Drastic decline of floodpulse in the Cambodian floodplains (the Mekong River and the Tonle Sap system)

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Abstract. The Cambodian floodplains experience a yearly floodpulse that is essential to sustain fisheries and the agricultural calendar. Sixty years of data from 1960-2019 are used to track the changes to the floodpulse there. We find that minimum water levels in 2010-2019 have increased by up to 1.55m at Kratie and maximum water levels have decreased by up to 0.79m at Prek Kdam when compared to 1960-1991 levels, causing a reduction of the annual flood extent. Concurrently, the duration of the flooding season has decreased by about 26 days (Kompong Cham) – 40 days (Chaktomuk), with the season starting later and ending much earlier. Along the Tonle Sap River, the average annual reverse flow from the Mekong to the Tonle Sap Lake has decreased by 56.5%, from 48.7 km^3 in 1962-1972 to 31.7 km^3 in 2010-2018. As a result, wet-season water levels at Tonle Sap Lake have dropped by 1.05m in 2010-2019 since 1996-2009, corresponding to a 20.6% shrinkage of the Lake area. We found that upstream contributors such as the current hydropower dams cannot fully account for the observed decline in floodpulse. Instead, local anthropogenic causes such as irrigation and channel incision are important drivers. We estimate that water withdrawal in the Cambodian floodplains is occurring at a rate of (2.1 ± 0.3) km^3/yr. Sediment decline and the ongoing sand-mining operations have also caused channel erosion. As the floodpulse is essential for the ecological habitats, fisheries and livelihoods of the region, its reduction will pose major implications throughout the basin, from the Tonle Sap system to the Vietnamese Mekong Delta downstream.

1 Introduction

The Mekong River in Southeast Asia has attracted much attention as water infrastructure developments have accelerated in the past years (Best, 2019; Soukhaphon et al., 2021). Due to its transboundary nature, the cross-border hydrological impacts of anthropogenic alterations have become a contentious topic (Stone, 2010). For instance, Keovilignavong et al. (2021) described how the recent 2019-2020 Mekong drought was politicised bystates and agencies.

The Cambodian floodplains and the Tonle Sap Lake system is home to a unique geographical phenomenon. During the dry season, the Lake empties into the Mekong. However, during the wet season, large tracts of the floodplains are inundated, and flow is reversed from the Mekong to the Lake. This annual flood pattern is critical for both fisheries productivity (Halls and

Hortle, 2021; Sabo et al., 2017; Ziv et al., 2012) and the agrarian communities that are reliant upon the annual floodwaters for replenishment of nutrients and water (Arias et al., 2012; Grundy-Warr and Lin, 2020).

Due to the significance of the annual floods, the ecological and hydrological services provided by the Cambodian floodplains is best understood as a consequence of the floodpulse (Junk et al., 1989). Elsewhere, hydrological alterations to the floodpulse have been quantified in the Amazon basin (Zulkafli et al., 2016) and Missouri basin (Bovee and Scott, 2002). Within other parts of the Mekong, the floodpulse has been investigated vis-à-vis its relationships to climate (Räsänen and Kummu, 2013; Västilä et al., 2010) or ecosystems (Arias et al., 2013; Kong et al., 2017; Ngor et al., 2018). These studies indicate that quantification of the floodpulse can be useful in the understanding of the hydrology of a floodplain system.

In the Cambodian floodplains, water levels in the Tonle Sap Lake and the Mekong mainstream have a close relationship (Guan and Zheng, 2021; Inomata and Fukami, 2008), meaning that any alterations to flows on the mainstream will affect the hydrology on the Lake. Studies on the Tonle Sap Lake has predicted dry-season water levels to increase and wet-season water levels to decrease (Arias et al., 2012; Kummu and Sarkkula, 2008). Indeed, remotely-sensed data has confirmed that the surface area of the Lake has been on a declining trend since 2000 (Ji et al., 2018; Lin and Qi, 2017)

Overall, the Cambodian floodplains can protect neighbouring Phnom Penh and the VMD downstream from floods by storing large volumes of water during the wet season (Fujii et al., 2003; MRC et al., 2004). In addition, the effects of upstream water infrastructure development, such as the Lancang dams, on the VMD are also dampened by the buffering effect of the floodplains (Dang et al., 2005). However, despite its importance, the hydrological changes experienced by the Cambodian floodplains over the past decades have been poorly understood.

This study first aims to quantify the floodpulse along the Cambodian floodplain using sixty years of data from 1960-2019. Then, we want to identify the anthropogenic factors that have caused the alterations to the floodpulse. Through this approach, we offer novelty in two ways. First, we studied the Cambodian floodplains in its entirety, as compared to other authors who only investigated the Tonle Sap system (Chen et al., 2021; Kummu and Sarkkula, 2008) or the Mekong system (Binh et al., 2020b). Second, we synthesised knowledge of the various anthropogenic drivers in the region and associated them with observed hydro-geomorphological impacts. In so doing, we present the implications of current human activities on the Cambodian floodplains and the wider region.

2 Study Area

Beginning from Stung Treng, the lower reaches of the Mekong winds through a large floodplain that is seasonally inundated during the wet season (Figure 1). Connected to the floodplain is the Tonle Sap system that expands from an area of 2500km^2 during the dry season to up to 15 000km^2 during the wet season (Ji et al., 2018). The whole floodplain is underlain by a mosaic of tropical ecosystems such as gallery forest, shrublands and aquatic herbaceous vegetation(Araki et al., 2007; Arias et al., 2013; Kummu and Sarkkula, 2008), and man-made landuse such as rice fields and canals (Mahood et al., 2020; Olson and Morton, 2018). When water level exceeds 12m at Kompong Cham, extensive overbank flooding will occur on both banks of the Mekong (Inomata & Fukami, 2008; MRC et al., 2004). Concurrently, along the Tonle Sap River, water flows from the Mekong to the Tonle Sap Lake, bringing along its supply of sediments and nutrients (Campbell et al., 2009; Lu et al., 2014; Siev et al., 2018).

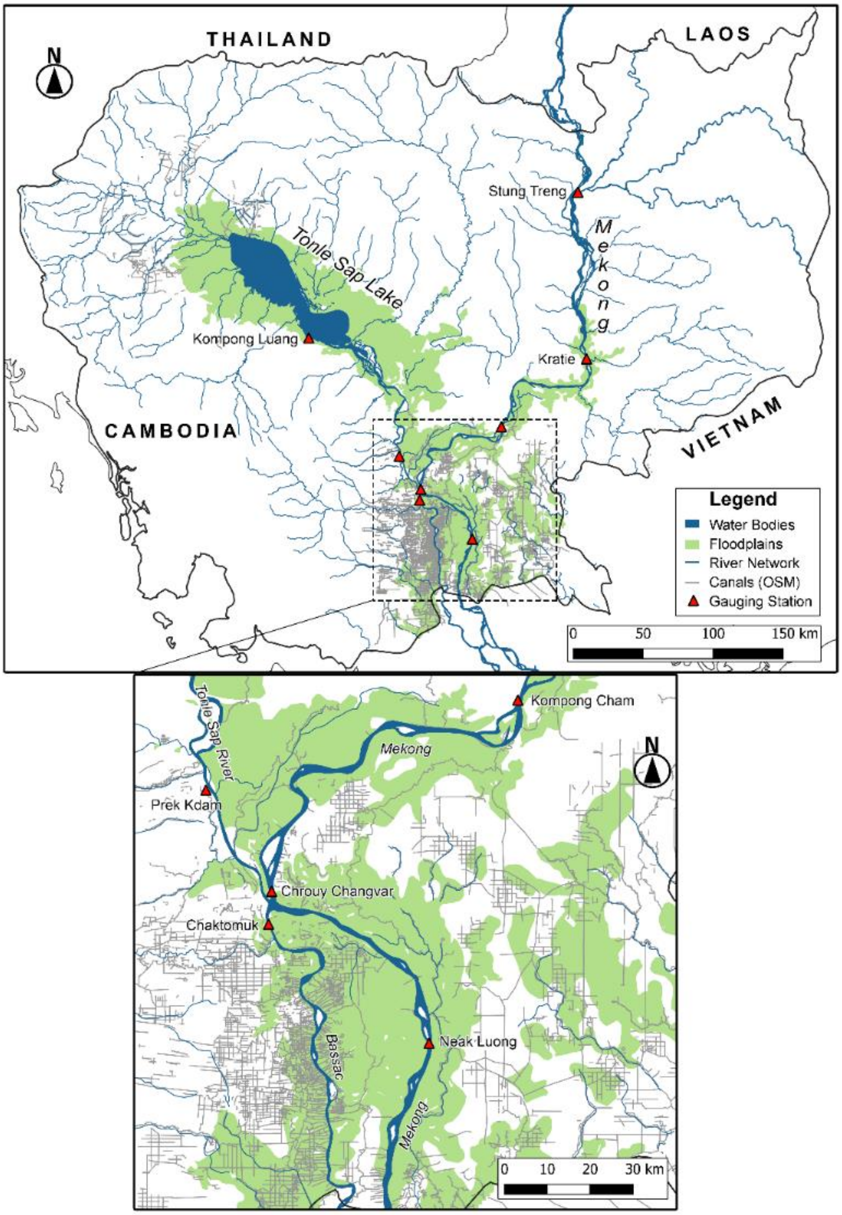

Figure 1. Map of Cambodian floodplains. Key hydrological stations referenced in the paper are highlighted. Canals in grey are extracted from OpenStreetMap and copyrighted to OpenStreetMap contributors 2021. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.”.

