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Future hydrological alterations in the Mekong Delta under the impact of water resources development, land subsidence and sea level rise

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ABSTRACT

Study region: The Mekong floodplains and delta are among the most agriculturally productive and biologically diverse waterscapes of the world, but sea level rise, land subsidence, and the proposed upstream development of over 126 hydropower dams and extensive delta-based water infrastructure have raised concern due to potential impacts on the hydrology of the region.
Study focus: This study aims to quantify the effects of water infrastructure development, land subsidence and sea level rise on hydrological regimes of the Mekong floodplains and delta through the development and application of a hydrodynamic model.
New hydrological insights for the region: Depending on hydrological characteristics of each region (river-dominated, transitional or tidal), the influence of each potential driver may vary. The operation of proposed hydropower dams would change river-dominated upper floodplain's water levels by 26 to 70% and −0.8 to −5.9% in the dry and wet season respectively, but the impact diminishes throughout the floodplains. In the wet season, the upper Vietnamese Delta changes from a transitional stage to a river-dominated stage, and localized water infrastructure development in the upper delta has the greatest effect on water levels in the region. Land subsidence combined with sea level rise could have the greatest future influence on flooding in the delta if current rates are extrapolated. Sustainable water management strategies are thus necessary to mitigate changes in the floodplains and delta and increase resilience to sea level rise and land subsidence.

1. Introduction

River floodplains are among the most biologically productive and ecologically diverse regions in the world. However, modifications to their flow regimes caused by both direct human interventions (such as dam construction, flood protection, or river diversions) and climate change have accelerated in recent times (Lehner et al., 2011; Doll and Schmied, 2012). Hydrology is a fundamental driver of floodplain ecosystems, and any hydrological alteration is likely to result in subsequent changes to aquatic biota and riverine ecology (Townsend and Hildrew, 1994; Stanford et al., 1996; Poff et al., 1997).

The hydrology of the Mekong floodplains and delta has not been heavily influenced by upstream development in terms of

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discharge yet (Kuenzer et al., 2012; Dang et al., 2016), but it is highly affected by local water infrastructure development, sea level rise and land subsidence (Deltares, 2013; Erban et al., 2014; Dang et al., 2016). All these factors, however, are interrelated. For example, sea level rise may propagate flooding (Van, 2012), resulting in the requirement of flood prevention systems in extensive areas of the floodplains and delta. The development of water and transportation infrastructure, subsequently, defines human settlements throughout the delta. An increase in population density then results in intensification of well pumping, which causes soil compaction and land subsidence as described in Erban et al. (2014).

Hydrological alterations in the Mekong and their implications for floodplain management have been the subject of a number of recent modeling studies. For instance, the cumulative influence of hydropower dams and climate change on the Cambodian lowlands was studied by Västilä et al. (2010) and Arias et al. (2014a); these two studies, however, did not consider the effect of hourly tidal variation on the Vietnamese delta. Moreover, the impact of delta-based water infrastructure on flooding in the delta was studied by Le et al. (2007, 2008) and Triet et al. (2017). Le et al. (2007, 2008) and Triet et al. (2017) analyzed changes in maximum water levels and maximum flooding extent, but did not report on other hydrological indicators, which are also key drivers of ecological and agricultural productivity in floodplains (Townsend and Hildrew, 1994; Poff et al., 1997; Arias et al., 2013). A different study on impacts of climate change on flooding propagation in the delta concluded that larger inundated areas and longer flooding durations would be observed along the coastal part of the delta due to sea level rise (Van, 2012). Despite these important findings, the study did not include ongoing water infrastructure development, making it difficult to assess the relative contribution of different drivers of change. The impact of sea level rise on the delta in the dry season was discussed in Smajgl et al. (2015), but the authors focused on adaptation strategies for climate change resilience rather than hydrological alterations. Given the current status of the literature in the Mekong Delta, a comprehensive quantification of contributions from all major drivers of large scale change is thus needed to better evaluate future water resources management alternatives.

The Mekong floodplains and delta, as other large lowland drainage systems around the world, are affected by complex natural and anthropogenic drivers. Understanding the inter- and intra-annual impact of each driver on the different zones of the Mekong floodplains and delta may also help understand hydrological processes of river floodplains worldwide, and will help formulate appropriate water resources management and development plan options. Thus, this paper aims to quantify the cumulative and marginal effect of hydropower dams, delta-based water infrastructure development, sea level rise and land subsidence on spatial and temporal hydrological patterns using a complex and detailed application of a hydrodynamic model for the Mekong floodplains and delta. Monthly water levels, flood extents, flood depths, flood durations, 30-day maximum water levels, 30-day minimum water levels and water levels' raising and falling rates were the hydrological indicators considered in the extent of this paper.

2. Study area

The Mekong River in South East Asia is ranked 12th in length and 8th in water discharge in the world. The Mekong originates in the Tibetan Plateau and then flows through China, Myanmar, Laos and Thailand before pouring into the alluvial floodplains and delta in Cambodia and Vietnam. The Mekong floodplains and delta can be classified into three regions: the Cambodian Lowland (CBL), the Tonle Sap Floodplain (TSF) and the Vietnam Mekong Delta (VMD; Fig. 1). In the middle of the floodplain at Phnom Penh, Cambodia's capital, the Mekong branches off into the Tonle River towards the Tonle Sap Lake, and the Mekong and Bassac Rivers towards the Vietnamese delta, where there is a complex river and canal network. The Tonle Sap Lake plays an important role in hydrological regulation for the Mekong floodplains and delta by storing and releasing water from its 76.05 million m^3 water storage capacity (Koponen et al., 2007).

The Mekong basin is facing the development of water infrastructure for different purposes. The upper part of the basin has a large potential for hydropower development because of its mountainous terrain. Since 1991, the construction of 74 dams has significantly changed hydrological regimes in the basin (Cochrane et al., 2014; Lu et al., 2014; Räsänen et al., 2017). The influence of dam construction on hydrology is, however, currently limited to the upper Mekong floodplains, because the current combined reservoir capacity is much lower than the annual flow of the Mekong River in the floodplains (Dang et al., 2016). However, if all proposed dams are constructed, the cumulative impact of dams may cause substantial changes to hydrological regimes of the lower Mekong, upstream of the floodplains (Lauri et al., 2012) and the Tonle Sap floodplain (Arias et al., 2014b).

After the Vietnamese reunification in 1975, the government strongly incentivized the development of water infrastructure to reduce poverty (Hoanh et al., 2014). Land redistribution, the widespread adoption of high-yielding and short-duration rice varieties, and the construction of low dykes to delay the August flood, increased rice productivity to much higher levels than the pre-1975 period (Kakonen, 2008; Howie, 2011; Hoanh et al., 2014). During the first decade of the 21st century, limited land availability for rice cultivation was the main obstacle to increase agricultural production further. Consequently, flood prevention systems for agricultural expansion and intensification grew by about 500,000 ha during the 2000 s (Kontgis et al., 2015), which included the construction of high dykes to keep out all flooding from compartments during the monsoon season. These flood control systems, however, have had a large impact on water levels' raising and falling rates, water levels' fluctuations and flood boundaries in the floodplains since 2007 as shown through a historical data analysis conducted by Dang et al. (2016).

Sea level rise and land subsidence will also likely pose additional pressure on the development of the region (Van, 2012; Deltares, 2013; Erban et al., 2014; Smajgl et al., 2015). Global sea level rise will certainly affect the coastal region of the VMD (Van, 2012, Smajgl et al., 2015). The challenge of either attempting to adapt to climate change or sustaining local development is unfolded in social and ecological systems of the VMD (Chapman and Darby, 2016). Moreover, land subsidence rates, which exceeded sea level rise at some locations in the delta (Erban et al., 2014), will likely worsen the flooding situation.

