during the dry season, which were not considered in this study; yet, a previous comparison of alterations from hydropower dams versus cumulative alterations of hydropower with irrigation did not show any major differences in the lower Mekong (Piman et al., 2013b). In order to more comprehensively address this issue, further modeling studies in the Mekong should compare the effects of hydropower with irrigation development.

Significant hydrological alterations are expected in the Tonle Sap and the rest of the lower Mekong floodplains if proposed hydropower development plans are to be formalized. Ongoing trends and large economic incentives in the hydropower business imply that most of the hydropower potential will actually be exploited and dams will be built even in locations where there is a high risk of disruptions to environmental flows. For instance, some of already operating dams in the 3S, such as Yali dam commissioned in 1994 in the Sesan River, were built without much consideration of transboundary environmental impacts and have in fact caused much damaged downstream in Cambodia (Wyatt and Baird, 2007). Clear evidence of more recent trends are the Xayaburi dam in the Mekong mainstream in Lao and the Lower Sesan 2 at the confluence of the 3S tributaries in Cambodia. Both of these dams have been already commissioned despite not only being highlighted as having potentially large ecological impacts in the scientific literature (e.g., ICEM, 2010; Ziv et al., 2012) but also after rising much controversy in the international media. Under a likely, "development as usual" scenario, the most feasible alternative to mitigate disruptions in the Mekong of both existing and proposed dams consist on retrofitting current design and operation practices in order to optimize river services rather than just maximize hydropower generation. In other words, seasonal and diurnal operation rules should also aim at minimizing hydrological alterations downstream in addition to meeting electricity demands. From a hydrological point of view, run-of-the-river designs or operations in which power is gained primarily from flow volume and not elevation head would yield much lesser alterations. In addition to hydrological considerations, there are other aspects such as sediment releases and fish passages that need to be implemented. These factors have not been widely considered in assessment studies in the Mekong (with the exception perhaps of Kummu et al., 2010 and Ziv et al., 2012) and should therefore be the subject of further research.

5 Conclusions

This paper presented a study in which hydrological modeling and assessment tools were used to provide evidence of the expected hydrological alterations that hydropower development in the lower Mekong tributaries could bring to the Tonle Sap. Hydrological alterations caused by dams in the 3S were of similar magnitude as the DF scenario, which resembles water infrastructure development up to 2015 and particularly driven by China's Lancang-Jiang dam cascade in the upper Mekong. Definite future plans in combination with the full development of the 3S dam network will most likely cause significant and undocumented hydrological alterations to the Tonle Sap and the rest of the lower Mekong floodplains. The most significant alterations are in terms of water levels during the dry season (April and May) and rates of water level rise/drop; these hydrological parameters are crucial for biological factors such as tree seeds germination and fish migrations, and therefore major ecological disruptions are likely to follow. Although there could be a decrease in wet season water levels in years of low flow from the Mekong, wet season disruptions are not recurrent in years of larger floods. Given the importance of the 3S to the rest of the lower Mekong, we recommend that more detail studies of drivers of hydrological change in the 3S are carried out, including irrigation, land use/land cover conversion, and climate change. Moreover, optimization of hydropower operations considering both electricity generation and environmental flows should be sought as a feasible alternative to be further studied and implemented in existing and proposed dams in this critical tributary.

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Table 1. Description of water infrastructure development scenarios.

Scenario name	Description	Active storage (km^3)
Baseline (BL)	Simulated baseline conditions 1986-2000 (Piman et al., 2013b)	9.1
Definite Future (DF)	Water infrastructure development plans up to 2015, including 3.4 million ha irrigation areas, water supply demands, and 6 dams in the Upper Mekong (Piman et al., 2013b)	32.3 (additional 23.2 from BL)
3S hydropower development (3S)	Construction and operation of 42 hydropower and regulation dams in the main tributaries and sub-tributaries of the Sesan, Sekong, and Srepok rivers (Piman et al., 2013a)	35.4 (additional 26.3 from BL)
DF + 3S	Cumulative impact of the DF and 3S scenarios described above	58.6 (additional 49.5 from BL)

Table 2. Kruskal-Wallis test results for comparison of annual parameters. Each column group represents a one-to-one comparison between baseline (BL), Definite Future (DF) and 3S hydropower (3S) scenarios. χ^2 represents the test statistic and *p* represents the probability value of χ^2. Significant p values (≤ 0.05) are highlighted.