We identify three main anthropogenic factors that can cause changes to the yearly floodpulse: upstream dam construction, irrigation and sand-mining. In the UMB, the Lancang cascade consisting of 11 dams over an 800m drop was built by China beginning with Manwan Dam in 1992 (Hecht et al., 2019). These dams have raised concerns due to their ability to alter the hydrological regime downstream (Lu et al., 2014a). For example, the two largest, Xiaowan and Nuozhadu, completed in 2010 and 2014 respectively, has a total reservoir capacity of 38.3km^3, which is more than half of the total capacities of all the reservoirs in the whole Mekong basin (MRFI, 2020). The cascade has been found to increase dry-season discharge and reduce wet-season discharge downstream (Li et al., 2017; Räsänen et al., 2012) to as far as Kratie (Räsänen et al., 2017). Nearer to the Cambodian floodplains, tributary dams such as the Pak Mun Dam in the Chi-Mun system have also been shown to regulate downstream Mekong flows (Cochrane et al., 2014). Dams in the 3S (Sekong, Sesan, Srepok) river basin can also affect the floodpulse downstream by increasing minimum water levels (Arias et al., 2014) or by decreasing wet season discharge (Piman et al., 2013a).

In recent years, the Cambodian floodplains have been developed to tap into its potential for rice production (Erban and Gorelick, 2016; Yu and Fan, 2011). Under the “Rice-White Gold” policy under the Cambodian government, the country fulfilled its objective to increase rice yield to 4 million tons in 2015 from just 20 thousand tons in 2009 (Royal Government of Cambodia, 2010). The boom in rice production was possible with both the use of high-yielding rice varieties and an expansion of irrigation infrastructure that allowed dry-season cropping (ADB, 2019). With investments from international donors such as the World Bank and the Asian Development Bank (ADB) or countries such as Japan and China, Cambodia has both upgraded its ageing irrigation schemes and constructed new canals and reservoirs (Sithirith, 2017) (Table S1 in Supporting Information). However, these water infrastructures consume large volumes of water – Erban and Gorelick (2016) estimate that full dry-season irrigation could use up to 31% of the total Mekong and Bassac flow.

Another anthropogenic activity that has increased pace is sand-mining within the river channels (Kondolf et al., 2018; Schmitt et al., 2017). In Cambodia alone, it was estimated that at least 34.4 million cubic meters of sediments were mined per year (Bravard et al., 2013). Of this amount, 18.1 million cubic meters was mined within the short stretch of Mekong from Kompong Cham to the Vietnamese border (Bravard et al., 2013). As the large volumes of sediment are being removed from the river bed, sediment contribution from the Upper Mekong is unable to replenish these losses (Hackney et al., 2020). The problem is so severe in the neighbouring VMD that sand-mining has resulted in up to 1.3m decrease in water levels, exacerbating the impacts of sea-level rise or saltwater intrusion (Brunier et al., 2014; Vu et al., 2018). On the Cambodian side, Hackney et al. (2021) estimate that sand-mining has caused riverbed incision at a rate of -0.26m/yr from 2013 to 2019 with no signs of abatement.

3 Materials and Methods

3.1 Data

Water level and discharge data were obtained from the Mekong River Commission (MRC, 2021). On the Mekong mainstream, we got data from Stung Treng, Kratie, Kompong Cham, Chrouy Changvar and Neak Luong. We also obtained data from Prek Kdam (Tonle Sap River), Chaktomuk (Bassac River) and Kompong Luang (within Tonle Sap Lake) These stations were selected due to their good coverage of the Cambodian floodplains and documentation of their historical records from 1960 onwards (Table 1). However, there are some gaps in the digital data downloaded from the MRC data portal at https://portal.mrcmekong.org/home. To these gaps, we consulted physical data records at the MRC office and Ministry of Water Resources and Meteorology, Cambodia. While most of these missing entries were found and filled, there are still some years without documentation despite our best efforts (Figure S1 in supplementary). Precipitation data were also obtained from the MRC for Kompong Cham and Chaktomuk.

Table 1. Summary of obtained data records from the various stations

		Actual Data		Computed Data	
		Water Level	Discharge		
Mekong mainstream	Stung Treng	1960-2019	1960-2019	2005-2019	Calibrated to 2000-2004 rating curve because new rating curve depressed discharge values from 2005 onwards.
	Kratie	1960-2019	1960-1969 1980-2019		
	Kompong Cham	1960-2019	1960-2011	2012-2019	Used the rating curve from MRC et al. (2004) to estimate discharge for missing years
	Chrouy Changvar	2000-2019			
	Neak Luong	1960-2019	1960-2011	2012-2019	Used the rating curve from MRC et al. (2004) to estimate discharge for missing years
Tonle Sap River	Prek Kdam	1960-2019	1962-1972 1995-2018		
Bassac River	Chaktomuk	1960-2019	1960-2011	2012-2019	Used the rating curve from MRC et al. (2004) to estimate discharge for missing years
Tonle Sap Lake	Kompong Luang	1996-2019			

At Kompong Cham, Neak Luong and Chaktomuk, missing discharge data from 2012-2019 were calibrated from their corresponding water levels using the rating curves derived in MRC et al. (2004). To test the validity of these curves, they were used to generate predictions of discharge values from 2003-2011. The predictions were then compared with actual discharge readings measured during the same period to obtain their respective R^2 score. The plots of actual and predicted values are available in Figure S2 in supplementary.

$$\text{Kompong Cham (KC): } Q_{KC} = (8.869H_{KC} + 29.811)^2(H_{KC} - H_{CC})^{0.3} + 2412.182 \text{ } (R^2=0.998)$$

$$\text{Neak Luong (NL): } Q_{NL} = (12.718H_{NL} + 62.250)^2(H_{CC} - H_{NL})^{0.2} \text{ } (R^2=0.993)$$

$$\text{Chaktomuk (CK): } Q_{CK} = (13.943H_{CK} + 19.992)^{1.8} \text{ } (R^2>0.999)$$

where Q is discharge and H is water levels. H_{CC} refers to water level at Chrouy Changvar.

The high R^2 scores indicate high accuracy of the predicted discharge values and thus, justify their use for further analyses. Additionally, we identified an unreported change in the rating curve at Stung Treng. The new curve was implemented on 1 January 2005 and depressed discharge values afterwards, making them unsuitable for comparison with data prior (Lu and Chua, 2021). Therefore, post-2004 discharge data must be calibrated with the previous rating curve. The previous rating curve was obtained by plotting discharge and water level data from 2000-2004 and then seeking the best fit line with the smallest RMS error. The resulting polynomial relation achieved high accuracy with $R^2>0.999$:

$$\text{Stung Treng (ST): } Q_{ST} = 207.549{H_{ST}}^2 + 2598.316H_{ST} - 4854.477 \text{ } (R^2>0.999)$$

3.2 Methodology

Figure 2 offers a timeline of major anthropogenic processes occurring in the Mekong basin from 1960 to 2020. There are three distinct phases of water infrastructure development: 1960-1991, 1992-2009 and 2010-2019. 1960-1991 constitutes the pre-dam era and can be treated as the historical baseline before any major water infrastructure development. Following the construction of the first dam on the Mekong mainstream – Manwan Dam, the growth era from 1992-2009 has seen extensive hydropower development both on the Mekong mainstream and its tributaries upstream in China, Thailand, and Laos. For example, during this period, China constructed the Manwan, Dachaoshan and Jinghong dams in the Upper Mekong Basin, with a total storage capacity of no less than 2.95km^3 (MRFI, 2020). Within Cambodia, irrigation infrastructures were still small-scale and sand-mining is only in the scale of 13.5MT/yr (United Nations, 2017). However, after 2010, the pace of dam construction increased with the operationalisation of mega-dams in China such as Xiaowan and Nuozhadu dams with a combined storage capacity of up to 38.3km^3, thereby marking the start of the mega-dam era (MRFI, 2020). Concurrently, the Cambodian government announced the "Rice-White Gold" policy paper in 2010, sparking a burst of intensive irrigation projects in the Cambodian floodplain (ADB, 2019a; Royal Government of Cambodia, 2010). By 2019, the pace of sand-mining has increased to almost 50.2 MT/yr (Hackney et al., 2021), almost four times its 2009 rate.

