ANALYSIS OF WATER LEVEL CHANGES IN THE MEKONG FLOODPLAIN IMPACTED BY FLOOD PREVENTION SYSTEMS AND UPSTREAM DAMS

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ABSTRACT

The rapid construction of water infrastructure in the Mekong Basin, including upstream dams and delta-based flood prevention systems, is raising public concerns due to potential impacts on ecosystems and agricultural productivity. Sixty eight multi-purpose dams, accounting for 71 billion m^3 of active volume in total, had been built since the 1960s. It is estimated that an additional sixty seven dams with 68 billion m^3 of active volume will be operational in the next ten years, resulting in highly regulated downstream flows. The Normalized Difference Vegetation Index (NDVI) was analyzed based on the MODIS satellite sensor images (temporal solution of 16-days), which indicates that the flood protected areas had increased nearly 3 times in the past 14 years (from 2000 to 2014) in the upper part of the Vietnam Mekong Delta. Flood prevention systems were built to increase rice production from two to three crops a year and to protect residential areas in the floodplain. This development has caused a significant reduction in water retention capacity of the floodplain and higher water levels in adjacent floodplain areas. Changes in historical water levels along the lower Mekong River ranging from the most upstream (Kratie) to the middle (Kampong Cham, Phnom Penh, Tan Chau, Chau Doc and Can Tho) and the coast station (Vam Kenh) were also analyzed. Historical alterations in water level patterns (maximum, minimum, rise rate, fall rate and fluctuations) over time were then associated with the development of either dams or flood prevention systems. Rise rates at the Kratie station in the upper part of the floodplain gradually decreased by 25% between 1960 and 2013, but remained rather constant at Phnom Penh, the middle of the floodplain. In the lower part of the floodplain, alterations to water levels, rise rates and fall rates have been higher since 2006, and this corresponds to the operation of flood prevention projects in the Vietnam Mekong Delta. The impact of existing upstream dams on the Vietnam Mekong Delta is currently buffered by the Tonle Sap Lake and Cambodian floodplains. Overall, the conclusion is that the development of flood prevention systems is currently a key driver of water level changes in the delta.

Keywords: Mekong Floodplain, Vietnam Mekong Delta, hydropower dam, flood protection and historical data analysis.

1. INTRODUCTION

The transboundary Mekong River originates in the Tibet Plateau and flows 4,180 km through China, Myanmar (Burma), Laos, Cambodia and Vietnam before reaching the East Sea of Vietnam (also known as the South China Sea). The Mekong Floodplain consists of three regions with a close hydrologic relationship: the Tonle Sap Floodplain, the Cambodian Lowland and the Vietnam Mekong Delta (Figure 1a). Approximately 10% of the Cambodian population lives around the Tonle Sap Lake and depend on agriculture and fishing activities, which contribute to 72% of the protein requirements of this nation (Keskinen, 2006; Hortle, 2007; Nourteva et al., 2010; Keskinen et al., 2011). The Tonle Sap Lake plays an important role in hydrologic regulation of flows from the Mekong River by seasonally storing and releasing water (Arias et al., 2014). The Cambodian Lowland's population is around 5 million and this is the most agriculturally productive land in Cambodia (Fujii et al., 2007). The Vietnam Mekong Delta has around 17 million people and most of them work in agriculture-related fields (Tuan et al., 2007). The region provides up to 52% of rice and 70% of fruit production in Vietnam and is therefore called the "rice bowl" of the basin (Dung, 2010). Additionally, the Mekong floodplain is home to many species of birds, fish and mammals (Campbell et al., 2006; Davidson, 2006; Arias et al., 2014).

Recently, as a result of high demands for electricity by a booming population and for water for farming activities, multiple dams are being constructed rapidly in the Mekong Basin. These projects have received great public concern because they alter the hydrologic regime of the Mekong River. Since the 1960s, 68 dams (71 million m^3 active volume) have been constructed (Figure 1a) and it is projected that there will be a total of 135 dams in operation in the next ten years (MRC, 2010; ICEM 2010) with a total active volume of 139 million m^3. Thus, it is important to determine the impact of existing dams on the Mekong River's hydrologic regime. Previous studies have shown that alterations in water levels at upstream stations in the Mekong from Chiang Sean to Stung Treng have already occurred since 1991 because of the operation of upstream hydropower dams (Cochrane et al., 2014). However, the influence of hydropower dams on the floodplain, especially the Vietnam Mekong Delta, requires further investigation.