	BL-DF		BL-3S		DF-3S	
Parameters	χ^2	*p*	χ^2	*p*	χ^2	*p*
Monthly water levels						
January	0.00	0.98	0.00	0.95	0.01	0.92
February	0.72	0.40	0.53	0.47	0.01	0.92
March	2.55	0.11	2.42	0.12	0.02	0.90
April	7.84	**0.01**	6.72	**0.01**	0.08	0.77
May	8.07	**0.00**	6.94	**0.01**	0.41	0.52
June	1.93	0.16	0.95	0.33	0.59	0.44
July	0.19	0.66	0.02	0.90	0.19	0.66
August	0.27	0.60	0.17	0.68	0.01	0.92
September	0.80	0.37	0.47	0.49	0.07	0.79
October	1.21	0.27	1.03	0.31	0.01	0.92
November	0.72	0.40	0.47	0.49	0.03	0.85
December	0.41	0.52	0.23	0.63	0.08	0.77
Annual parameters						
1-day minimum	7.84	**0.01**	6.72	**0.01**	0.62	0.43
3-day minimum	7.84	**0.01**	6.72	**0.01**	0.62	0.43
7-day minimum	7.84	**0.01**	6.72	**0.01**	0.65	0.42
30-day minimum	7.50	**0.01**	6.09	**0.01**	0.59	0.44
90-day minimum	4.92	**0.03**	3.80	**0.05**	0.31	0.58
1-day maximum	1.03	0.31	0.95	0.33	0.00	1.00
3-day maximum	1.03	0.31	0.95	0.33	0.00	1.00
7-day maximum	1.03	0.31	0.87	0.35	0.00	0.98
30-day maximum	0.95	0.33	0.87	0.35	0.00	0.98
90-day maximum	0.95	0.33	0.95	0.33	0.08	0.77
Date of minimum	0.29	0.59	0.07	0.79	0.14	0.71
Date of maximum	0.04	0.85	0.00	0.98	0.04	0.85
Base flow index	18.79	**0.00**	17.72	**0.00**	1.60	0.21
Fall rate	8.94	**0.00**	8.96	**0.00**	0.20	0.66
Rise rate	2.69	0.10	0.65	0.42	0.80	0.37
Low pulse duration	0.00	0.98	0.00	0.98	0.02	0.90
High pulse duration	0.00	1.00	0.00	0.97	0.01	0.92
Number of reversals	0.00	0.96	0.11	0.73	0.08	0.78

Table 3. Summary of monthly and minimum/maximum hydrological parameters. Largest alterations to occur during the dry season (April, May, 1-day min, 3-day min, 30-day min, 90-day min).

Parameters	Baseline (BL)						Definite Future (DF)					Definite Future + 3S hydropower (DF + 3S)				
Monthly water levels	Median	CD[a]	Min	Max	Low RVA[b] Boundary	High RVA Boundary	Median	CD	Min	Max	HAF[c]	Median	CD	Min	Max	HAF
January	4.93	0.13	4.46	5.84	4.80	5.19	4.88	0.13	4.38	5.94	0.0	4.96	0.15	4.36	6.00	-0.33
February	3.87	0.13	3.51	4.65	3.82	4.09	3.95	0.13	3.56	4.76	0.0	4.06	0.14	3.64	4.85	0.00
March	2.94	0.15	2.65	3.60	2.89	3.11	3.14	0.14	2.83	3.77	0.0	3.28	0.15	3.01	3.92	-0.33
April	2.15	0.13	1.90	2.69	2.08	2.27	2.41	0.12	2.12	2.94	-0.6	2.62	0.12	2.36	3.15	-1.00
May	1.60	0.29	1.33	2.16	1.50	1.70	1.93	0.23	1.57	2.47	-0.8	2.21	0.19	1.83	2.70	-1.00
June	2.34	0.47	1.21	3.89	1.74	2.46	2.62	0.43	1.62	3.99	-0.2	2.71	0.34	1.88	4.06	0.20
July	3.97	0.57	2.48	7.13	3.43	4.10	4.03	0.55	2.71	6.94	0.0	4.04	0.46	2.84	6.77	0.00
August	6.27	0.33	4.39	8.86	5.54	7.04	6.12	0.34	4.37	8.59	0.2	6.05	0.32	4.31	8.50	0.40
September	8.01	0.21	6.77	9.67	7.42	8.60	7.82	0.23	6.53	9.60	0.2	7.66	0.25	6.34	9.60	0.00
October	8.56	0.18	7.42	9.26	7.82	8.82	8.42	0.21	7.08	9.22	0.2	8.31	0.23	6.78	9.22	-0.20
November	7.68	0.16	6.79	8.67	7.33	8.08	7.54	0.16	6.52	8.66	0.0	7.52	0.18	6.33	8.64	0.00
December	6.25	0.15	5.61	7.33	6.06	6.68	6.14	0.17	5.39	7.36	-0.4	6.17	0.20	5.29	7.39	-0.40
Min/Max periods																
1-day min	1.41	0.33	1.15	2.05	1.36	1.60	1.75	0.27	1.45	2.36	-0.4	2.05	0.21	1.73	2.60	-1.00
3-day min	1.42	0.33	1.15	2.05	1.36	1.60	1.75	0.27	1.45	2.37	-0.4	2.06	0.21	1.73	2.61	-1.00
7-day min	1.43	0.33	1.16	2.07	1.37	1.61	1.76	0.27	1.46	2.38	-0.4	2.06	0.21	1.73	2.62	-1.00
30-day min	1.52	0.31	1.22	2.18	1.45	1.69	1.84	0.25	1.51	2.48	-0.4	2.11	0.20	1.78	2.71	-1.00
90-day min	1.97	0.28	1.56	2.69	1.81	2.03	2.22	0.23	1.78	2.94	-0.6	2.46	0.16	2.04	3.14	-1.00
1-day max	8.71	0.18	7.51	9.80	7.93	9.01	8.55	0.22	7.40	9.74	0.2	8.43	0.23	7.12	9.74	-0.20
3-day max	8.71	0.18	7.51	9.80	7.93	9.00	8.55	0.21	7.40	9.74	0.2	8.43	0.23	7.12	9.74	-0.20
7-day max	8.69	0.18	7.50	9.78	7.92	8.99	8.54	0.22	7.39	9.73	0.2	8.42	0.23	7.11	9.73	-0.20
30-day max	8.58	0.19	7.42	9.67	7.84	8.92	8.43	0.21	7.29	9.60	0.2	8.32	0.24	7.08	9.59	-0.20
90-day max	8.12	0.20	7.04	9.27	7.48	8.52	7.96	0.22	6.84	9.17	0.2	7.86	0.24	6.64	9.15	-0.20