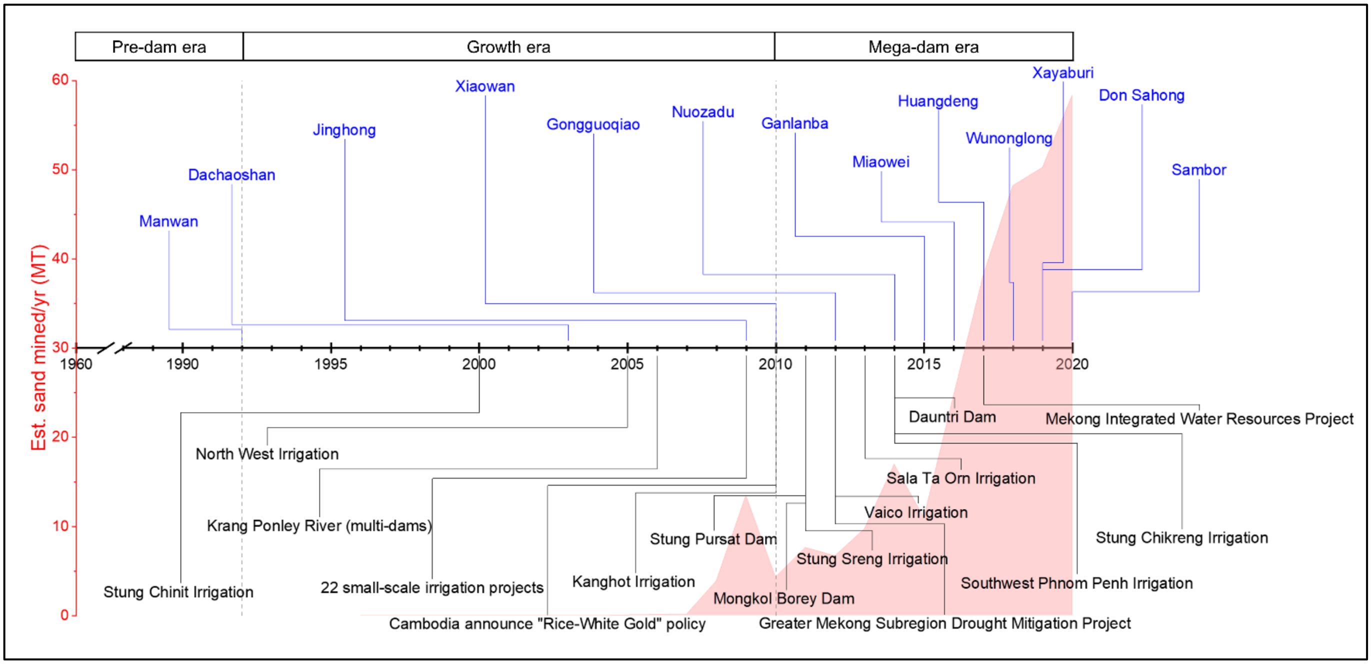

Figure 2. Timeline of major water infrastructure activities in the Cambodian floodplains and the wider Mekong Basin. Blue labels indicate the mainstream dams constructed across the Mekong (including the Lancang Cascade). Black labels indicate irrigation projects within Cambodia. Red chart represent the estimated rate sand mined per year in MT. Mining data from 1998-2015 were obtained from United Nations (2017) while mining data from 2016-2020 were obtained from Hackney et al. (2021)

This division of our study period into the three eras allows us to view any hydrological changes within the context of wider basin developments in the Mekong. Furthermore, this division is consistent with other studies in the region (Binh et al., 2020b; Guan and Zheng, 2021; Li et al., 2017; Räsänen et al., 2017), allowing for the cross-comparison of results. However, due to missing data years at some stations, the study duration might not be consistent. Nevertheless, our analysis would still reflect the general trend and central tendency across the different timeframes because only average values were compared.

3.2.1 Floodpulse

The various parameters to characterise floodpulse as seen in Figure 3a were determined from the equations below:

$$MIN_{annual}/\text{m} = \text{lowest water level of a year}$$

$$MAX_{annual}/\text{m} = \text{highest water level of a year}$$

$$AMPLITUDE/\text{m} = MAX_{annual} - MIN_{annual}$$

$$THRESHOLD\ (FT)/\text{m} = 50^{\text{th}}\ \text{percentile of all water levels in study period}$$

$$START\ DATE = \text{Date when water level} > FT\ \text{AND remain more than}\ FT\ \text{for next 10 days}$$

$$END\ DATE = \text{Date when water level} < FT\ \text{AND remain less than}\ FT\ \text{for next 10 days}$$

$$DURATION/\text{days} = \text{Days between}\ START\ DATE\ \text{and}\ END\ DATE$$

$$PEAK\ DATE = \text{Date of}\ MAX_{annual}$$

$$RISE\ RATE/\text{mday}^{-1} = \frac{MAX_{annual} - FT}{Days\ from\ START\ DATE\ to\ PEAK\ DATE}$$

$$FALL\ RATE/\text{mday}^{-1} = \frac{MAX_{annual} - FT}{Days\ from\ PEAK\ DATE\ to\ END\ DATE}$$

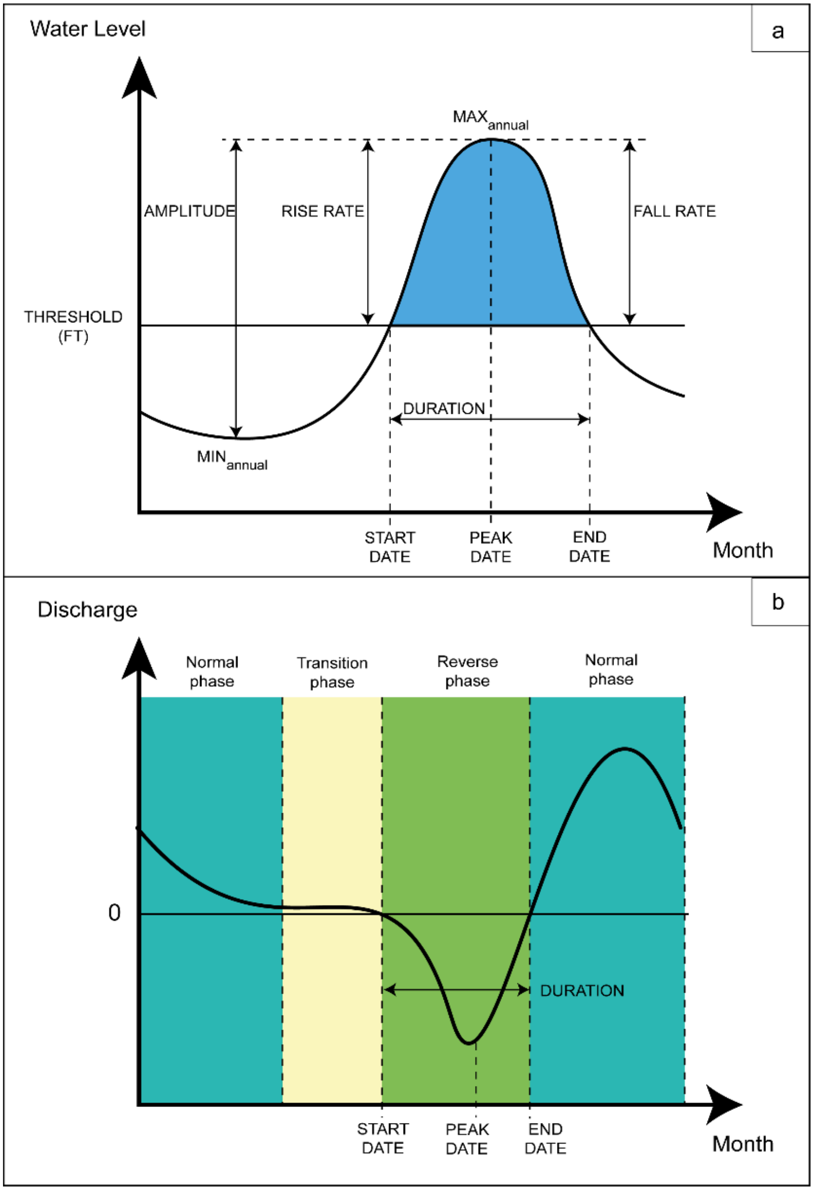

Figure 3a (top). Schematic of floodpulse variables in virtual annual water level plot in the Cambodian floodplains. Figure 3b (bottom). Schematic of the various phases at Prek Kdam observed through a typical annual discharge plot. Negative discharge values indicate reverse flow from the Mekong to the Tonle Sap Lake.

Comparisons of the means of numerical variables such as *AMPLITUDE*, *RISE RATE* and *FALL RATE* were validated with Welch's t-test. For comparison of dates, the date was first converted to its Julian date. Thereafter, the median date of each study period was compared and validated with a Mann-Whitney test.