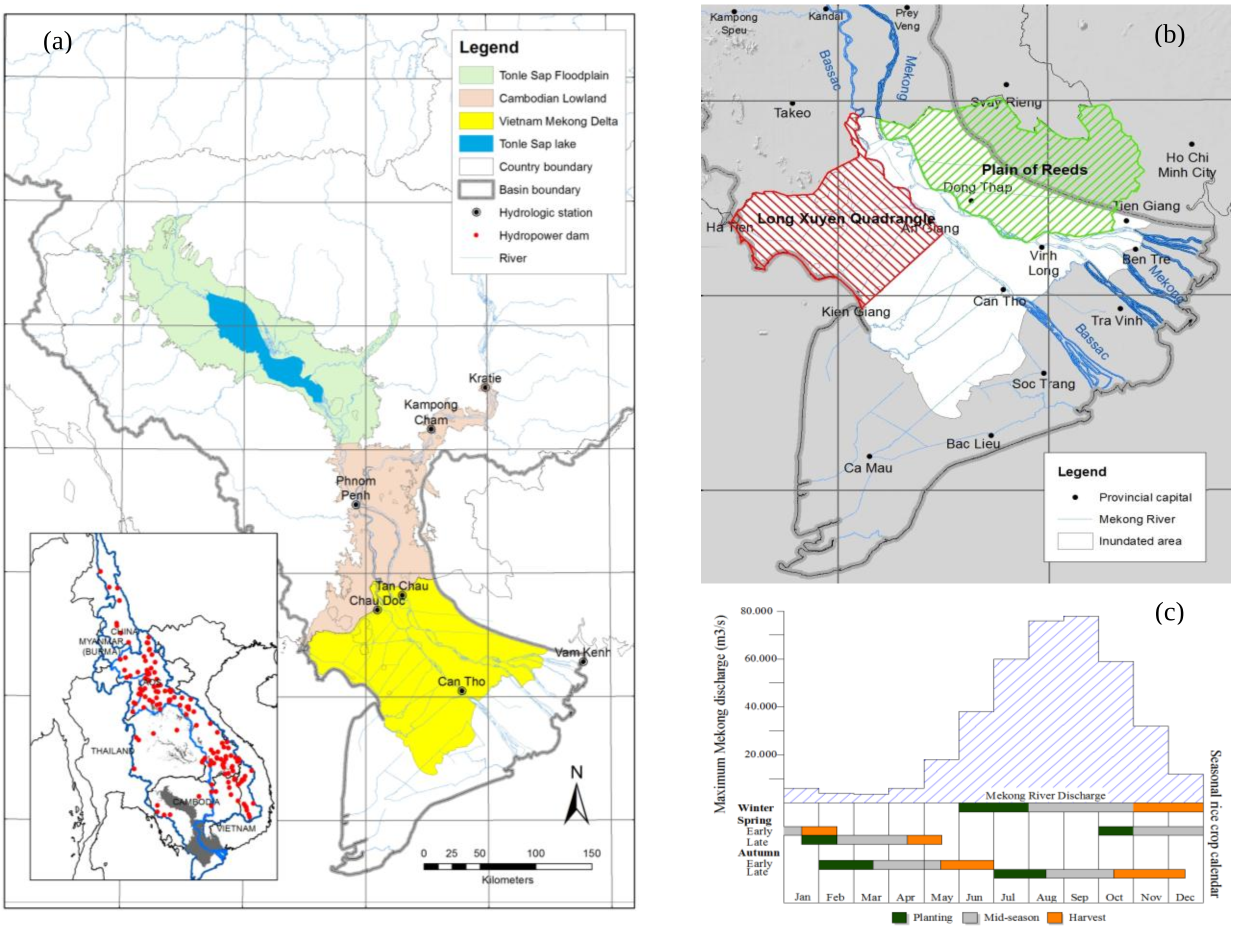


Figure 1. (a) - Hydropower dam development in the Mekong River Basin, location of the Mekong Floodplain in the region and gauging stations; (b) - Floodplain regions in the Vietnam Mekong Delta and province centers; and (c) - Rice cultivation in the Vietnam Mekong Delta (Data source: MRC, 2013)

In the lower part of the floodplain, the high flooded zone in the Vietnam Mekong Delta includes: the Long Xuyen Quadrangle, the Plain of Reeds and the region between the Mekong and Bassac Rivers (Manh et al., 2013; Figure 1b). These three regions are high productive rice cultivation regions, but they often suffer from excessive floods during the wet season. Since the 1990s, the Vietnam Government reformed the national economy to a “socialist-oriented market economy”, the so-called “Doi moi” (Renovation); consequently, water infrastructure (especially flood prevention systems) has been developed widely to protect these rice cultivation areas and residential areas. The Vietnam Mekong Delta currently has a dense artificial canal network and large numbers of multi-purpose structures (Hoa et al., 2007; Hung et al., 2011). Manh et al. (2013) stated that many regions had high dykes (full-dyke) protecting a first rice crop (Winter Spring), a second rice crop (Summer Autumn) and a third rice crop (Autumn Winter) allowing for three crops of rice a year (triple rice crop, Figure 1c). There are also semi-dyke (lower dyke) systems for the first two crops, which are referred to as double rice crops. Low dykes allow overtopping flows to occur which leads to the reduction of water levels in rivers in the wet season (Figure 2). High dykes work even during high floods to protect the intensive rice farming system, but can cause hydrologic problems as they reduce water retention capacity in various parts of the floodplain. Consequently, flood protection systems can cause the re-distribution of flooding areas in the floodplain.

Besides altering flooding extents, the development of high dykes and operation of sluice gates may also lead to significant changes in water level extremes and rates of changes in water levels (rise rate, fall rate and number of water level fluctuations) in the floodplain. Rise and fall rates refer to the means of all positive and negative differences of consecutive water level values over time (The Natural Conservancy, 2009). Number of fluctuations refers to the frequency of water level condition changes. Differences in maximum and minimum water levels show variation in flow magnitudes; rise rate, fall rate and number of fluctuations show the alteration of water levels over time.

In general, alterations to natural hydrologic regimes can influence the stability of aquatic biota and riverine ecology (Bunn and Arthington, 2002). Changes in rise rate, fall rate and number of water fluctuations may lead to several subsequences, for example: altering drought stress on riverine vegetation, changing the nutrient entrapment capacity of waterways and influencing the interaction between water and local geology causing geomorphologic changes (Poff et al., 1997; Bunn and Arthington, 2002). The changes of natural environment patterns lead to the proliferation of specific taxa, favor some exotic creatures and reduce susceptible habitats (Bunn and Arthington, 2002); and consequently, the current food web could be altered.