[a]CD = coefficient of dispersion ([75^{th} percentile – 25^{th} percentile]/50^{th} percentile); [b]RVA: Range of Variability Approach; [c] HAF: Hydrologic Alteration factor, which is the percent difference between the expected baseline frequency and the simulated frequency for the impact scenarios

Table 4. Summary of annual hydrological parameters. Largest alterations factors (HAF) estimated for base flow index and water level fall rate.

Parameters	Baseline (BL)						Definite Future (DF)					Definitive Future + 3S hydropower (DF + 3S)				
	Median	CD[a]	Min	Max	Low RVA[b] Boundary	High RVA Boundary	Median	CD	Min	Max	HAF	Median	CD	Min	Max	HAF
Base flow index	0.31	0.17	0.27	0.37	0.29	0.32	0.37	0.09	0.33	0.43	-1.00	0.42	0.08	0.38	0.47	-1.00
Date of minimum	24/05	0.04	05/05	14/06	18/05	28/05	20/05	0.04	01/05	12/06	-0.20	20/05	0.04	06/05	13/06	-0.20
Date of maximum	08/10	0.02	16/09	24/10	04/10	09/10	08/10	0.02	17/09	29/10	0.33	06/10	0.03	17/09	30/10	0.20
Low pulse duration	91	0.3	48	120	86	101	81	0	34	113	-0.20	67	0.5	14	100	-0.5
High pulse duration	91	1	44	144	76	117	85	0.9	28	143	0.00	90	1.1	6	142	0.0
Rise rate (cm d^{-1})	5.3	21.9	3.7	6.8	5.1	5.9	4.8	21.1	3.0	6.4	-0.33	4.7	2.6	3.3	6.0	-0.83
Fall rate (cm d^{-1})	-3.2	-12.5	-3.6	-3.0	-3.4	-3.1	-2.8	-10.7	-3.4	-2.7	-0.20	-2.6	-1.5	-3.3	-2.4	-0.60

[a]CD = coefficient of dispersion ([75^{th} percentile – 25^{th} percentile]/50^{th} percentile); [b]RVA: Range of Variability Approach; [c] HAF: percent difference between the expected baseline frequency and the simulated frequency for the impact scenarios

Table 5. Changes in spatial patterns of flooding in the Tonle Sap.