3.2.2 Reverse Flow at Prek Kdam

The parameters to characterise reverse flow (RF) where water flow from the Mekong to Tonle Sap Lake is stated below:

$$\text{ANNUAL RF/km}^3 = \sum RF \text{ in a year}$$

$$\text{MAX}_{\text{RF}} \text{ /cms} = \text{highest RF of a year}$$

Three phases of the flow pattern are observed: Normal phase, transition phase and reverse phase (Figure 3b). The normal phase is when water flow from the Tonle Sap towards the Mekong. The transition phase begins on the date when the river record water flowing in the reverse direction for the first time in the year. The reversal phase starts when water continues to flow towards the lake and does not switch direction until the water abruptly changes back to the normal phase flow. Note: not all years have a transition phase.

3.2.3 Discharge changes

At each station, the mean discharge (in cms) from June to September was computed. By comparing average values during the pre-dam and mega-dam eras, the change in floodpulse across the entire Cambodian floodplain can be visualised. Additionally, difference in discharge (Q_{diff}) between the downstream stations of Chaktomuk (CK) and Neak Luong (NL), and the upper station of Stung Treng (ST) was calculated to estimate the amount of water loss/gain in the Cambodian floodplains.

$$Q_{diff} = (Q_{CK} + Q_{NL}) - Q_{ST}$$

If $Q_{diff} = 0$, then it means that the amount of water entering the floodplain system is roughly equivalent to the amount exiting. If $Q_{diff} > 0$, then it means that there is additional water to the Cambodian floodplains from outside the Mekong mainstream. This addition can come from precipitation or discharge from tributaries. Conversely, if $Q_{diff} < 0$, then it means that water is lost to outside the Cambodian floodplains through diversion or evapotranspiration.

4 Results

4.1 Mekong River mainstream

4.1.1 Changes to annual flood extent

The annual flood extent is given by the yearly maximum and minimum water levels of the Mekong. Compared to the pre-dam era from 1962-1991, minimum water level was higher during the growth era from 1992-2009 (Figure 4). The trend continued into the mega-dam era (2010-2019) with significant increases recorded at all stations except Chaktomuk (Table S2 in supporting information). For reference, the minimum water levels were higher by 0.60m at Stung Treng; 1.55m at Kratie; 0.60m at Kompong Cham and 0.10m at Neak Luong.

Furthermore, maximum water levels have decreased at all stations downstream of Kratie during the mega-dam era as compared to the pre-dam era. For example, Neak Luong and Chaktomuk experienced 0.55m and 0.76m drops respectively. Correspondingly, amplitude of the floodpulse decreased. Comparing records from the mega-dam era to the pre-dam era, amplitude dropped by 7.9% at Kratie; 5.6% at Kompong Cham; 10.6% at Neak Luong; and 8.9% at Chaktomuk. This observed increase in dry-season minima and decrease in wet-season maxima is consistent with studies in other parts of the Mekong Basin (Binh et al., 2020b; Li et al., 2017; Räsänen et al., 2017), demonstrating that the impacts of water infrastructure development are evident within the Cambodian floodplains.

In practical terms, more areas of the riverbanks are now permanently inundated during the dry season. As the flood amplitude decreases, the annual flood extent is reduced, meaning that some parts of the floodplains are no longer being flooded during the wet season.

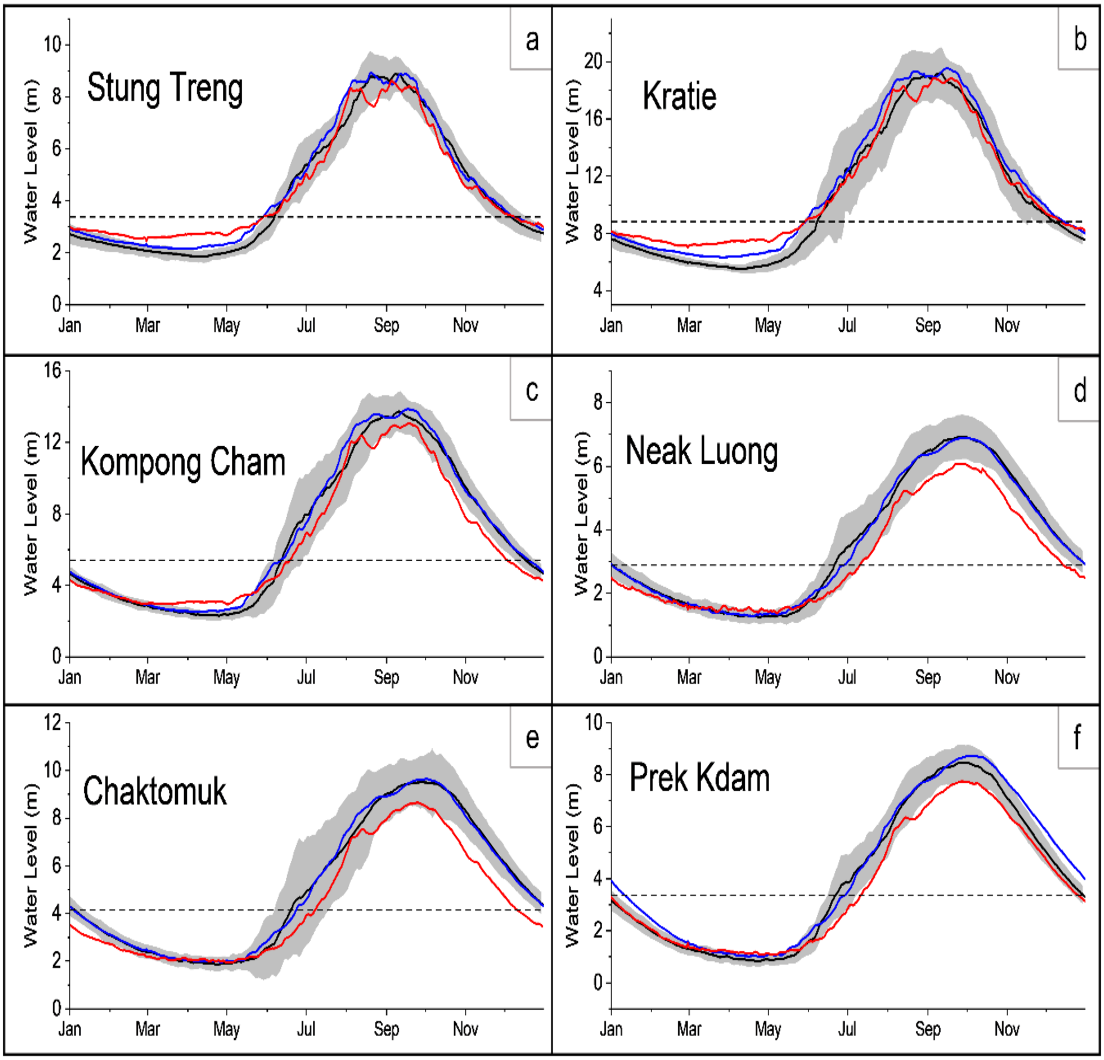

Figure 4. Variation of mean water levels at various stations within the Cambodian floodplains over time. (Dotted horizontal line: flood threshold; black curve: water levels from 1960-1991; blue curve: water levels from 1992-2009; red curve: water levels from 2010-2019. Shaded region represents 1 standard error of mean water levels from 1960-1991)

4.1.2 Changes to annual flood duration

When compared against 1960-1991 records, the flood seasons in 1992-2009 did not show many significant changes. However, the mega-dam era showed greater alterations in flood timing. Downstream from Kratie, flood duration decreased significantly by 26 days at Kompong Cham; 36 days at Neak Luong; and 40 days at Chaktomuk. The drastic shortening of the flood season by up to more than a month was caused by both a delay in floodpulse and an early end to the flooding. The delay in the start of the flooding season was observed to increase with further distance downstream. For instance, while the start date was only later by 9 days at Kompong Cham, it was later by 11 days at Chaktomuk and 15 days at Neak Luong. For the end dates of the flood season, it was earlier by 18 days at Kompong Cham; 25 days at Chaktomuk; and 18 days at Neak Luong. Thus, for areas downstream of Kratie, the floodwaters have indeed arrived later and receded earlier, resulting in a shorter wet season and a longer dry season.

4.1.3 Changes to rise and fall rates

Changes in rise/fall rates reflect influences of upstream water infrastructures. During the rising limb of the wet season, reservoirs would have to release the water stored during the dry season in preparation for the incoming water (Richter et al., 1997; Singer, 2007). Also, the presence of irrigation canals increases the conveyance speed of floodwaters across the floodplains, resulting in an increased rise rate. After the wet season, upstream reservoirs or irrigated fields would retain water (Cochrane et al., 2014). As flows to the main channel is reduced, the fall rate would be correspondingly higher.