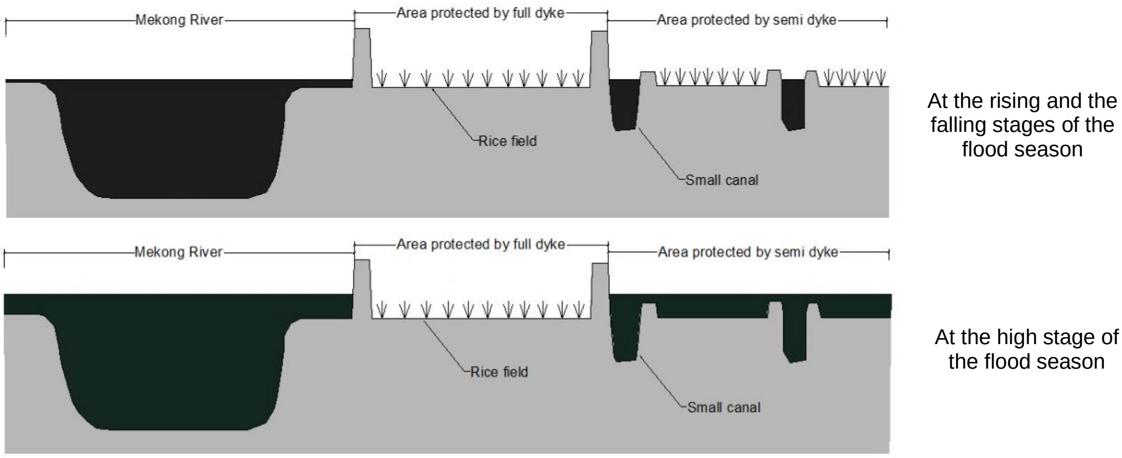


Figure 2. Operation of full and semi dykes in the Vietnam Mekong Delta (described in details in Hung et al., 2011)

The main aim of this paper is to quantify contemporary alteration of water levels in the floodplain and to determine how changes to hydrologic regimes are related to water infrastructure development (dams and flood prevention systems). It was hypothesized that in the current situation, the impact of hydropower dams on the floodplain was limited while the development of delta-based flood prevention systems was the main reason for the alteration of water levels. An up-to-date database of dam development in the Mekong Basin was used to determine the time when dams went into operation. Flood prevention systems in the delta were detected by aerial images which showed the changes in farming system (triple rice crop) related to flood protection.

2. MATERIALS AND METHODOLOGY

Historical data: Data for daily observed water levels from 1960 to 2013 were obtained for the Kratie, Kampong Cham, Phnom Penh, Tan Chau, Chau Doc and Can Tho gauging stations (Figure 1a) from the Mekong River Commission (MRC). Hourly gauged data for the Tan Chau, Chau Doc, Can Tho and Vam Kenh monitoring stations from 2000 to 2011 were obtained from the South Region Hydrology-Meteorology Centre of Vietnam. These datasets have been previously used and verified in multiple papers about the Mekong (e.g, Kummu et al. (2010), Xue et al. (2011), Arias et al. (2012), Piman et al. (2013), Dung et al. (2013) and Manh et al. (2014)). Among these stations, Kratie is considered as the entry point of the research area; Kampong Cham can represent the Cambodia Lowland; Phnom Penh (located at the conjunction between the Mekong, Tonle Sap and Bassac Rivers) can show the regulation ability of the Tonle Sap Lake; Tan Chau and Chau Doc stations record hydrologic regime alterations in the upper part of the Vietnam Mekong Delta; Can Tho is in the center of the delta; and finally, Vam Kenh is located at a river mouth of the Mekong.

Hydropower data: Dam reservoir volumes and first operation dates were collected from the MRC hydropower database (2013) which was initially launched in 2009 and was later updated in 2013. This database has also been used in other related studies (e.g, Kummu et al. (2010), Piman et al. (2013) and Cochrane et al. (2014)).

Satellite images: The MODIS NDVI 16-day composite data (MOD13Q1) in the Sinusoidal Projection was downloaded from the NASA Earth Observing System Data Gateway and used for this study. This product was already corrected for atmospheric distortions as described in Solano et al. (2012). The Normalized Difference Vegetation Index (NDVI), which is calculated from visible (red 620 ÷ 670 nm) and near-infrared (841 ÷ 876 nm) reflectance, is a widely recognized index to detect vegetation patterns and was used in this study. NDVI was also used to detect the changes in flooding extents over time as in Sakamoto et al. (2007). If there is a change of NDVI values of an area in the flood season over years, the area has have a shift from double crop to triple crop (Dung et al., 2011); and a flood prevention system might go into operation in order to protect the area. As a result, the first operations of flood prevention systems could be tracked by remote sensing images.

Recorded water levels were analyzed with the Indicators of Hydrologic Alteration (IHA), developed by the Nature Conservancy (2009), which uses daily water levels or water discharges as input. This software has the ability to compare the changes in trends in 32 different parameters in the pre- and post-construction times of hydropower dams or other water infrastructure. Among these parameters, rise rate and fall rate are the most sensitive indexes to hydrological alterations in the Lower Mekong (Cochrane et al., 2014). In this study, the year 1991 was used to separate the low development stage of hydropower dams from the high development stage as stated in Cochrane et al. (2014). For flood prevention systems, different years were tested to distinguish the two development stages. In order to check the significance of changes, the non-parametric Kruskal-Wallis test, which is commonly used to compare two or more independent samples with different sizes, was applied.