Percent of days inundated in 15 years (%)	BL	DF		DF + 3S	
	Area (km^2)	Area (km^2)	Area change from BL (%)	Area (km^2)	Area change from BL (%)
0.5 - 10	1758	1935	10.1	2042	16.1
10 - 20	1417	1468	3.6	1582	11.7
20 - 30	1421	1361	-4.3	1275	-10.3
30 - 40	1667	1554	-6.7	1480	-11.2
40 - 50	1533	1420	-7.3	1349	-12.0
50 - 60	1391	1229	-11.7	1018	-26.8
60 - 70	931	866	-7.0	962	3.3
70 - 80	949	941	-0.9	885	-6.7
80 - 90	693	614	-11.4	623	-10.2
90 – 100	4910	5188	5.7	5334	8.6

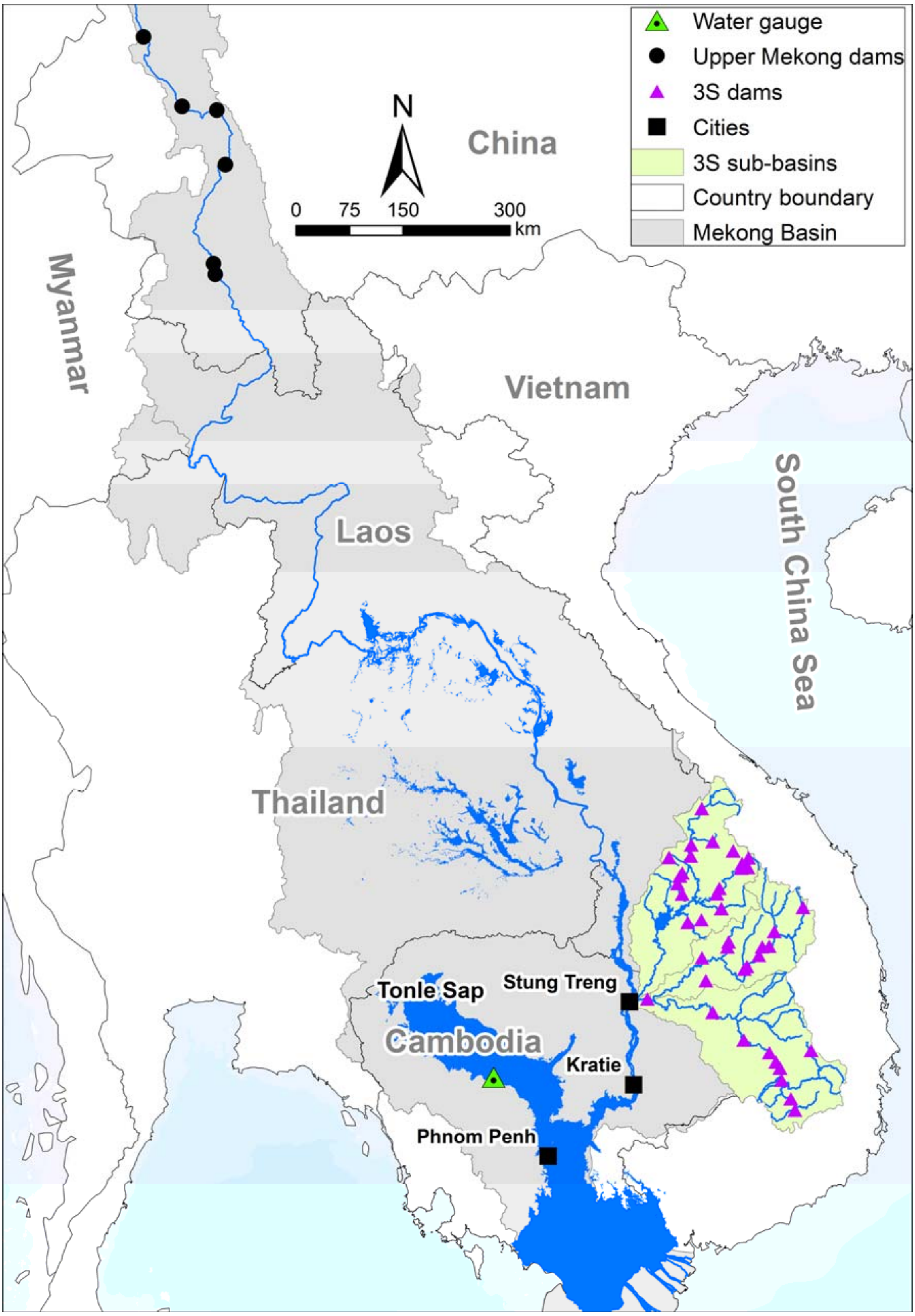

Figure 1. Map of the Mekong Basin highlighting the Tonle Sap floodplain and dams in the Definite future (black dots) and 3S development scenarios (violet triangles). The green triangle shows the Kampong Luong water level gauge location on the Tonle Sap.