The Mekong floodplains and delta are responsible for a large proportion of the agricultural and fisheries production in Vietnam

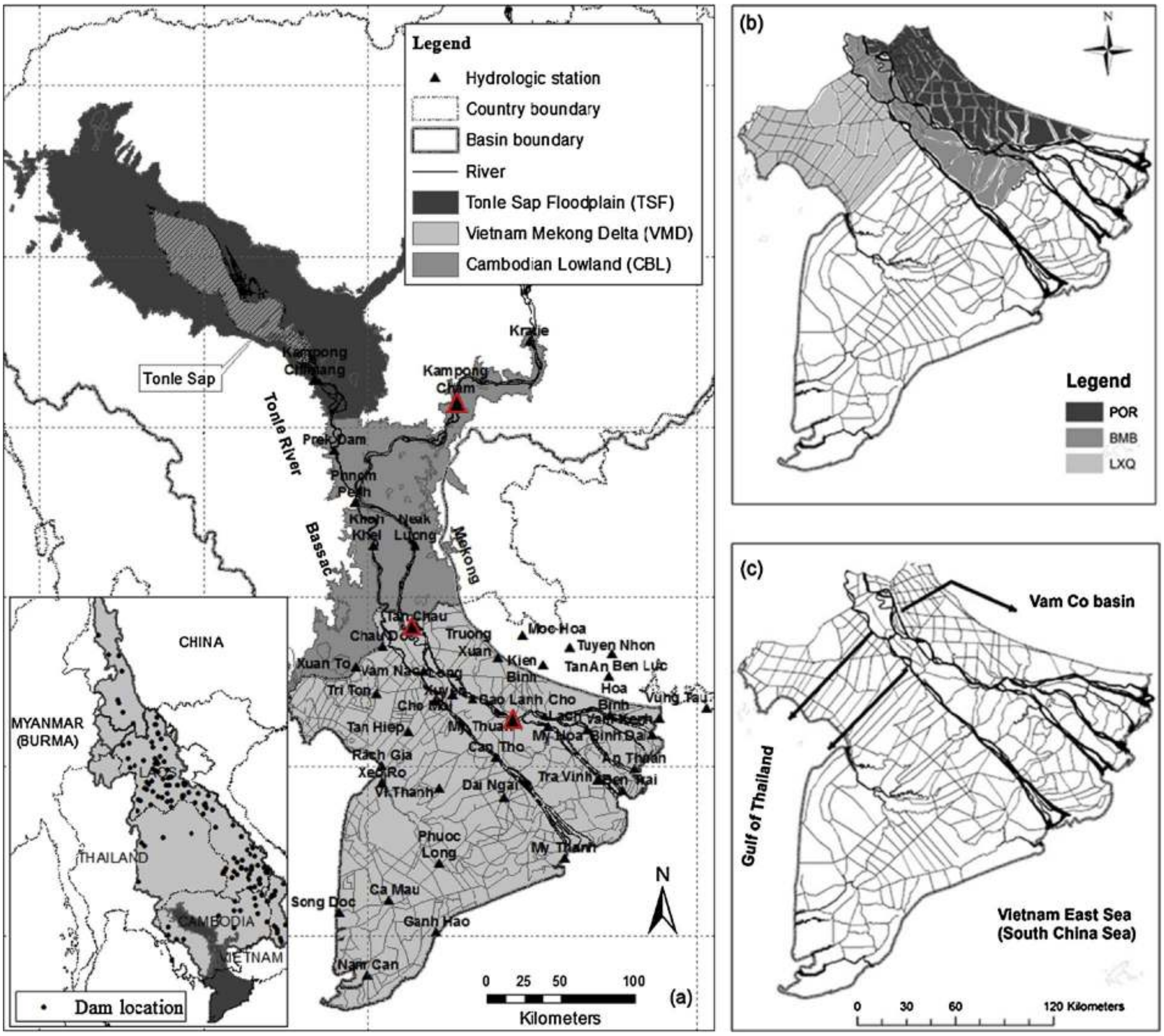

Fig. 1. (a) – Sub-regions and hydrological stations in the Mekong floodplains and delta (My Thuan, Tan Chau, and Kampong Cham stations are shown with large triangles). The map inset shows the regional location of the floodplains and delta and potential upstream hydropower development (Data: MRC, 2015); (b) – Compartments in the Plain of Reeds (POR), the Long Xuyen Quadrangle (LXQ) and the region between the Mekong and Bassac River (MBR) and (c) – river diversion directions after Deltares (2013) in the VMD.

and Cambodia (Hortle, 2007; GSO, 2013). Fish catch in the region provided up to 75% of protein demands in Cambodia, contributes significantly to the subsistence of local livelihoods (Nuorteva et al., 2010; Keskinen et al., 2011). Given the high dependency of the region's livelihoods on water resources, the consequences of development of upstream and localized water infrastructure on the hydrological regime should be carefully examined in conjunction with sea level rise and land subsidence.

3. Methodology

To study the impact of water infrastructure development, sea level rise and land subsidence in the large and tidal-influenced Mekong floodplains and delta, the hydrodynamic model DHI MIKE 11 was chosen. The software was applied in previous studies in the Mekong floodplains and delta (Nguyen et al., 2011; Nguyen et al., 2015; Smajgl et al., 2015) and a detailed hydraulic network for the whole Mekong floodplains and delta was available from the Institute for Water and Environment Research, Vietnam (Fig. 2a). The model was developed during the time the main author worked at the institute; it was used for unpublished work and it was further calibrated and validated for the aim of this study.

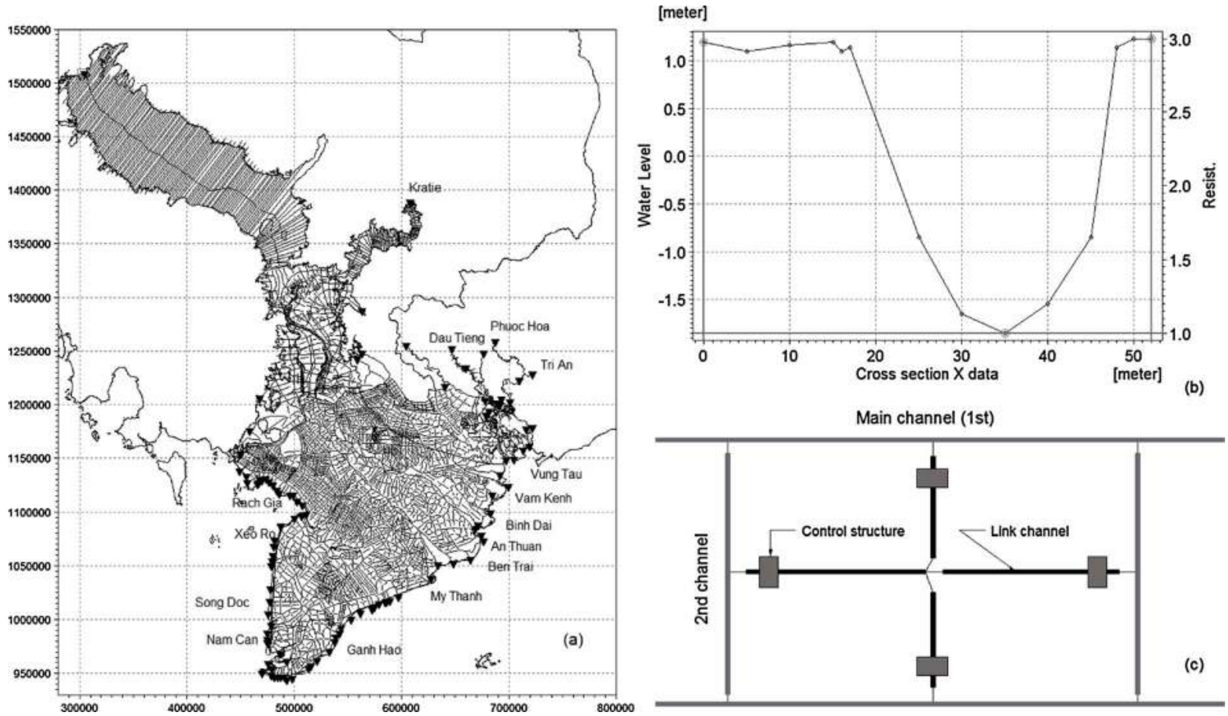

Fig. 2. Key elements of the MIKE 11 model applied to the Mekong floodplains showing (a) hydraulic river network and boundaries, (b) cross section of canal, and (c) link channels.