3. RESULTS

3.1. Historical data analysis

Pre- and post- 1991 data analysis of water levels for the upstream stations at Kratie (Table 1), Kampong Cham and Phnom Penh Port showed that there was a non-significant increase ($p>0.1$) in monthly mean water levels from 1960 to

2013. At these three stations, 30-day maximum water levels in the pre- and post- phases changed only about 1 ÷ 2% while 30-day minimum water levels increased 10%, 16% and 7%, respectively.

Table 1. Indicators of hydrological alterations and alteration factors at Kratie

Indicators of hydrological alterations	Pre-impact period: 1960 ÷ 1990				Post-impact period: 1991 ÷ 2013		
	Means	Coeff. of var.	RVA Boundaries[a] Low	RVA Boundaries[a] High	Means	Coeff of var.	Hydrologic alteration factor[b]
Mean monthly values (m)							
January	7.000	0.069	6.780	11.520	7.360	0.108	-0.530
February	6.330	0.076	6.100	11.520	6.828	0.081	-0.883
March	5.800	0.076	5.660	11.520	6.500	0.112	-0.883
April	5.560	0.067	5.490	11.520	6.778	0.138	-0.883
May	6.260	0.121	6.120	11.520	7.300	0.218	-0.296
June	9.915	0.284	7.970	14.010	9.905	0.367	-0.178
July	13.980	0.290	9.200	20.700	13.850	0.296	0.174
August	18.320	0.150	11.520	21.260	18.870	0.130	0.292
September	18.790	0.071	11.520	22.240	18.880	0.159	-0.883
October	14.900	0.150	12.310	20.040	15.790	0.184	-0.648
November	10.430	0.197	9.380	13.890	11.090	0.264	-0.296
December	8.250	0.079	7.890	11.520	8.630	0.142	-0.061
Extreme water conditions (m)							
1-day minimum	5.370	0.095	5.280	11.520	6.170	0.125	-0.648
3-day minimum	5.373	0.087	5.300	11.520	6.195	0.128	-0.648
7-day minimum	5.399	0.073	5.350	11.520	6.222	0.132	-0.648
30-day minimum	5.518	0.069	5.499	11.520	6.408	0.133	-0.648
90-day minimum	5.795	0.069	5.736	11.520	6.693	0.117	-0.765
1-day maximum	21.090	0.069	18.600	23.020	21.430	0.094	-0.413
3-day maximum	21.060	0.069	18.200	22.990	21.320	0.092	-0.061
7-day maximum	20.760	0.069	17.860	22.870	21.090	0.095	-0.296
30-day maximum	19.340	0.071	16.090	21.930	19.570	0.107	-0.296
90-day maximum	16.990	0.119	13.710	20.270	17.520	0.135	0.057
Timing of extreme water conditions							
Date of minimum	108	0.055	73	121	97.5	0.074	-0.178
Date of maximum	250	0.071	217	283	260	0.110	-0.785
Pulses Frequency/duration (days)							
Low pulse count	1	1.000	0	3	1	2.000	-0.354
Low pulse duration	62	1.081	3	102	19	1.421	-1.000
High pulse count	2	1.000	0	3	2	0.500	-0.225
High pulse duration	46	0.859	3	125	53.5	1.458	-0.412

[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

Alterations in rise rates, fall rates and number of water fluctuations were also low at these three stations (Table 2). When comparing averaged rise rate between the pre-1991 and post-1991 periods, this factor decreased by 25% in Kratie, decreased by 10% in Kampong Cham and remained the same in the Phnom Penh Port. Fall rates in Kratie and Phnom Penh Port, meanwhile, did not change from one period to the other, except for Kampong Cham where the fall rate decreased by 14%. Finally, the number of water level fluctuations decreased in both Kampong Cham (-11%) and Phnom Penh Port (-20%) stations in spite of a slight increase in Kratie (+6%).

Analysis of the Chau Doc and Tan Chau stations in the Vietnam Mekong Delta indicated that there was a strong modification in the delta's hydrologic regime in the last decade, especially since 2006 (Table 3). The rise and fall rates doubled compared to the previous period (Figure 3 and 4). While in the pre-2006 stage rise rate fluctuated between 0.03 and 0.04 m/day in Chau Doc, it increased to 0.06 m/day in 2007 and remained high (0.05 ÷ 0.07 m/day) in the later years. The fall rate in Chau Doc also changed from -0.04 m/day in 2006 to -0.06 m/day in 2007 and maintained a decreasing tendency from 2006. In Tan Chau, the mean of rise rates and fall rates in the post-2006 stage almost doubled compared to those in the pre-2006 stage. According to the Kruskal-Wallis tests, all alterations in rise and fall rates in these two stations were significant ($p<0.001$).