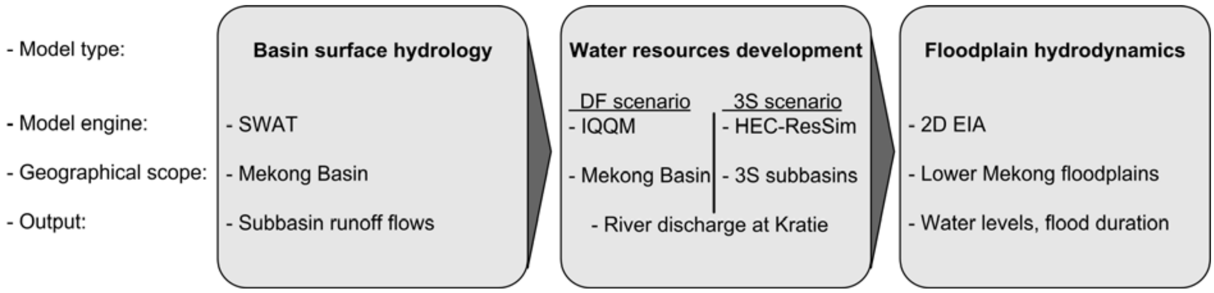

Figure 2. Models used and their general features. DF = Definite Future.

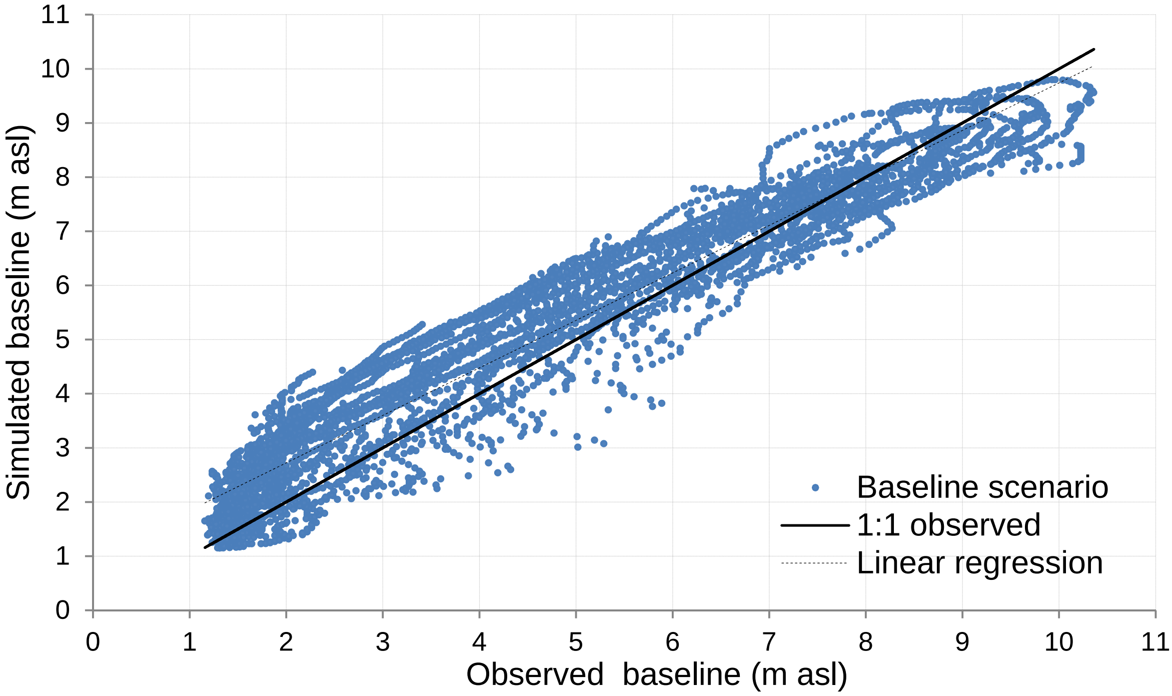

Figure 3. Observed versus projected daily water levels (in meters above sea level, m asl) during 1986-2000.