3.1. Hydraulic network

The hydraulic network includes the region from Kratie in Cambodia to the estuarine boundary in Vietnam (Fig. 2a). The network has 25,427 nodes, making 3586 branches and link channels. The network is sufficiently detailed to resolve the floodplain hydraulics at the regional scale.

Surveyed cross sections (an example in Fig. 2b) collected from different projects represent segments of river channels and other flowing-water bodies. Because the floodplains were divided into compartments enclosed by dykes, overland flows on each compartment were simulated by link channels with the storage capacity obtained from the 90 m resolution Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM, also used in Nguyen et al. (2011) and Smajgl et al. (2015)). The link channels used the relationship between elevation and terrestrial volume of the compartments within those areas between main channels to simulate flooding storage capacity. Nguyen et al. (2011) described this method in their studies, but they used cross sections to simulate terrestrial parts of the floodplains. Using the relationship between elevation and volume, as done in this study, has the advantage that the model can take into consideration the storage capacity of whole compartments. Where applicable, link channels were connected with the river system by control structures (Fig. 2c).

Catchment runoff from precipitation was simulated by the integrated MIKE11/NAM model in which the floodplains and delta were divided into 1819 sub-catchments. NAM (Nedbør-Afstrømnings-Mode) is a lumped catchment runoff model which has been widely used for research purposes (e.g. Madsen, 2000; Butts et al., 2004). Rainfall and evaporation data from 39 stations were used in the NAM model to account for moisture content changes in each catchment. The rainy season overlaps with the flood season in the floodplains when soil has high moisture content (saturated conditions) so all rainfall is assumed to contribute to run-off.

Hourly measured sea levels at 11 coastal stations were used as downstream boundaries (Fig. 2a). Discharge boundaries were obtained from Kratie, Dau Tieng, Phuoc Hoa and Tri An stations, and discharge data series at Kratie were used as an upstream boundary of the Mekong. Water level, discharge, evaporation and rainfall data were provided by the Mekong River Commission and the South Region Hydrology – Meteorology Center of Vietnam.

3.2. Model calibration and validation

The model was calibrated with recorded water levels at 33 stations (Fig. 1a). These data sets were employed in previous studies of the impact of water infrastructure and climate changes on water levels (Cochrane et al., 2014; Lu et al., 2014; Dang et al., 2016; Triet et al., 2017). Water levels, instead of discharges, were used to calibrate and validate the model because downstream from Kratie the Mekong's flow regime is highly influenced by the floodplains' storage capacity (MRC, 2012), and overland flow velocity during the flood season are not accurately measured (Dang et al., 2016). The calibration was done by adjusting Manning's (n) roughness coefficient in waterways. The values of Manning's n in main river segments ranged from 0.016 to 0.024, and from 0.022 to 0.027 for secondary branches; ranges are as recommended in Chow (1959). Roughness coefficients for floodplains (link channels) varied from 0.033 to 0.035 based on a land cover map (Source of data: SIWRP, 2000). In order to validate the hydrodynamic model, the Nash-Sutcliffe coefficient E was used (Nash and Sutcliffe, 1970):

$$E = 1 - \frac{\sum_{t=1}^{n} (H_t - H_{mt})^2}{\sum_{t=1}^{n} (H_t - \overline{H})^2} \quad (1)$$

Where: $\overline{H}$ is the mean of observed water levels

H_t and H_{mt} are observed and modeled water level at time t, respectively

The model was calibrated manually on an hourly basis for the year 2000 and was validated for the years 1998, 2001 and 2002 for the VMD. 1998 was considered a dry year, and 2000–2002 were wet years in the floodplains and delta (MRC, 2012). Because the year 2007 marked the rapid development of high dykes for flood prevention in the VMD (Dang et al., 2016), data for years after 2007 were not used for calibration and validation purposes. Preliminary analysis with available hourly water levels from 2007 to 2014 at Phnom Penh and Kratie showed that tide had little impacts on water levels in these stations; the use of daily water levels measured at 7:00 AM and 7:00 PM for 1998, 2000–2002 for the Cambodian lowlands was thus sufficient for calibrating the model upstream of the VMD.

Inundation patterns derived from the hydrodynamic model were validated with analogous information derived from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images. The product MOD09A1 was downloaded at the peak time of the wet season in 2000 to generate maximum inundation maps as described in Dang et al. (2016). The inundation maps derived by the satellite images and model simulations were compared using the Cohen's kappa coefficient (Smeeton, 1985), which was calculated as following:

$$k = \frac{p_0 - p_e}{1 - p_e} \quad (2)$$

Where: p_o is the relative observed agreement between flood maps calculated by the percentage of flooded and non-flooded areas appearing in both maps.

p_e is the hypothetical probability of chance agreement based on the percentage of flooded areas.

$$p_0 = p^{11} + p^{00} \quad (3)$$

$$p_e = p_{flooded} + p_{unflooded} \quad (4)$$

$$p_{flooded} = \frac{p^{11} + p^{10}}{p^{00} + p^{01} + p^{10} + p^{11}} X \frac{p^{11} + p^{01}}{p^{00} + p^{01} + p^{10} + p^{11}} \quad (5)$$

$$p_{unflooded} = \frac{p^{00} + p^{10}}{p^{00} + p^{01} + p^{10} + p^{11}} X \frac{p^{00} + p^{01}}{p^{00} + p^{01} + p^{10} + p^{11}} \quad (6)$$

Where: p^{11} is the number of "flooded" pixels in simulation and MODIS observation

p^{00} is the number of "unflooded" pixels in simulation and MODIS observation

p^{10} is the number of pixels which are "flooded" in simulation and "unflooded" in MODIS observation

p^{01} is the number of pixels which are "unflooded" in simulation and "flooded" in MODIS observation

A cell was considered as a "flooded" cell if the water depth was more than 10 cm.

The TSF was not considered for this spatial evaluation because a large fraction of this semi-natural floodplain is covered with varying types of vegetation canopies (tall gallery forests, grasslands and bush) which can reduce the accuracy of the inundation pattern derived from MODIS (Nguyen et al., 2013).

3.3. Hydrodynamic modeling scenarios

In order to understand the impact of dams, delta-based water infrastructure, sea level rise and land subsidence on the floodplains, six different scenarios were simulated with the hydrological conditions of the dry (1998), normal (1999) and wet years (2000) as summarized in Table 1 and described in detail as follows. Each driver was assessed independently to see how they impact on the floodplains; this is so-called a sensitivity-based, scenario-neutral approach (Prudhomme et al., 2010). This approach was also used in Nguyen et al. (2015) to study the impact of dams, climate change and sea level rise on sedimentation in the Vietnam Mekong Delta (VMD). Dam and water infrastructure development plans may change in the future, but the most critical cases were chosen to examine how far dam and dyke construction would affect the floodplains.

BL scenario: the baseline scenario was based on the years 1998, 1999 and 2000, which were the driest (below 26%), normal (above 6%) and wettest (above 38%) years on record, respectively, in terms of annual flood volume in the lower Mekong Basin over the past 50 years before the rapid development of water infrastructure in 2007 (MRC, 2012).

HP scenario: upstream flows were modified to simulate full hydropower development (126 dams) as in Lauri et al. (2012) and Arias et al. (2014a), and downstream boundaries were kept similar to the BL. In this scenario, monthly outflows from reservoirs were simulated to maximize energy production by optimally managing reservoir active storage using linear programming (LP) optimization (Lauri et al., 2012). Although the future development of dams may be uncertain, the level of hydrological alterations caused by

Table 1
Scenarios used to study the impact of different human-made and climatic factors on the Mekong floodplains.

Scenario	Name	Acronym	Description
1	BL	Baseline	Year 1998/1999/2000 flows
2	HP	Hydropower development	Year 1998/1999/2000 flows + 126 hydropower dams (maximize electricity generation)
3	WID	Delta-based water infrastructure development	Year 1998/1999/2000 flows + protected POR, MBR and LXQ (maximize agricultural development)
4	WIDR	Delta-based water infrastructure development and river diversion	Year 1998/1999/2000 flows + protected POR, MBR and LXQ + river diversion (maximize agricultural development but consider a mitigation option)
5	LS	Land subsidence	Year 1998/1999/2000 flows + land subsidence
6	SLR	Sea level rise	Year 1998/1999/2000 flows + sea level rise (17 cm and 38 cm, so-called SLR17 and SLR38 scenarios)

dams will range from the pristine condition (BL scenario) to this full dam development scenario.