Table 2. Hydrological alteration of selected indicators for pre- and post- 1991 periods in the upper part of the floodplain. No significant changes between the two periods according to the Kruskal-Wallis test (p>0.1)

Monitoring station	Indicators of hydrological alteration	Pre-impact (1960 ÷ 1990)		Post-impact (1991 ÷ 2013)	
		mean	coeff. of var.	mean (% diff.)	coeff. of var. (% diff.)
Kratie	Rise rate (m/day)	0.150	0.333	0.113 (-25)	0.394 (+7)
	Fall rate (m/day)	-0.070	-0.286	-0.070 (+0)	-0.286 (-6)
	Number of fluctuations	58.0	0.259	61.5 (+6)	0.213 (+17)
	30-day maximum (m)	19.340	0.071	19.570 (+1)	0.107 (+50)
	30-day minimum (m)	5.518	0.069	6.408 (+10)	0.133 (+93)
Kampong Cham	Rise rate (m/day)	0.100	0.200	0.090 (-10)	0.264 (+32)
	Fall rate (m/day)	-0.070	-0.286	-0.167 (-14)	-0.167 (-41)
	Number of fluctuations	60.0	0.183	53.0 (-11)	0.335 (+83)
	30-day maximum (m)	13.740	0.081	14.010 (+2)	0.119 (+47)
	30-day minimum (m)	2.242	0.130	2.614 (+16)	0.167 (+28)
Phnom Penh Port	Rise rate (m/day)	0.060	0.083	0.060 (+0)	0.250 (+200)
	Fall rate (m/day)	-0.050	0.000	-0.050 (+0)	0.000 (0)
	Number of fluctuations	49.0	0.184	39.0 (-20)	0.436 (+137)
	30-day maximum (m)	8.539	0.074	8.705 (+2)	0.086 (+17)
	30-day minimum (m)	0.812	0.172	0.879 (+7)	0.321 (+87)

Table 3. Hydrological alteration of selected indicators for pre- and post- 2006 periods in the lower part of the floodplain

Monitoring station	Indicators of hydrological alteration	Pre-impact (1985 ÷ 2006)		Post-impact (2007 ÷ 2013)		Kruskal-Wallis test [a]
		mean	coeff. of var.	mean (% diff.)	coeff. of var. (% diff.)	
Tan Chau	Rise rate (m/day)	0.040	0.250	0.060 (+50)	0.250 (0)	***
	Fall rate (m/day)	-0.030	-0.333	-0.060 (+100)	-0.333 (0)	***
Chau Doc	Rise rate (m/day)	0.030	0.000	0.060 (+100)	0.000 (0)	***
	Fall rate (m/day)	-0.036	-0.275	-0.060 (+65)	-0.333 (+21)	***

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

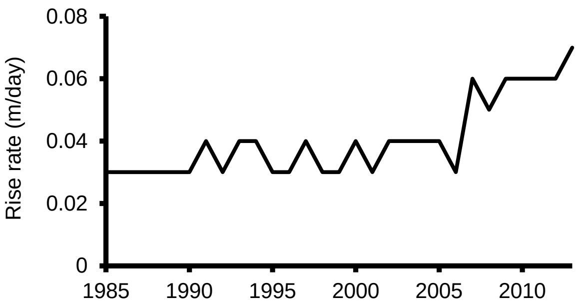


Figure 3. Rise rate at Chau Doc between 1985 ÷ 2013

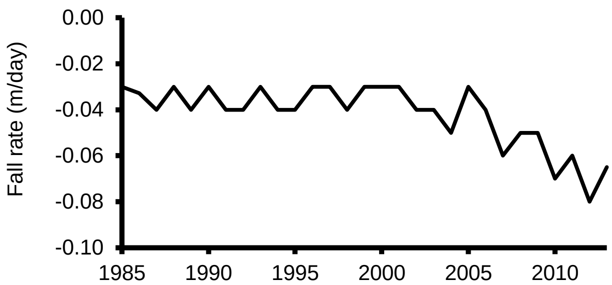


Figure 4. Fall rate at Chau Doc between 1985 ÷ 2013

In the center of the delta at Can Tho, averaged, maximum and minimum water levels have risen over the last 30 years (Figures 5, 6 and 7). This is especially true in the last decade, when water levels in Can Tho have continued to increase in spite of the opposite trends in upstream flows, but with the same trend as sea level rise. To further investigate this issue, we chose three years (2000, 2007 and 2011) when upstream floods were high while flooding patterns and sea levels were similar. Figure 8 shows that the flood in 2000 was higher than those in 2007 and 2011; in 2000 the maximum water level in Chau Doc (upstream) (H_{max}=+4.89 m) was higher than those in 2007 and 2011 (H_{max}=+3.54 m and +4.24 m). Meanwhile, the corresponding water levels in Vam Kenh (coastal station) were nearly the same (H=+1.57 m, +1.56 m and +1.62 m). However, the maximum water level in Can Tho (middle) in 2000 was lower than those in 2007 and 2011 (H_{max}=+1.79 m, +2.03 m and +2.15 m) (Figure 9). This indicates that water processes and/or management within the delta have become an increasingly important factor in controlling the Mekong's net discharge and water levels.