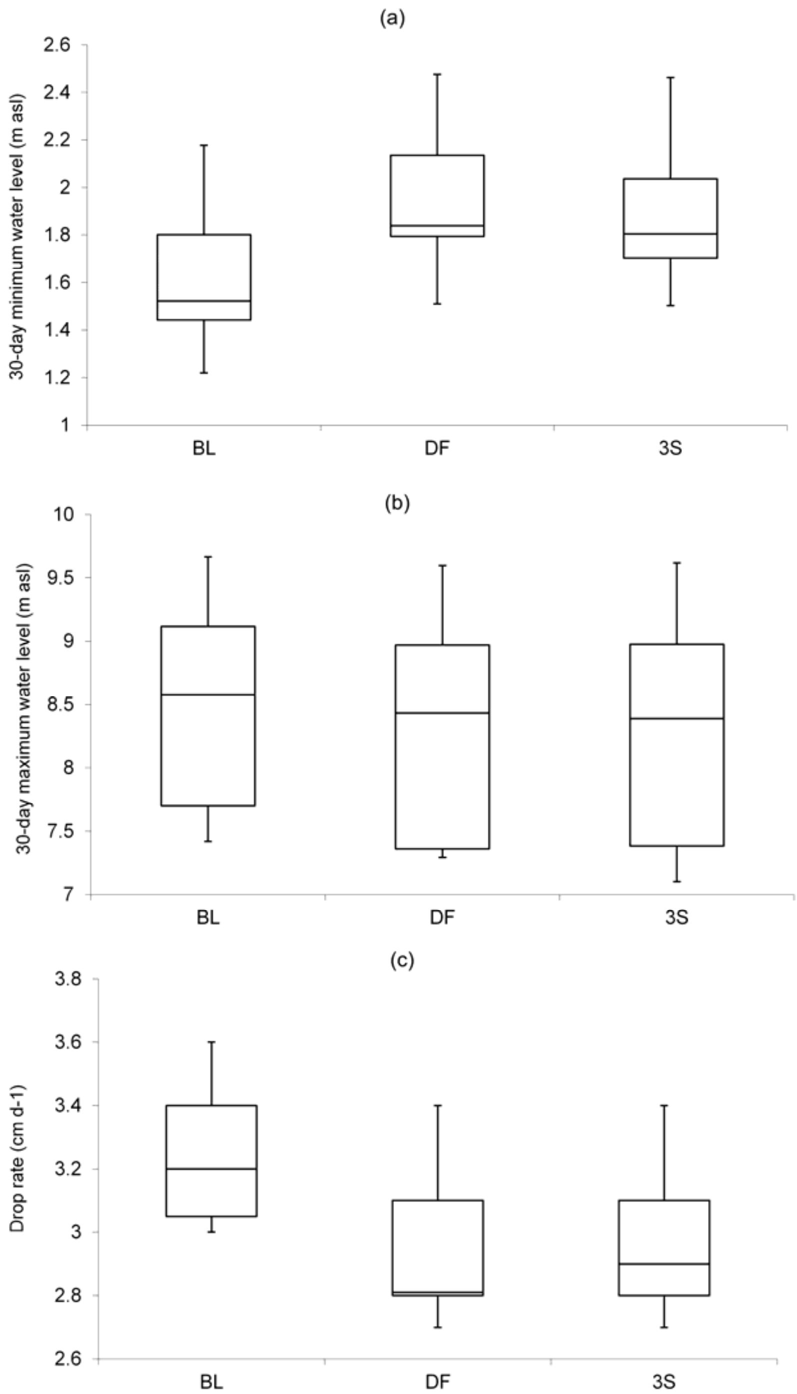

Figure 4. Boxplots of hydrological parameters from the baseline (BL), Definite Future (DF), and 3S hydropower development (3S) scenarios. 30-day minimum and drop rate for both DF and 3S are significantly different from BL ($p \leq 0.05$). Water fall/drop rate refers to the difference between the annual minimum and maximum water levels divided by the duration between them. There are no significant differences in 30-day maximum water level among scenarios.