WID scenario: in the WID scenario, the LXQ, POR and MBR were protected by dykes for rice cultivation throughout the flood season as proposed in Deltares (2013; Fig. 1b), the so-called "Food Production Scenario". Upstream and downstream boundaries conditions were maintained as in the BL. A large proportion of the floodplains have been already protected by dykes (60–70%) during the 1st decade of the 21 century, and the effect of dykes on water levels along the main stream was demonstrated by historical data analysis in Dang et al. (2016). A future in which the whole upper VMD is protected for rice cultivation is, thus, very likely.

WIDR scenario: this scenario was based on the WID scenario, but it included a bypass in which water was transferred to neighboring areas (Fig. 1c). This was simulated by doubling river widths with the purpose of reducing the pressure of water infrastructure development on the hydrology of the protected regions, which represented the major flood diversion scenario as in Deltares (2013).

LS scenario: the land subsidence scenario was simulated by using the land subsidence map of Erban et al. (2014). Land subsidence rates varied spatially and these were used to modify the topography (SRTM DEM) of the floodplains accordingly. Storage capacity of link channels was thus recalculated in many parts of the delta because the subsidence rate varied throughout the floodplains. It was assumed that water extraction rates would be constant over the study period (2000-2050) and only vertical subsidence was considered as in Erban et al. (2014). The subsidence rates ranged from 0 to 4 cm per year, and the areas where subsidence rates were high (> 1 cm per year) included cities like Can Tho and the coastal part of the Mekong Delta.

SLR scenario: upstream discharges were similar to the BL scenario, but downstream water level boundaries were increased based on measured data, corresponding to the projected sea level rise in 2050. Global sea level is predicted to rise in a range from 17 to 38 cm corresponding to different emission scenarios (IPCC, 2014). Sea level rise was the focus of this scenario as it will likely be the driver of climate change effects in the delta, as opposed to basin rainfall-runoff. A recent modeling effort by Hoang et al. (2016) projected climate change impacted water levels along the Mekong, but projected flow alterations at Kratie were considered insignificant in the timeframe of this study (up to 2050).

3.4. Indicators of hydrological alterations

The modeling scenarios were analyzed for changes in 30-day minimum water levels, 30-day maximum water levels, monthly average water levels, water level rise/fall rates, maximum flood extent and flood duration, indicators which are frequently the most altered by water infrastructure development (Tockner and Stanford, 2002). These were also the indicators historically identified as having changed under the effects of water infrastructure in the Mekong floodplains (Dang et al., 2016). The non-parametric Kruskal-Wallis test was used to determine if sets of indicators derived from each scenario were different from each other.

As a quasi-2D hydrodynamic model was employed in this study, in order to derive inundation maps, the Invert Distance Weighting (IDW) method was used to interpolate between known water level points in the model.

4. Results

4.1. Model calibration and validation and regional classifications

Overall, there was a good fit between observed and simulated water levels with Nash-Sutcliffe coefficients E ranging from 0.61 to 0.98 through the study region (Fig. 3).

Because of the minor influence of tides on water level fluctuations, Nash-Sutcliffe coefficients E were highest at stations in Cambodia (ranging from 0.70 to 0.98). In the VMD, E coefficients ranged between 0.65 and 0.89, and were especially high for stations on the Mekong and Bassac Rivers. High correlation coefficients (E > 0.8) values were also found between modeling and measured water levels at the key stations for the calibration and validation years of 1998 and 2000–2002 (Fig. S1 in Supplemental data).

Fig. 4a and b illustrate the inundation map derived from the MOD09A1 product and the baseline simulation result from September 29, 2000. This date was chosen to check the agreement between the two inundation maps because it was close to the date when the water level reached its maximum at Tan Chau (September 23, 2000), and the proportion of cloud cover was low. $p_e = 0.64$ and $p_o = 0.83$ resulting in a Cohen's kappa of $k = 0.63$, which indicated that the remotely sensed inundation map coincided well

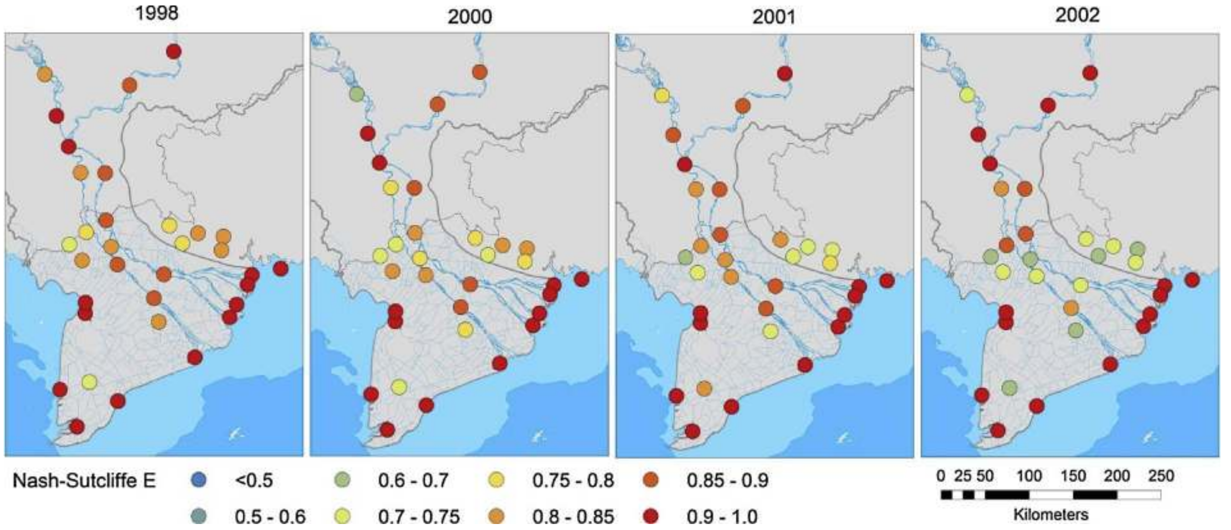

Fig. 3. Nash-Sutcliffe E coefficients of model efficiency between observed and simulated water levels for calibration and validation years using daily and hourly data.

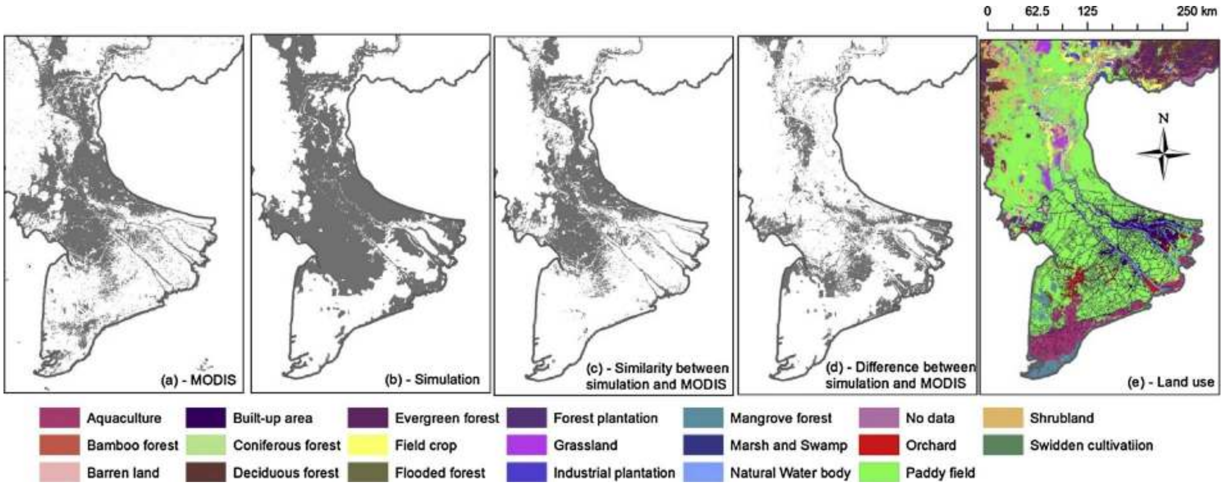

Fig. 4. Inundation maps of the year 2000 derived from MODIS (a), numerical simulation results (b), areas of inundation similarity and difference between MODIS and modeling (c and d), and land use map the Mekong floodplains and delta.
(e, source: MRC, 2003).

with the modeling inundation map. The areas of similarity between the MODIS imagery and modeling results were large (83%; Fig. 4c). However, land use also influenced the accuracy of the MODIS-derived inundation maps (Fig. 4e). In the lower VMD, while water levels were low, “Orchard” and “Built-up area” land uses in the region made the observations by the satellite become less accurate and contributed to the discrepancy between MODIS and the modeling results. Additionally, in the middle and coastal parts of the delta, water depths were shallow so satellite-based inundation maps may be influenced by bottom reflectance and vegetation.