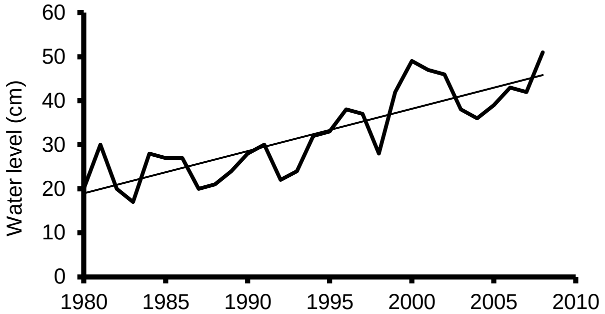


Figure 5. Annually averaged water levels at Can Tho

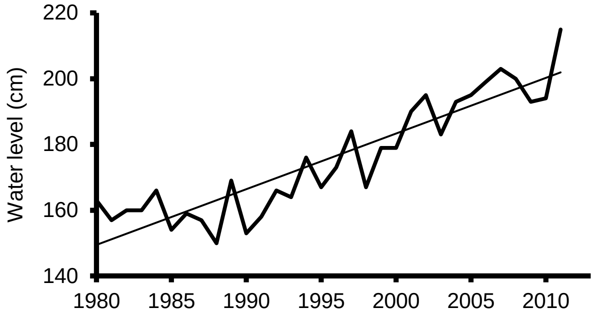


Figure 6. Maximum water levels at Can Tho

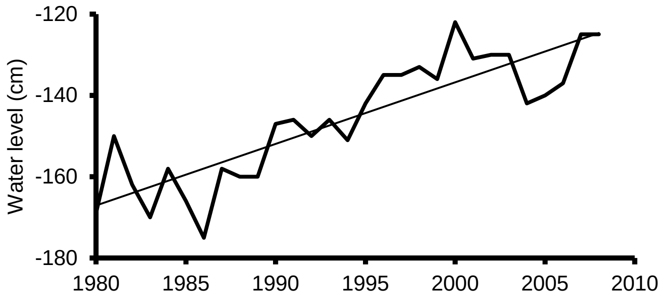


Figure 7. Minimum water levels at Can Tho

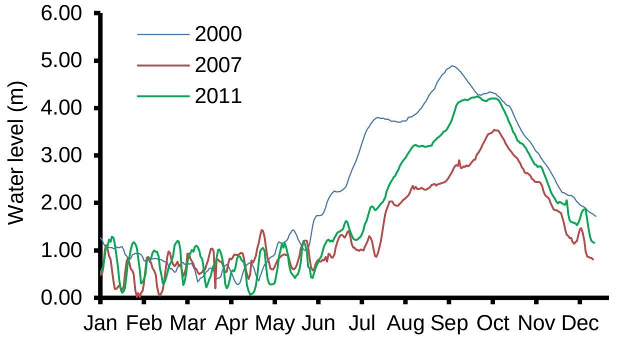


Figure 8. Daily water levels in Chau Doc in 2000, 2007 and 2011

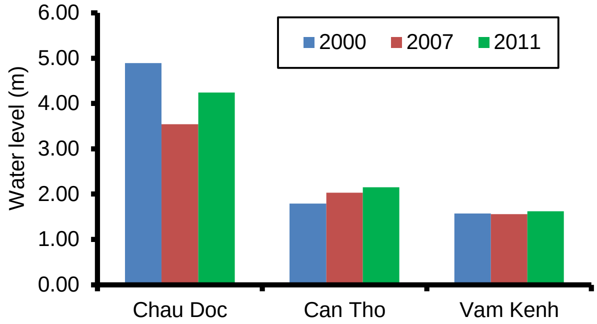
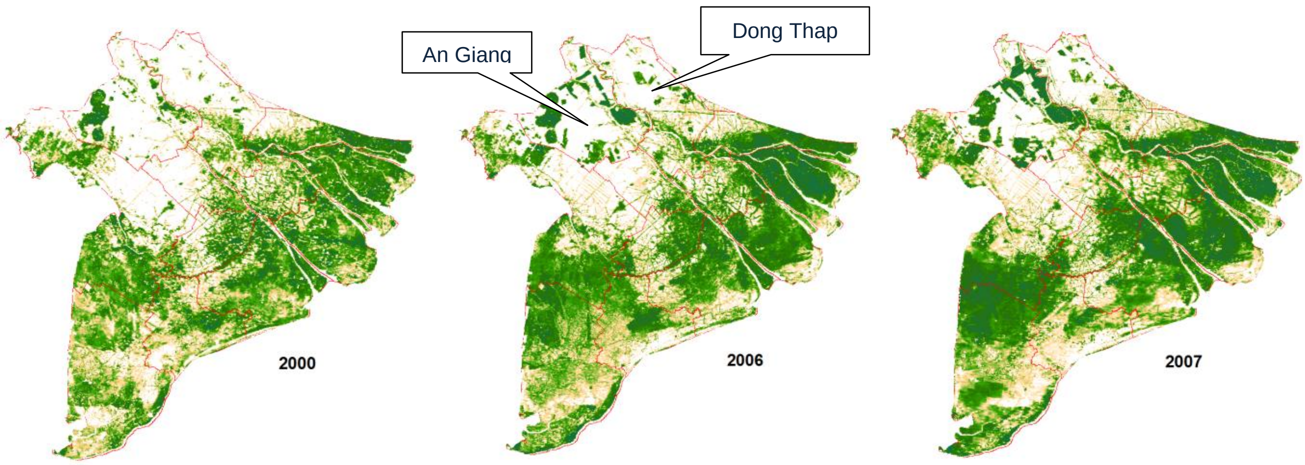


Figure 9. Maximum water levels at Chau Doc, Can Tho and Vam Kenh in 2000, 2007 and 2011.

3.2. Remote sensing data analysis

We analyzed NDVI estimated from satellite images for the Vietnam Mekong Delta for the last decade when significant water alterations occurred. NDVI images of the delta for sample years (2000, 2006, 2007, 2008, 2010 and 2013) are shown in Figure 10. Green areas represent emergent vegetation while white areas present regions underwater. The series of images show that the inundation extents have been reduced significantly although recorded water levels in those years were comparably similar. For example: at the peak in the wet season of the year 2000, around 71% of An Giang, an upstream province in the Vietnam Mekong Delta, was flooded while the inundated area of this province in 2011 was 30%. Few years such as 2010 and 2012, the flooded areas only accounted for 15% and 17% of the province area respectively (Table 4). At the same time, the annual rice area increased dramatically from 464.4 ha in 2000 to 641.3 ha in 2013, especially between 2006 and 2008 around 61 thousand ha of rice was cultivated in addition.