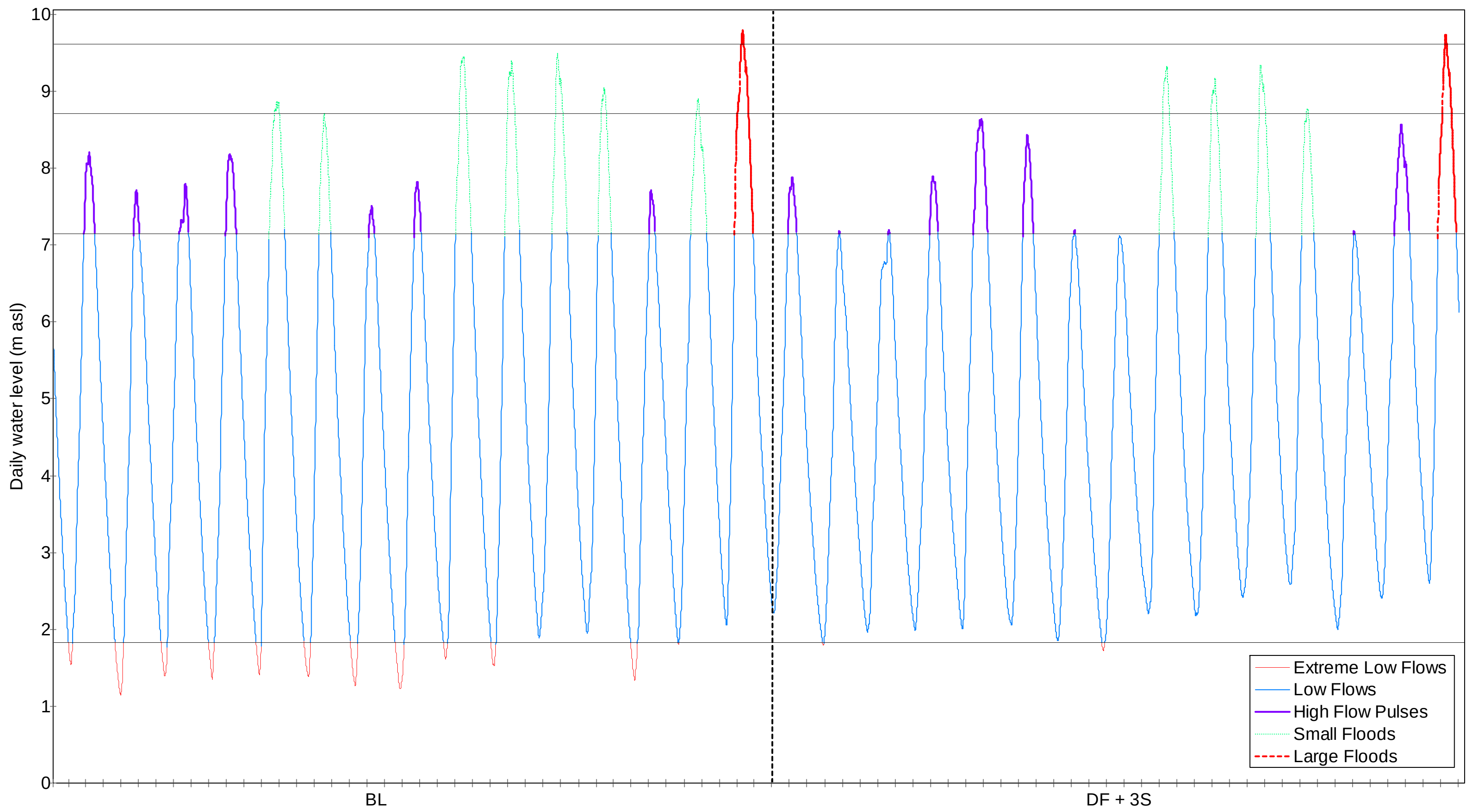

Figure 5. Comparison of daily water levels and environmental flow components between the baseline scenario (BL) and the combine effect of the Definite Future and the 3S Hydropower scenario (DF + 3S).