Arguably, the main source of uncertainties in this study came from the definition of channel network and river cross sections in the hydrodynamic model. The model domain covers an extension of around 70,000 km^2, creating a complex logistical challenge to collect thousands of cross sections of the river and canal network. Moreover, the heterogeneity in the physiography of river catchments may cause different levels of water resistance, resulting in different roughness coefficient even in a short river segment. Nevertheless, the high correlation coefficient between modeling results and measured water levels increase the accuracy in modeling results.

It is important to note that the locations of the boundaries among the river-dominated, tidal and transitional regions were dynamic. In the dry season, water fluctuations were still observed at Phnom Penh, but the magnitude of water levels’ fluctuation along the river from Phnom Penh to the region near the border between Vietnam and Cambodia were small (less than 0.25 m; Fig. 5a and c). Thus, the Cambodia lowlands and the Tonle Sap floodplain can be classified as river-dominant regions. The Vietnam Mekong Delta includes transitional and tidal regions. The effects of tides on water levels in the coastal part of the delta are prominent. In the flood season, the upper VMD turns into a river-dominated region (Fig. 5b and d). There is not much difference between the dry year (Fig. 5a and c) and the wet year (Fig. 5b and d) in terms of seasonal boundaries.

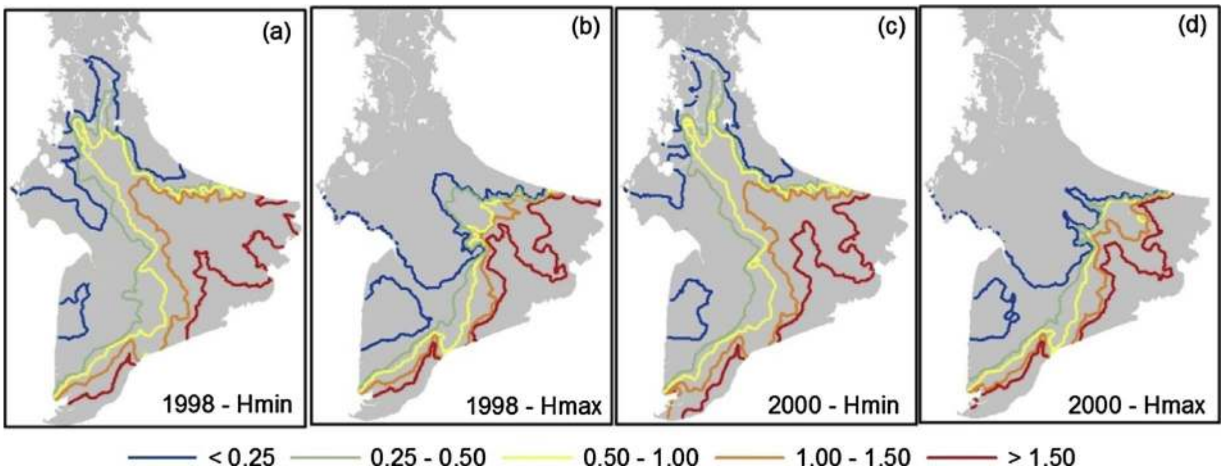

Fig. 5. Magnitudes of daily water level changes at the driest time (Hmin: a & c) and wettest time (Hmax: b & d) in the driest year (1998) and wettest year (2000).

Three key locations, Kampong Cham, Tan Chau and My Thuan (locations in Fig. 1), which are in each region, were chosen to illustrate the impact of each scenario on monthly water levels and other hydrological indicators.

4.2. Future impacts on monthly mean water levels along the Mekong mainstream

Modeling results showed that the magnitude of impacts of different drivers on water levels varied considerably from one region to another. Mean monthly water levels in the dry (1998), normal (1999) and wet (2000) years along the Mekong River varied according to different scenarios simulated (Fig. 6).

Hydropower dams (HP scenario) increased monthly mean water levels in the dry season and reduced monthly mean water levels in the wet season throughout the Mekong mainstream from Kampong Cham, Tan Chau to My Thuan (Fig. 6). In the wet year, mean water levels increased by 25.5% in the dry months and decreased by 0.8% in the wet months at Kampong Cham compared to the BL scenario. In the dry year, the influence of hydropower on monthly water levels was observed; dam operation increased water levels by 70% in the dry months and decreased water levels by 5.9% in the wet months. This indicates that hydropower dams could affect water levels in a dry year more severely than in a wet year and in the dry season more heavily than in the wet season. The difference in monthly water levels between BL and HP diminished downstream (Fig. 6). In the middle and coastal parts of the VMD, the difference in mainstream water levels between BL and HP was small (less than 10 cm at My Thuan; Fig. 6c, f and i). Statistically, there were significant differences in monthly water levels from Kratie to Chau Doc and Tan Chau observed between the BL and HP scenarios according to the Kruskal-Wallis test (p-values < 0.05), but the difference in monthly water levels from Can Tho and My Thuan to the river mouth was insignificant (p-values > 0.05).

Contrary to the effect of dams, the impact of flood prevention systems on mainstream water levels was observed in the wet season in the normal and wet years (Fig. 6e and h). Mean of monthly water levels were projected to increase by 15% (about 0.4 m; p-values < 0.05) at Tan Chau in the wet months (from June to December) in 2000 (Fig. 6h), and the mean of water level was predicted to increase by only 5% in the same period in 1998 (Fig. 6b). Water levels were also expected to increase slightly by around 0.03–0.05 m at the lower stations of My Thuan during the wet season in 1998 (Fig. 6c) and 2000 (Fig. 6i).

The widening of canal systems in the VMD (WIDR) resulted in a maximum water level decrease of about 6 cm in the wet season at Tan Chau in the wet year (Fig. 6h), but did not affect water levels in other parts of the mainstream compared to the WID scenario.

Sea level rise was the most important driver contributing to rising water levels (p-values < 0.05) at My Thuan. If the sea level rose the expected 17 cm, annual water levels at My Thuan would increase about 10 cm and 12 cm during the dry year and the wet year, respectively (Fig. 6c and i). Sea level rise by 38 cm will cause an increase of 30 cm in the wet year at My Thuan (Fig. 6i). This rise is nearly a three-fold increase from the HP scenario projections. Modeling results suggests that hydrological regimes of the middle and the lower delta part of the Mekong River would be much more heavily affected by the tidal regime than by upstream alterations.

Although land subsidence increased water retention capacity in different parts of the floodplains, monthly water levels with respect to mean sea levels did not change in the LS scenario. At Can Tho and My Thuan, where the land subsidence rates were almost 4 cm/year (Erban et al., 2014), observed changes in water levels were minor (Fig. 6).

As expected, modeling results showed that water level alterations in a normal year (1999) ranged between the changes in the driest year (1998) and a wettest year (2000), thus the analysis of the characteristics of the normal year are embedded in the range provided by the other two years analyzed.