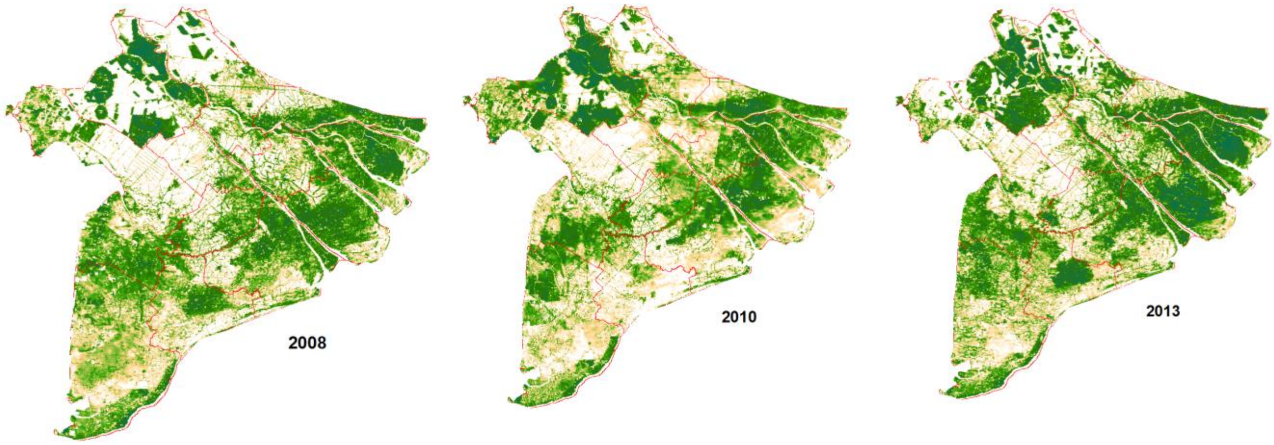


Figure 10. NDVI images of the Vietnam Mekong Delta at the peak of the wet season for several years derived from Terra MODIS images (Green = emergent vegetation, White = underwater)

Table 4. Inundated areas, maximum water levels and annual rice areas in An Giang province, Vietnam Mekong Delta

Year	Total area = 3,406km^2		WL Tan Chau (m)	WL Chau Doc (m)	Annual rice area (thousand ha)[a]
	Inundated (km^2)	% inundated			
2000	2,419	71%	5.06	4.89	464.4
2006	2,073	61%	4.17	3.69	503.5
2007	1,646	48%	4.08	3.54	520.3
2008	1,365	40%	3.73	3.12	564.5
2009	1,416	42%	4.08	3.52	557.3
2010	515	15%	2.96	2.60	586.6
2011	1,060	30%	4.77	4.24	607.6
2012	573	17%	3.18	2.83	625.1
2013	695	20%	4.31	3.70	641.3

[a] Obtained from Vietnam General Statistics Office Website at www.gso.gov.vn

4. DISCUSSION

Most alterations of contemporary water levels indicate human activity interventions or a change in climatic condition; understanding alterations in water levels is important to ecological, agricultural and social studies. Although the hydrologic regimes of the Cambodian lowlands and the Vietnam Mekong Delta are intrinsically related, the two regions are in different stages of water infrastructure for flood prevention and irrigation development. Thus, alterations in their hydrology were analyzed separately.

Alterations in the Cambodian lowland hydrology have been seldom documented in the literature, even under the current level of upstream hydropower development. In general, in order to increase the amount of electricity generation, hydropower reservoirs tend to store water during the wet season for later use in the dry season; consequently, dry season water levels increase and wet season water levels decreases downstream. When comparing between the amounts of water held by dam reservoirs and the annual discharge of the Mekong River, dams can only cause a small change in water levels in the flood season. The total active storage capacity of hydropower dams in the basin was around 7,854 Mm^3 at the end of 1991 while the mean volume in the floodplain is about 473,040 Mm^3 (Walling, 2008; MRC, 2010). Thus, historical data analysis for Kratie, Stung Cheng and Phnom Penh Port showed a potential average increase of 2% and 5% in the wet and dry season respectively, which are small numbers compared to seasonal water level fluctuations in the region. Nevertheless, if all the dams go into operation in 2020, the total water storage capacity of reservoirs will increase up to around 139,000 Mm^3 which can change significantly the hydrologic regime of the whole Mekong Basin and floodplain.

Secondly, the operation of dam reservoirs may reduce rise rates downstream in the flood season (Cochrane et al., 2014) and the floodplain may also influence this reduction as well because of the flat topography. Additionally, since the Tonle Sap floodplain can store more than around 76 km^3 of water, it can buffer the impact of dam reservoirs. As a result, rise rates decrease through the floodplain from Kratie to Phnom Penh. Fall rates, meanwhile, remain the same in the floodplain, excepting the small decrease at Kampong Cham. The reason may relate to the topography of the Cambodian Lowland. In the Cambodian Lowland, the floodplain becomes wider at Kampong Cham and then narrower at Phnom Penh (Figure 1a). Hence, if rise rate increases upstream, more water is retained in this area and fall rates eventually decrease.

As there are minor alterations of rise rate, fall rate and seasonal water levels at Kampong Cham and a few changes in these hydrologic characteristics at Phnom Penh, it is likely that the current impact of hydropower dams is limited to the upstream region of these two stations in Cambodia.