At Kompong Cham, Chaktomuk and Neak Luong, both rise and fall rates were observed to increase during the mega-dam era, as compared to the pre-dam era. The largest change in rise rate was observed at Chaktomuk with a 53.8% increase from 0.062m/day to 0.096m/day. In terms of fall rates, the largest percentage change was observed at Kompong Cham: a 23.8% increase from 0.089m/day to 0.111m/day. These observed alterations hint at anthropogenic hydrological regulation in the region.

4.2 Tonle Sap System

4.2.1 Changes to water exchange at Tonle Sap River

At Prek Kdam (Figure 4f), the hydrological changes mirrored that in the Mekong mainstream. Compared against pre-dam records, the mega-dam era saw minimum water levels increased significantly by 0.25m and maximum water level decreased by 0.79m. This resulted in a significant 12.9% reduction in amplitude – from 8.27m to 7.20m. Furthermore, the flood duration was shorter by around 20 days. The average start date in the mega-dam era was 10th July, a significant 15-day delay from 25th June previously during the pre-dam era.

The total annual outflow from the Tonle Sap Lake to the Mekong decreased from 74.54km^3 in 1962-1972 to 62.81km^3 in 2010-2019 (Figure 5a and Table S3 in Supporting Information). Similarly, reverse flow from the Mekong to the Tonle Sap decreased from 49.67km^3 in the pre-dam era to only 31.74km^3 in the mega-dam era – a drastic reduction of 56.5%. In addition, the duration of the reverse phase has decreased by around 13 days, from 125 days in 1962-1972 to 112 days in 2010-2019.

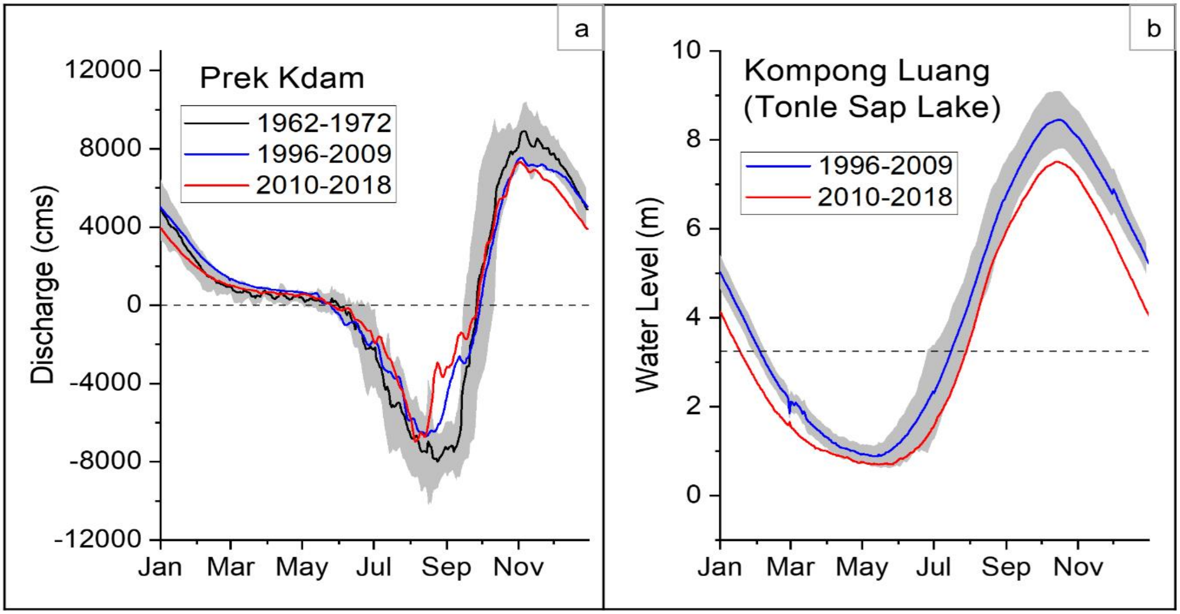

Figure 5a (left). Change in discharge at Prek Kdam over time. Shaded region indicates standard error of mean discharge during 1962-1972. Figure 5b (right). Change in water level at Kompong Luang over time. Shaded region indicates standard error of mean water level during 1996-2009.

4.2.2 Changes to Tonle Sap Lake flooding pattern

At the Kompong Luang station in the Tonle Sap Lake, annual minimum water levels decreased from 0.70m in 1996-2009 to 0.60m in 2010-2019 (Figure 5b and Table S4 in Supporting Information). Similarly, yearly maximum water level dropped significantly from 8.58m (1996-2009) to 7.52m (2010-2019). Using the water level (H) to volume (V) and area (A) relation as derived by Kummu et al. (2014),

$$A = -5.5701H^3 + 137.40H^2 + 470.29H + 1680.2 \text{ (R}^2\text{>0.99)}$$
$$V = 0.7307H^2 - 0.3554H + 0.9127 \text{ (R}^2\text{>0.99)}$$

the 1.05m drop in maximum water level meant that 3990 km^2 of previously seasonally inundated land is now permanently dry. Correspondingly, the reduction in maximum water volume is a drastic 12.1 km^3. This reduction translates to a decrease in 20.6% of maximum area and 23.4% of maximum water volume. During the dry season, the minimum area is now 3.1% smaller (2080 km^2 to 2010 km^2) and contain 5.8% less water (1.02 km^3 to 0.96 km^3).

This observed decrease in both minimum and maximum water levels is consistent with recent scholars who monitored the change in Tonle Sap Lake area using remote sensing methods (Ji et al., 2018; Lin and Qi, 2017; Wang et al., 2020). However, the observed decrease in dry season flow does not follow hydro-modelling results that suggest that water level should be higher during the dry season at the Tonle Sap Lake (Arias et al., 2012, 2014; Kummu and Sarkkula, 2008; Piman et al., 2013b). We postulate that the models adopted might not have considered the development of water infrastructures at the Tonle Sap Lake tributaries. For instance, reservoirs are being developed at Stung Sreng and Stung Pursat —two key tributaries of the Lake

(ADB, 2019a). These irrigation projects could have decreased dry season flow to the lake, resulting in the decrease of dry season water level in Tonle Sap Lake.

Additionally, there was a significant drop in flood duration, from 198 days to 163 days. This reduction was caused by an early end to the flood season. During 1996-2009, the average end date of the flood season was 31st January but during 2010-2019 the season ended roughly on 18th January, earlier by 13 days. The shortened flooding season follows the same trend as in the Mekong mainstream.

4.3 Changes to the floodpulse

Figure 6 shows a schematic of the annual floodpulse on the Cambodian floodplains. During the pre-dam era of 1960-1991, discharge at Stung Treng during the wet season was 25 500cms. Downstream at Kratie, discharge reduced slightly to 24 000cms which could be caused by overland flooding between Stung Treng and Kratie. From Kratie to Kompong Cham, as additional water arrived from the surrounding watersheds, discharge increased to 27 100cms. Thereafter, extensive overland flooding was experienced at the Chaktomuk confluence of Mekong, Bassac and Tonle Sap Rivers. At Prek Kdam, 4270cms of water flowed to the Tonle Sap Lake. At Chaktomuk and Neak Luong, 2800cms and 16 400cms of water continued to flow towards the Vietnamese Delta via the Bassac and Mekong Rivers respectively.