4.3. Future impacts on maximum flooding extent and flood depth

For the BL scenario, maximum flood extent was about 54,000 km^2 in the year 2000, of which 27% was in the TSL, 18% in the CBL,

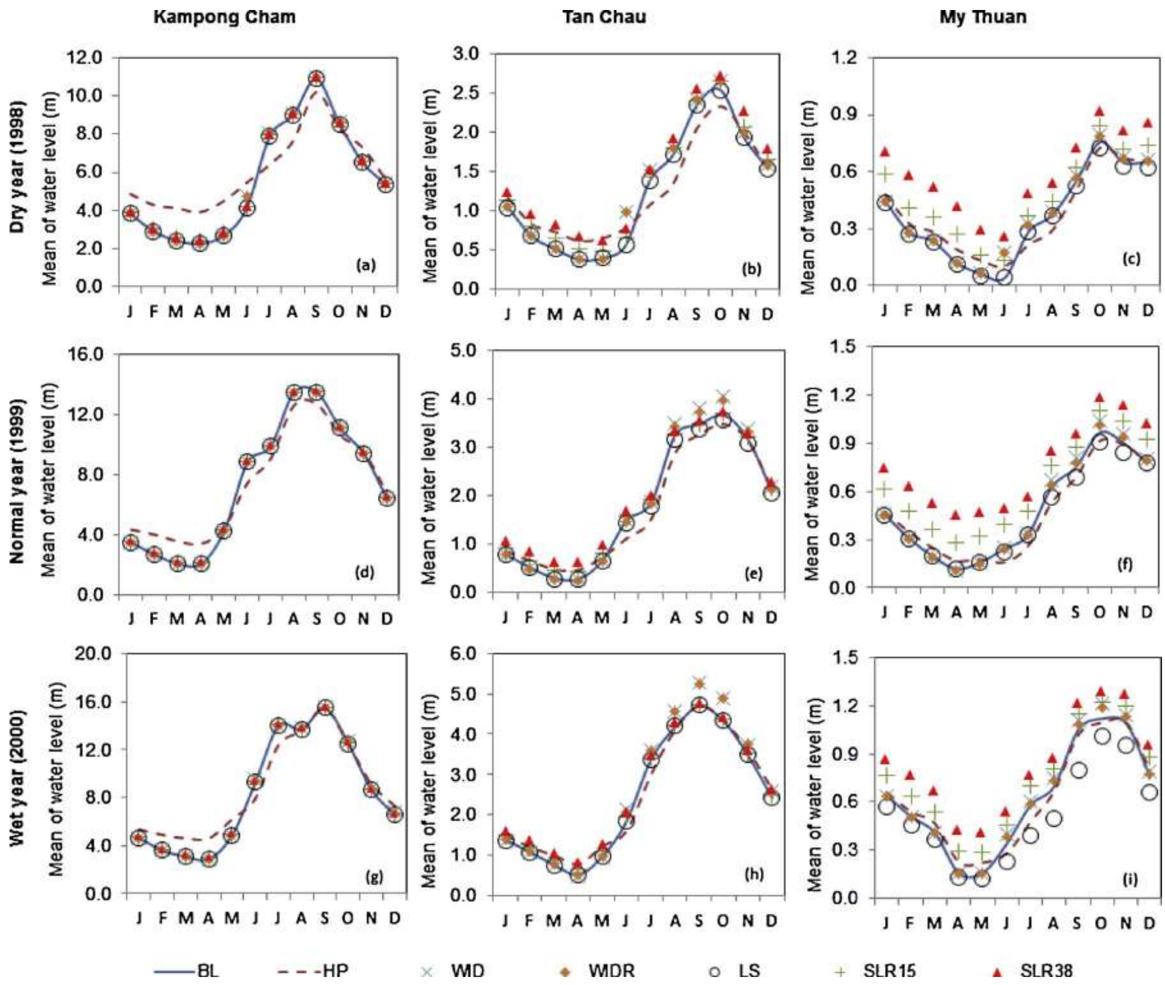

Fig. 6. Simulated mean monthly water levels along the Mekong River according to different scenarios. Please refer to Table 1 for scenario descriptions.

and 55% in the VMD. Full dam development is expected to reduce maximum flooding extent by 6% in the wet year (2000; Fig. 7h) and by 3% in the dry year (1998; Fig. 7b) compared to the BL (Fig. 7g and a); however, delta-based water infrastructure, sea level rise and land subsidence are expected to have greater effects in the VMD than in the Cambodian lowlands (Fig. 7c, d, e, f, i, j, k and l).

Maximum water depths tend to decrease in the upper part of the Mekong Delta according to the HP scenarios, but the impact of hydropower dams on the middle and coastal regions was very limited (Fig. 8).

In the WID scenario, maximum water levels increased along the riverine corridor between the Mekong and the Bassac Rivers to the East Sea (Fig. 8). Maximum water level increased up to 1.0 m at the Vietnam-Cambodia border, but only increased by 0.1–0.3 m in the middle of the delta.

Continuing future land subsidence (LS scenario) would be a major driver of change, causing increased maximum water depths in the whole Vietnamese delta although maximum water levels decreased. The influence of land subsidence on the maximum flooding depths is more pronounced in the wet year rather than in the dry year. The changes in flood depth are likely relative to the change in ground elevation rather than water levels which should be compared with a datum. This is because the alterations in water levels are low as mentioned in the previous section.

The middle and coastal parts of the delta were heavily influenced by sea level rise. Overall, the total extent of effected areas under the SLR38 scenario in the VMD was about 32,500 km^2 (93% of the entire zone) if sea level increases by 38 cm. Sea level rise had a very limited effect on maximum flood depths at POR, LXQ and MBR (Fig. 8).

4.4. Future impacts on flooding duration

In general, the total unflooded areas and the regions where the inundation time was greater than one month in the wet year (2000) were 1.45 times less than in the dry year (1998). Hydropower dams (HP scenario) would not reduce the total extent of flooding, but would reduce the length of inundation duration of those areas that are normally flooded for more than 6 months (ie. wetland areas, Fig. 9).

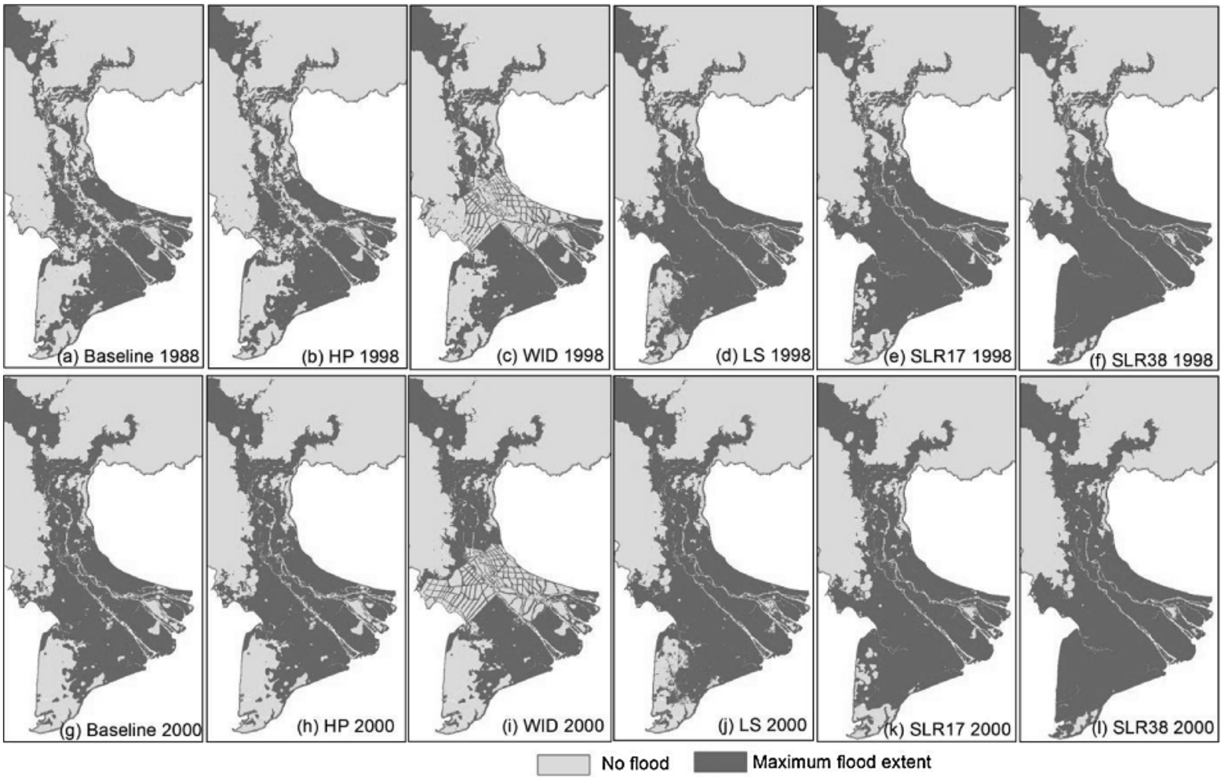

Fig. 7. Maximum flood extent for scenarios of Baseline (a and g), HP (b and h), WID (c and i), LS (d and j), SLR17 (e and k) and SLR38 (f and l) for the dry year (1998) and wet year (2000).