Despite minor changes upstream of Phnom Penh, rise and fall rates increased two-fold in the years 2006 - 2007 in the Vietnam Mekong Delta. Thus, these alterations are likely a result of changes inside the delta rather than upstream. MODIS-derived NDVI images showed that large inundated regions were reduced in the year 2007 compared to 2006. In the Cambodia Lowland and the Tonle Sap Floodplain, emergent vegetation, including seasonally flooded forests, often covers inundated areas so it is difficult to detect flooding boundaries by satellite images alone without the use of radar data (Trung et al., 2013). Nevertheless, in the case of the Vietnam Delta, a large percentage of lands are used for rice cultivation which cannot survive under submerged conditions for more than a few days. Thus, the relationship between water levels in rivers and flooding areas in the Vietnam Mekong Delta is a good proxy for large scale human intervention in the region.

High dyke systems have been built in the upstream provinces of the Vietnam Mekong Delta (Figure 11 and 12). During the flood season, water is impounded between the dyke systems and water levels increase and decrease more rapidly than as normal due to sluice gate operations, causing increased rise rates and fall rates.

It is important to note that the three floodplain sub-regions in the Vietnam Delta are in different stages of water infrastructure development. Firstly, in the Long Xuyen Quadrangle, hydrologic alterations are reflected by both Tan Chau and Chau Doc stations in An Giang Province of Vietnam. Remote sensing and recorded data analysis showed that there was no relationship between inundated areas of An Giang Province and water levels at Tan Chau and Chau Doc stations over time. Inundated areas in this particular province decreased corresponding to the increase of rice cultivation (Table 4). Thus, it is strongly believed that flood prevention systems in this part of the delta, which are built to enable a triple rice crop, are changing hydrologic regimes of the region. Secondly, the region between the Mekong and Bassac River has recently introduced water infrastructure development. Among the flood protected regions in 2007, the North Vam Nao project in this region was developed next to the locations of the Tan Chau and Chau Doc stations. It has been documented that about 52% of the region was protected in the year 2007 corresponding to 12,000 ha. This project may also influence on water level patterns of the region in addition to the water infrastructure development in the Long Xuyen Quadrangle. Besides the two above regions, dyke systems have been developed in the Plain of Reeds to protect rice cultivation as well; but many of the rice fields are flooded during the high flood stage of the flood season (Hung et al., 2011; Manh et al., 2014). As a result, many parts of the Plain of Reeds are still naturally inundated, and there no observed significant changes in this region. However, Figure 10 shows that few small protected areas now begin appearing in this region as well in 2013.

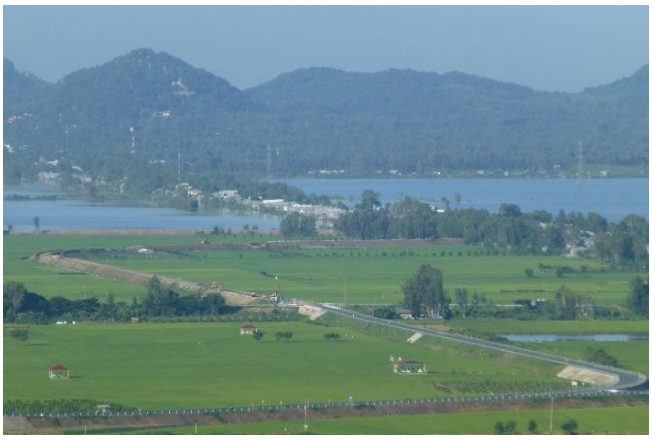


Figure 11. Out-dyke and in-dyke regions in Vietnam Mekong Delta

Figure 12. Dyke in combination with inter-province road in Vietnam Mekong Delta

Finally, as upstream provinces of the delta develop full dyke systems to protect rice cultivation, water tends to move downward to the center of the delta towards Can Tho and other central provinces making water levels in this region increase over the years. As a result, this requires provinces in the delta center to build up their flood prevention systems, which would propagate flooding to other neighboring areas. This will then trigger other provinces develop their own flood prevention systems.

5. CONCLUSIONS

The Mekong floodplain's natural hydrological patterns are being threatened by current and future hydropower dam and delta-based water infrastructure development. The impact of each driver is temporally complex and spatially varied.

The Tonle Sap floodplain and the Cambodia Lowland have a great water storage capacity which currently acts to dampen the impact of hydropower dams on the Vietnam Delta. Although hydropower operation has been observed to impact water levels along the Mekong River, its impact on the Mekong Floodplain is limited as demonstrated by the analysis of the historical data from Kratie, Kampong Cham and Phnom Penh. However, data acquired from the MRC hydropower dam database show that the amount and active volume of reservoirs will increase dramatically in the near future. Modeling is necessary to assess the future impact of hydropower dam development on the floodplain.

In the upstream part of the Vietnam Delta, flood prevention development is likely the main driver of observed hydrologic alterations. In order to shift from double crops to triple rice crops, more flood prevention systems are being built. The construction of flood prevention system has limited the areas that become fully inundated and has changed the hydrology of the delta far more than upstream dams.

In the lower part of the Vietnam Delta, the downward shift of flooded areas due to upper flood prevention systems is the main reason of increased flooding. Sea level rise and land subsidence due to ground water extraction will also likely poses more pressure on the development of provinces in this region in the future. An integrated master plan is necessary to ensure a sustainable development of the delta in the future.

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