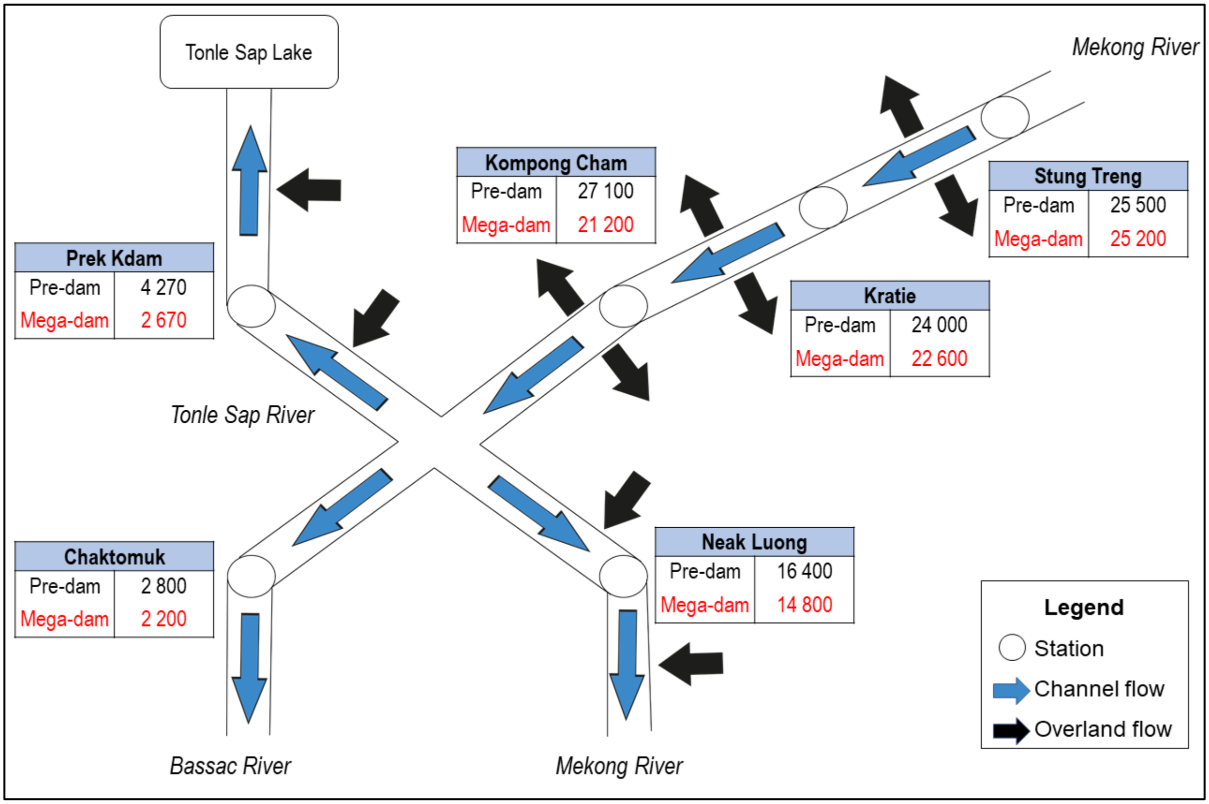

Figure 6. Schematic of wet season discharge on the Cambodian floodplains during the pre-dam and mega-dam era. Across all stations, there is a reduction of discharge during the mega-dam era of 2010-2019.

During the mega-dam era of 2010-2019, there were reductions in wet-season discharge across all stations. At Stung Treng, discharge only decreased by 300cms, a small 1.2% reduction. At Kratie and Kompong Cham, discharge decreased to 22 600cms and 21 200cms, a larger percentage reduction of 5.8% and 21.7% respectively. All subsequent downstream stations also observed lower discharge. Flow towards the Tonle Sap Lake at Prek Kdam dropped from 37.5% to 2 670cms; discharge at Neak Luong and Chaktomuk decreased to 14 800cms and 2 200cms respectively.

As seen in Figure 7, whether Q_{diff} is positive or negative depends on the time of the year. In the dry months from October to April, Q_{diff} is generally positive, implying that there is a net contribution of water from the tributaries. Alternatively, in the wet months from June to September, Q_{diff} is generally negative as water is lost through the increased evapotranspiration from the flooding. This alternating gain-loss pattern is elucidated in Figure 8.

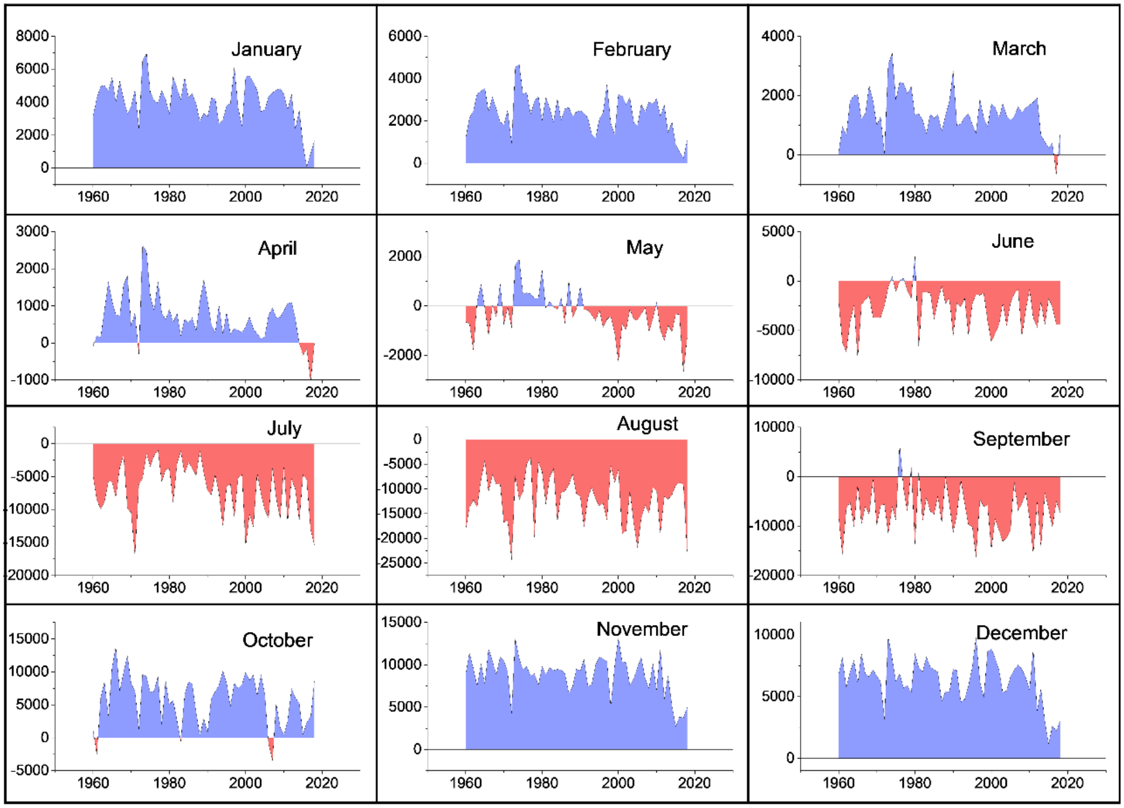

Figure 7. Monthly plots of Q_{diff}/cms from 1960-2019. Blue zones indicate Q_{diff}>0, meaning an addition of water from outside the Cambodian floodplains. Red zones indicate Q_{diff}<0, meaning a loss of water to outside the Cambodian floodplains. Generally, during the wet-season from June to September, Q_{diff}<0.

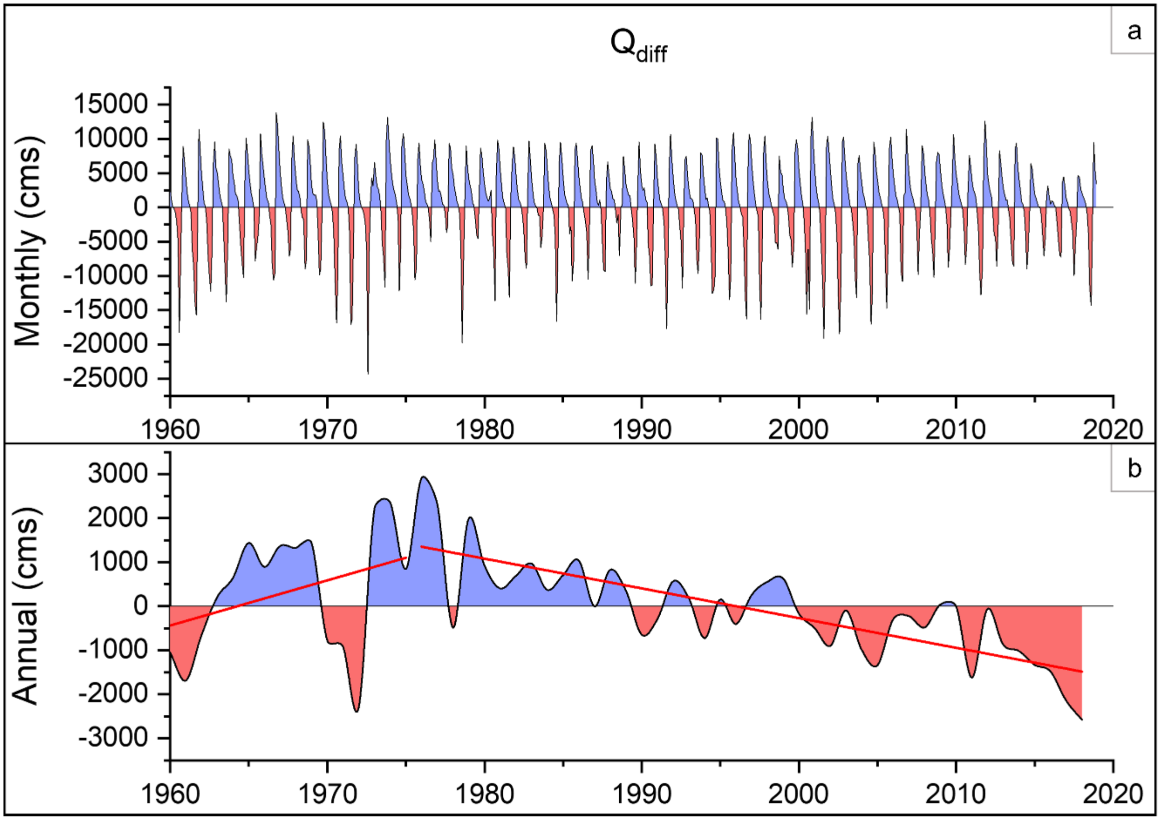

Figure 8a (top). Time-series plot of Q_{diff} from 1960 to 2019 with monthly steps. Figure 8b (bottom). Time-series plot of Q_{diff} from 1960 to 2019 with yearly steps. From 1976-2019, Q_{diff} decreased at a slope of -(68 ± 8) cms/yr ($p<0.01$).