The construction of water infrastructure was predicted to increase agricultural land availability, and this development decreased flooded areas by 6% during a dry year and increased permanent flooding areas (> 6 months). The widening of canal systems should potentially decrease flooded areas caused by water infrastructure development by a factor from 1.11 to 1.16.

Sea level rise would prolong flooded time by about 25% and 36% in the 1998 and 2000 scenarios if sea level increases by 38 cm. Land subsidence would expand flooded areas by 21% in the dry year and 12% in the wet year, and this phenomenon would exacerbate the permanent flooding areas (> 6 months) by 32% in the 1998 scenario and 36% in the 2000 scenario.

4.5. Future impacts on annual hydrological alteration indicators

Changes to annual indicators of hydrological alterations along the Mekong and Bassac Rivers are shown in Table 2. Overall, the magnitude of changes varied spatially according to scenarios, with hydropower bringing the largest alterations in the Cambodian lowlands, while sea level rise and water infrastructure development cause the greatest impacts on the VMD.

Dams reduced the rise rate by up to 11% at Kampong Cham, but the rates remained the same at Tan Chau and Can Tho. Water level fall rates, meanwhile, decrease by 11% at Kampong Cham. In terms of extreme water levels, full hydropower dam development increased 30-day minimum water levels by 74% at Kampong Cham and by 10% at Can Tho.

The development of water infrastructure development (WID and WIDR) in the form of flood prevention systems mostly changes rise/fall rates and maximum water levels. At Tan Chau, the rise rates increase by approximate 11% and the fall rates decrease by 20% in the both scenarios. In the WID scenario, 30-day maximum water levels increase by about 15–17% at Tan Chau and Can Tho.

Land subsidence does not change the 30-day minimum water levels, but results in 30-day maximum water level declining about 4–5% at Tan Chau and Can Tho. Sea level rise, on the other hand, affects extreme water levels. For examples, if sea level rises 38 cm, 30-day minimum water levels at Phnom Penh, Tan Chau, and Can Tho would increase by 14% (15 cm), 557% (28 cm) and 47% (44 cm) respectively. 30-day maximum water levels do not change much along the river upstream of Tan Chau, but from Can Tho to the river mouth it increases by 16% (24 cm).

5. Discussion

This study found that the results of the different scenarios of future alterations have different magnitudes and distinct characteristics in the Cambodian lowlands versus the Vietnam Mekong Delta. A discuss of the implications for each of these two regions follows.

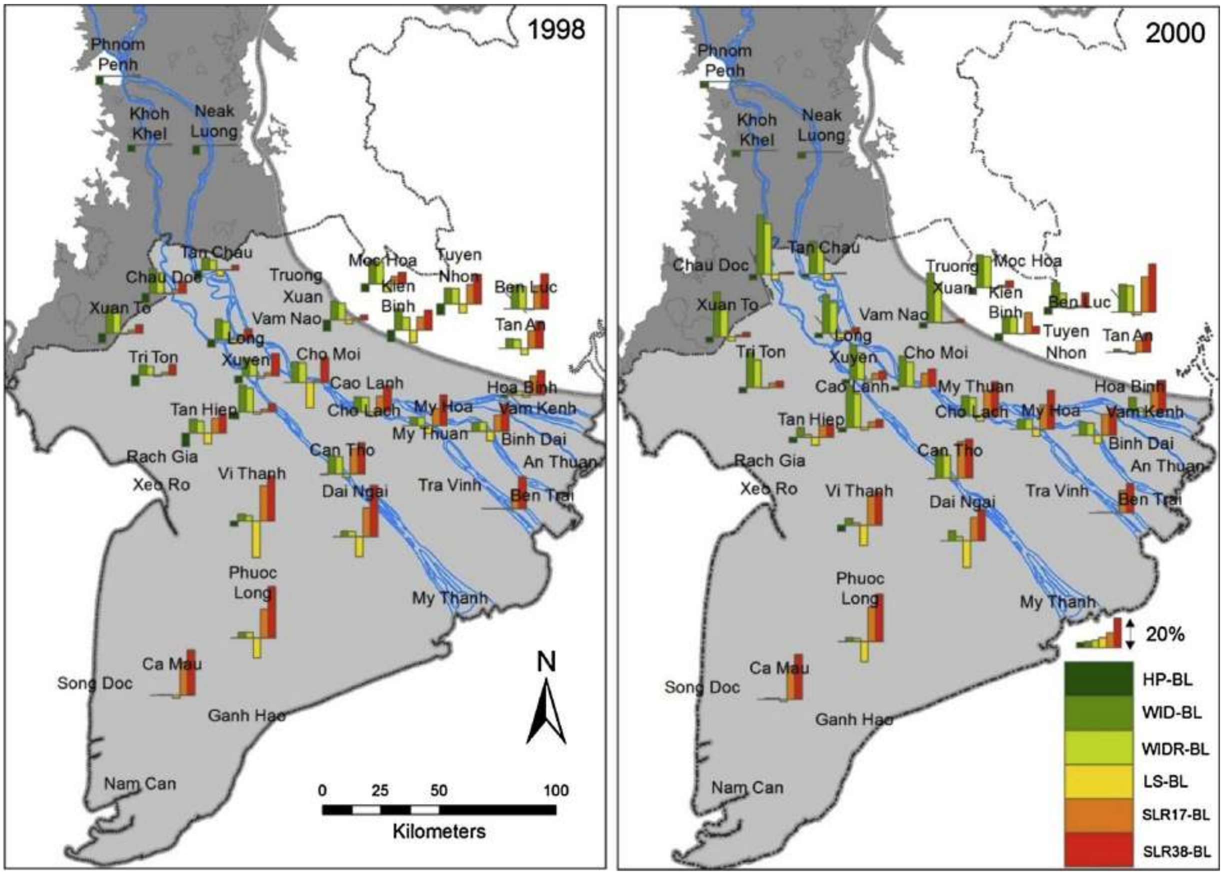

Fig. 8. Percentage differences in maximum water levels between the BL scenario and scenarios of HP, WID, WIDR, LS and SLR (17 and 38 cm) for the dry year (1998) and the wet year (2000).

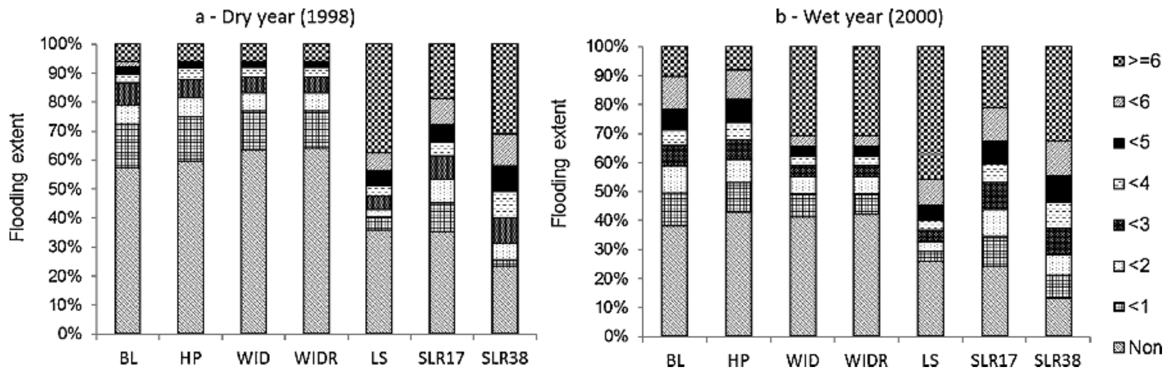

Fig. 9. Extent of areas inundated according to the number of months flooded corresponding to different scenarios in the dry year (1998) and wet year (2000).