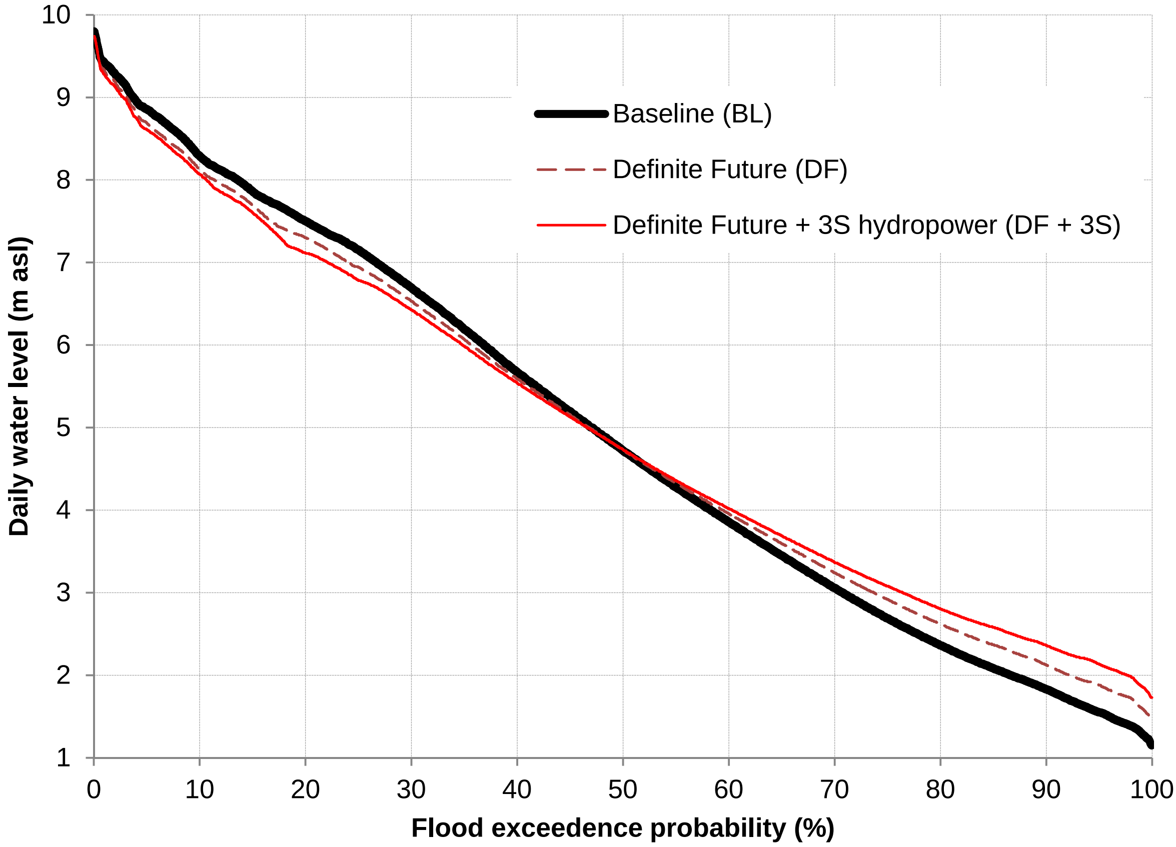

Figure 6. Exceedance probability plot of daily water levels. Greatest deviations expected for water levels near the 20% exceeding level (~ 7 m asl) and below the 70% exceeding level (less than 3 m asl).

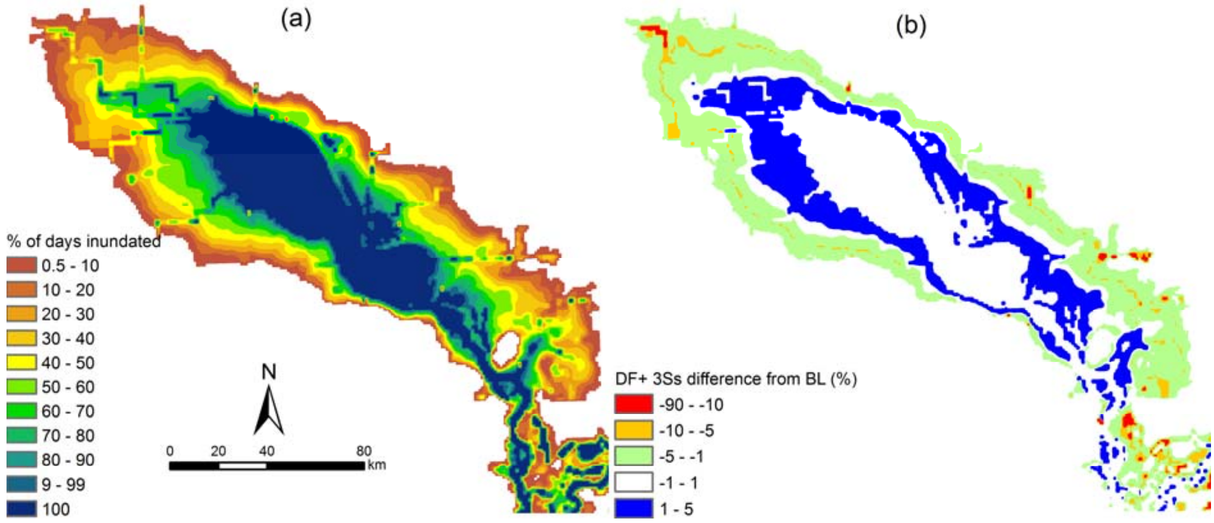

Figure 7. Maps representing duration of flooding during the 15 year simulations **(a)** Baseline (BL) flood duration map as percentage of total simulation time; **(b)** Map showing the difference in flood duration between DF + 3S and BL. Expected increase flood duration in the more frequently inundated areas (in blue) and a decrease in flood duration in the marginally inundated areas (in red, green and orange).