Figure 8b also showed two general trends in Q_{diff} across time. During 1960-1975, Q_{diff} was on an increasing trend. However, from 1976-2019, Q_{diff} decreased significantly at a slope of -(68 ± 8) cms/yr. This implied that the Cambodian floodplains have been losing water at a rate of (2.1 ± 0.3) km^3/yr.

5 Discussion

5.1 Impacts of upstream dams and precipitation

Section 4 has demonstrated that the floodpulse has indeed been decreasing across the Cambodian floodplains. However, whether the reduction is caused by upstream dams, climate or local operations is hotly debated. For instance, the claim that Chinese dams have minimal impact on the inundation area of the Tonle Sap by Wang et al. (2020) was refuted in a response letter by Kallio and Kummu (2021). To investigate these competing drivers, we compared the reduction of wet-season discharge across the various stations.

Since Stung Treng, the uppermost station of the Cambodian floodplains, only registered a reduction of 300cms, then the cumulative contribution of infrastructure and precipitation in the upper reaches of the Mekong only accounted for 300cms of discharge. Propagating this 300cms decrease further, the percentage of discharge reduction caused by upstream developments versus that by local developments can be ascertained. Thus, only 21% of reduction at Kratie and 5% of reduction at Kompong Cham could be attributed to the upper reaches (Table 2). Similarly, even though the downstream stations of Prek Kdam, Neak Luong and Chaktomuk also registered declines in discharge, only about 8% of the flow reduction at these three lower stations could be attributed to developments upstream. Furthermore, there were no significant changes to either maximum flood levels or flood duration at Stung Treng (Table S2 in Supporting Information).

Table 2. Percentage contribution of influences upstream of Stung Treng to the reduction of discharge at the various stations in the Cambodian floodplains.

	Wet-season discharge/cms		Total reduction/ cms	From upper reaches/ cms	% contribution	From Cambodian floodplains/ cms	% contribution
	Pre-dam	Mega-dam					
Stung Treng	25 500	25 200	-300	-300	100%		
Kratie	24 000	22 600	-1 400	-300	21%	-1 100	79%
Kompong Cham	27 100	21 200	-5 900	-300	5%	-5 600	95%
Downstream (Prek Kdam + Neak Luong + Chaktomuk)	23 470	19 670	-3 800	-300	8%	-3 500	92%

The changes in Q_{diff} further supports the argument that local factors are more likely to be the main reason for the reduction of floodpulse. The only natural mechanism able to explain the reduction in Q_{diff} as shown in Section 4.3 is that overbank flooding has become more frequent, leading to increased loss of water through evapotranspiration. However, from the analysis of floodpulse in Section 4.1, we have identified that both flooding extent and duration is on a decreasing trend. Therefore, the only plausible mechanism for the drop in Q_{diff} is local diversion of Mekong flows.

Also, as observed in Figure 9, measured rainfall in the Cambodian floodplains has remained roughly constant from 1960-2019, in line with observations via other sensing methods (Raghavan et al., 2018; Singh and Qin, 2020; Thoeun, 2015). This observation imply that local precipitation is not the driving factor for the reduction in discharge. Thus, the observed reduction of flood discharge in the Cambodian floodplains cannot be attributed solely to either upstream developments or natural climatic variability – local anthropogenic factors are likely the main reason.

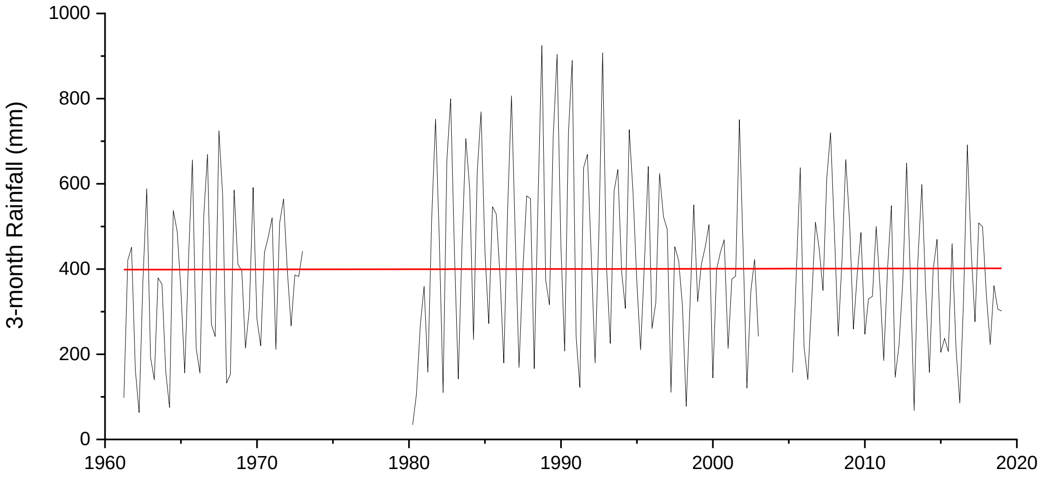

Figure 9. Mean 3-month rainfall at Kompong Cham and Chaktomuk from 1960-2019. There is no statistically significant trend in rainfall within the data period (Mann-Kendall test: p=0.8).

5.2 Impacts of water withdrawal

The scale of irrigation and construction of irrigation reservoirs has been increasing since the Cambodian government announced its "Rice-White Gold" policy with numerous large projects. For instance, reservoirs have been constructed along the tributaries feeding to Tonle Sap Lake. Further downstream, projects such as the Vaico irrigation project has seen canals constructed across the floodplains east of the Mekong. These infrastructures draw water from the Mekong, resulting in the observed decrease in Q_{diff}.

As Figure 7 shows, there has been a sharp and obvious decline in Q_{diff} during November and December from 2010 onwards, coinciding with the start of the Cambodian "Rice-White Gold" policy. This reduction follows the planting calendar of the dry-season cropping from around December to April (Cramb et al., 2020). While the wet-season cropping is primarily rainfed and does not require much diversion of water, dry-season croppings must be extensively irrigated (MRC, 2009). Consequently, farmers will store water during the preceding year's wet season for the upcoming second growing season (Phengphaengsy and Okudaira, 2008).

Although irrigation coverage has increased to approximately 22.6% of paddy land by 2015, the percentage is still much lower than neighbouring Thailand and Vietnam (Kea et al., 2016), meaning that Cambodia can still expand its rice production. As drought occurrences are likely to increase in the future (Oeurng et al., 2019), water availability will be the major challenge for the continued expansion of the Cambodian agriculture sector (Bresney et al., 2020; Sithirith, 2021).

5.3 Impacts of channel incision

There are two main drivers of channel incision: reduced sediment flux and sand-mining. Due to hydropower developments in the Upper Mekong Basin, sediment flux has declined in the past decades (Bussi et al., 2021; Kondolf et al., 2014; Kummu et al., 2010; Lu et al., 2014b; Wang et al., 2011). This sediment reduction results in the formation of 'hungry water' (Kondolf, 1997) that cause greater erosion of the channels, leading to channel deepening (Kondolf et al., 2018; Lu et al., 2007).

Concurrently, sand-mining has increased pace within the last decade, with mining areas expanding the most rapidly within the Chaktomuk confluence area at Phnom Penh (Hackney et al., 2021). Other areas identified as mining hotspots include the stretch from Phnom Penn to the Vietnamese border along both the Mekong and Bassac channels (Bravard et al., 2013).

Figure 10 shows the relationship between water levels during February at Neak Luong and Chaktomuk, versus that at Kratie. In the absence of man-made hydrological alterations, water levels at upstream Kratie will be tightly coupled with those at downstream stations throughout the year. However, water levels at Neak Luong and Chaktomuk have been decreasing with respect to water levels at Kratie. In other words, for the same water level at Kratie, the water level at Neak Luong/Chaktomuk has decreased from the 1960s to 2010s. During February, the changes in mean discharge at Neak Luong and Chaktomuk in the mega-dam era, as compared to that in the pre-dam era, is +8.3% and -23.3% respectively – the lowest percentage change among all months. Thus, changes in water level then would have a greater contribution from channel incision instead of from discharge change.

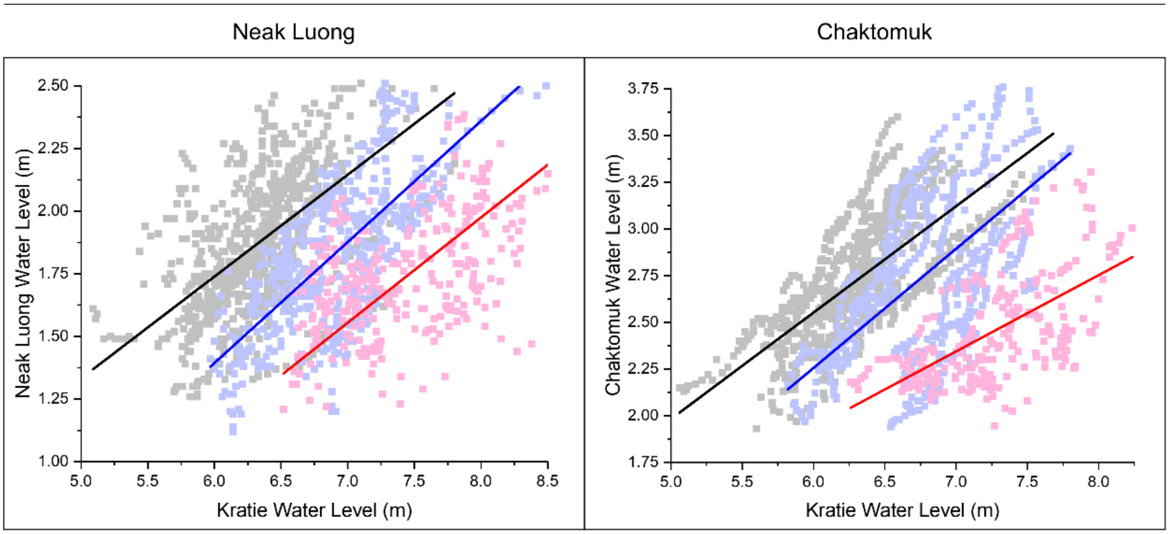

Figure 10. Comparison of water levels at Neak Luong/Chaktomuk against water levels at Kratie during February. (Black: 1960-1991; blue: 1992-2009; red: 2010-2019). Given the same water level at Kratie, water levels at Neak Luong/Chaktomuk have been decreasing over time.

The relationship given in Figure 10 shows that incision at the downstream stations has occurred relatively faster than incision at upstream Kratie. If incision is faster at Kratie, then the y-intercept of the best-fit lines would get progressively larger over time which is not the case. Given a fixed water level of 7.0m at Kratie, water level at Neak Luong has dropped by about 0.60m from the pre-dam to mega-dam era. Similarly, at Chaktomuk, water level dropped by about 0.79m. Actual measurements of water level reduction due to sand-mining are likely to be higher since incision at Kratie has not been factored in here. Thus, even without decreases in discharge, channel incision would have contributed to the reduction of water levels, leading to the observed decrease in flood pulse in the Cambodian floodplains.

5.4 Wider environmental implications

The Tonle Sap Lake has been decreasing in size throughout the years (Section 4.2.2; Kallio and Kummu, 2021; Wang et al., 2020) . A parallel can be drawn with Poyang Lake in Yangtze River. There, the Three Gorges Dam has reduced water level downstream. As water level was reduced, the hydraulic gradient from Poyang Lake to the Yangtze increased, resulting in a reduction of lake volume there (Zhang et al., 2014, 2015).

In the case of the Tonle Sap Lake, there is a reduction of water levels in the Mekong mainstream during the wet season. As expected from hydrological models (Inomata & Fukami, 2008; MRC et al., 2004), the reduced hydraulic gradient from the water levels between the Mekong and the Lake will lead to lesser water entering the Lake from the Mekong. During the pre-dam era, 74.54km^3 of water emptied into the Mekong during the normal flow phase while 49.67km^3 of water entered the Lake during the reverse flow phase annually, meaning that there was a net outflow of 24.87km^3. In the mega-dam era, only 68.81km^3 of water flowed into the Mekong during the normal phase and reverse flow decreased to 31.74km^3; net outflow from the Lake to the Mekong has increased to 31.07km^3. Comparing the difference in discharge towards the Mekong during the pre-dam and mega-dam era, the average annual outflow has increased by 6.20km^3. Without a corresponding increase in inflows from either precipitation or the Lake tributaries, the Lake will decrease in volume over time. Based on reconstructed water levels data by Guan and Zheng (2021), the Lake volume during 1960-1990 was estimated with the volume-stage relation by Kummu et al. (2014). Indeed, compared to the 1960-1990 values, the Tonle Sap Lake volume during 2010-2019 has decreased by 35.9km^3, in line with other studies that observed a shrinking of the Lake (Ji et al., 2018; Lin and Qi, 2017; Wang et al., 2020).

Downstream of the Cambodian floodplains, the VMD will also be affected by the decreased floodpulse. While hydropower dam operations can increase dry season water levels (Dang et al., 2016), the combined effects of local channel incision (Binh et al., 2020b) and irrigation operations will reduce dry season water. Since irrigation infrastructure in the VMD is even more developed than those in Cambodia (Tran and Weger, 2018), the impacts of dry-season extraction is likely to be even greater in the VMD. Therefore, the decreased floodpulse at Chaktomuk and Neak Luong is likely to propagate further downstream to the VMD. Also, a smaller floodpulse will bring fewer sediments to the VMD (Binh et al., 2021). As a result, current problems of land subsidence and seawater intrusion there may become more severe in the future (Binh et al., 2020a; Kantoush et al., 2017; Zoccarato et al., 2018).

The continued expansion of irrigation and sand-mining operations in the Cambodian floodplains may be unsustainable in the long run. The annual floodpulse is key to the regulation of the health of the floodplains, from fisheries to sediment replenishment. For instance, the annual floods increase soil health through buffering acidity and increasing its nutrients content (Dang et al., 2016; Sakamoto et al., 2007). A reduction of the floodpulse amplitude and duration will reduce the annual flood extent, thereby reducing the soil productivity. Concurrently, as the migration cycles of the fishes are intimately tied to the flooding extent, the shift in floodpulse timing will affect the catch rates (Baran and Myschowoda, 2009; Enomoto et al., 2011).

6 Conclusion

This study demonstrates that the floodpulse at the Cambodian floodplains has indeed changed drastically in the past decade. Compared to 1962-1991 levels, minimum water levels in 2010-2019 has increased by 0.10m (Neak Luong) – 1.55m(Kratie). As a result, flood amplitude has decreased by 5.6% (Kompong Cham) to 12.9% (Prek Kdam), meaning that the annual flood extent has reduced. Furthermore, the flood season has decreased by 26 days (Kompong Cham) – 40 days (Chaktomuk), with the flood season starting later and ending much earlier.

Correspondingly, the altered floodpulse along the Mekong mainstream affected the annual reverse flows along the Tonle Sap River. At Prek Kdam, total annual reverse flow dropped from 48.67 km^3 in 1962-1972 to 31.74 km^3 in 2010-2018, representing a dramatic drop of 56.5%. Correspondingly, the Tonle Sap Lake has also been altered by this huge change. There, minimum and maximum water levels have dropped by 0.10m and 1.06m respectively. These reductions correspond to a decrease in Lake area of 3.1% in the dry season and 20.6% during the wet season.

We also showed that it is unlikely that upstream dams are the main contributing factor for the decline in floodpulse. Instead, the hydrological alterations are more likely to be caused by local factors. The boom in irrigation infrastructure in the last decade has resulted in more water being diverted away from the Mekong and Tonle Sap Lake to the fields. We estimate that an average of (2.1 ± 0.3) km^3 of water is lost per year from the Cambodian floodplains from 1976-2019. Additionally, declining sediments combined with sand-mining operations have caused further channel erosion. Together, irrigation and channel incision has contributed to the observed reduction in floodpulse at the Cambodian floodplains.

As the hydraulic gradient governing the reverse flow to the Tonle Sap Lake decreases, the Lake may suffer a permanent reduction in water volume. Furthermore, the impacts of the runoff reduction will be felt further downstream in the VMD. This identified shift in floodpulse is non-trivial, with far-reaching ecological and environmental impacts across international borders. Therefore, policy planners must consider the long-term impact of their plans such that the harvesting of the Mekong can be conducted sustainably.

Data availability

Hydrological data are open source and can be downloaded from the MRC data portal at https://portal.mrcmekong.org/home. Precipitation data used in this study is also obtained from the MRC portal.

Author contribution

Samuel Chua: Conceptualization, Data curation, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Lu Xi Xi**: Conceptualization, Data curation, Methodology, Writing - review & editing, Funding acquisition. **Chantha Oeurng**: Data Curation, Methodology, Writing - review & editing. **Ty Sok**: Data Curation, Methodology, Writing - review & editing. **Carl Grundy-Warr**: Writing - review & editing.

Competing interests

The authors declare that they have no conflict of interest.

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