5.1. Hydrological changes in the Cambodian lowlands

Hydropower dams increase water levels in the dry season and decrease water levels in the wet season in the upper floodplains because, reservoirs retain water in the wet season for use in the dry season to extend generation output in the dry season. Water levels in the upper floodplain are strongly linked to the flow regimes because this is a river-dominated region, and dam operations would modify the hydrology of the Mekong floodplains in a similar way as to what has recently occurred in the upper basin and upper part of the floodplains (Kummu and Sarkkula, 2008; Piman et al., 2012; Cochrane et al., 2014; Lu et al., 2014; Räsänen et al., 2017). Dams mainly changed water levels in the dry season (Fig. 6), water level fluctuations and water levels' rising and falling rates (Table 2). These hydrological alterations in the upper floodplains, consequently, may endanger riverine ecology and aquatic species.

Hydropower is an attractive source of energy, currently providing 16.6% of the global electricity and 70% of all renewable

Table 2
Alterations of hydrological indicators along the mainstreams in the floodplains.

Scenario	Hydrological indicators	Cambodian Lowlands		Vietnam Mekong Delta	
		Kampong Cham	Phnom Penh	Tan Chau	Can Tho
BL	Rise rate (m/hour)	0.21	0.09	0.07	0.25
	Fall rate (m/hour)	−0.09	−0.06	−0.05	−0.15
	30 days min (m)	2.72	1.11	0.05	−0.93
	30 days max (m)	15.69	9.77	4.73	1.48
HP	Rise rate (m/hour)	0.19 (−11)	0.09 (0)	0.07 (0)	0.25 (0)
	Fall rate (m/hour)	−0.08 (-11)	−0.06 (0)	−0.05 (0)	−0.15 (0)
	30 days min (m)	4.72 (+74)	2.13 (+92)	0.37 (+640)	−0.84 (+10)
	30 days max (m)	15.54 (−1)	9.67 (−1)	4.62 (−2)	1.48 (0)
WID	Rise rate (m/hour)	0.21 (0)	0.10 (+11)	0.08 (+14)	0.26 (+4)
	Fall rate (m/hour)	−0.09 (0)	−0.07 (+17)	−0.04 (-20)	−0.15 (0)
	30 days min (m)	2.74 (+1)	1.12 (+1)	0.06 (+20)	−0.93 (0)
	30 days max (m)	15.71 (0)	9.82 (+1)	5.43 (+15)	1.71 (+16)
WIDR	Rise rate (m/hour)	0.20 (−5)	0.10 (+11)	0.08 (+14)	0.26 (+4)
	Fall rate (m/hour)	−0.09 (0)	−0.07 (+17)	−0.04 (-20)	−0.15 (0)
	30 days min (m)	2.73 (0)	1.12 (+1)	0.06 (+20)	−0.93 (0)
	30 days max (m)	15.70 (0)	9.82 (+1)	5.26 (+11)	1.66 (+12)
LS	Rise rate (m/hour)	0.21 (0)	0.09 (0)	0.06 (−14)	0.24 (−5)
	Fall rate (m/hour)	−0.09 (0)	−0.06 (0)	−0.04 (-20)	−0.14 (-5)
	30 days min (m)	2.72 (0)	1.11 (0)	0.04 (−20)	−0.92 (+1)
	30 days max (m)	15.69 (0)	9.77 (0)	4.55 (−4)	1.41 (−5)
SLR17	Rise rate (m/hour)	0.21 (0)	0.09 (0)	0.07 (0)	0.25 (0)
	Fall rate (m/hour)	−0.09 (0)	−0.06 (0)	−0.05 (0)	−0.15 (0)
	30 days min (m)	2.88 (+6)	1.18 (+6)	0.17 (+249)	−0.73 (+21)
	30 days max (m)	15.71 (0)	9.80 (0)	4.76 (+1)	1.57 (+6)
SLR38	Rise rate (m/hour)	0.21 (0)	0.09 (0)	0.07 (0)	0.25 (0)
	Fall rate (m/hour)	−0.09 (0)	−0.06 (0)	−0.05 (0)	−0.15 (0)
	30 days min (m)	3.09 (+14)	1.26 (+14)	0.33 (+557)	1.57 (+47)
	30 days max (m)	15.73 (0)	9.83 (+1)	4.81 (+2)	1.72 (+16)

*Values in parenthesis indicate a percent change from BL conditions.

electricity (REN21, 2016), but it is causing tension between Mekong countries and some of their main economic sectors. Increasing demand of electricity for economic development in China and South East Asia countries resulting in 7 mainstream dams (Dachaoshan, Gongguoquiao, Nuozhadu, Jinghong, Manwan, Xayaburi and Don Sahong; MRC database, 2014) are examples of this ongoing tension. Consequently, policy makers should have plans to confront the consequences on the floodplains and delta of upstream dam development.

This study also found that maximum flooding extent (Fig. 7), maximum flooding depth (Fig. 8) and inundation times (Fig. 9) did not change much in the HP scenario compared to the BL. The effect of dams reduces through the floodplains as the terrain becomes flatter. The regulation effect of the Tonle Sap Lake, as described in Arias et al. (2014b) may also contribute to this buffering effect.

5.2. Hydrological changes in the VMD

In the VMD, the main aim of localized flood prevention systems is to shift from double to triple crops, but this activity may alter hydrological regimes in the region. Water infrastructure development did not always have positive outcomes in terms of total income (Chapman and Darby, 2016). However, delta-based water infrastructure could become the main driver of hydrological alterations in the wet season if the development of such systems is not well managed. The influence of the system in the dry season is limited. This is because water infrastructure has been developed in the region which is transferred from a transitional stage to a river-dominated stage in the wet season (Fig. 5). Water infrastructure development modifies the delta hydrology in the wet season by two mechanisms: redistributing water retention capacity and reducing water transfer capacity of the floodplains.

The development of high dykes to enable a third rice crop results in excess water that can be discharged to other regions and make local water levels to increase, because the flood protection will limit areas to disperse water (Fig. 7c). The two main rivers (Bassac and Mekong) have much higher conveying capacity compared to canals, thus water will mostly flow towards the Vietnamese East Sea, and this lead to the increase of water levels in the middle delta and the neighboring basin (Fig. 6c, f and i). Additionally, the "M" shaped semi-diurnal tide of the Vietnamese East Sea enables easier water discharge to the east rather than to the west because of the diurnal tide of the Vietnamese West Sea (Van, 2012). This process will require downstream provinces to build their own flood prevention systems, which may then trigger another flood propagation process. This study confirmed the finding in Triet et al. (2017) that the construction of dykes increased shift water levels downstream, but we also found that there was the increase of local water levels. This may be a result of the reduction in water transfer capacity of the floodplains. The designation of freshwater conservation areas, which can be managed for multiple purposes, should be considered in the floodplains in order to prevent some of the water management issues expected to occur once all the factors of change begin to affect the VMD.

The widening of canals in the upper VMD illustrated in the WIDR scenario was considered as an approach to reduce the stress of water infrastructure development during the wet season. This may increase the availability of water in the dry season for irrigation, but the effect during the wet season would be only minor. The transfer capacity of canals, even when widened, is limited compared to the two main rivers which overflow in the wet season and thus widening of the canals may not result in a significant advantage. Furthermore, if water is transferred uncontrolledly to other regions, it may stimulate flooding problems in those regions. The changing in water balance among river basins requires a comprehensive inter-basin investigation study.

The middle delta in Vietnam is a transitional region where water levels will increase by the influence from upstream systems and downstream sea level rise. The influence of sea level rise on water levels is higher than that caused by upstream infrastructure development by either dams or localized water infrastructure. The reason for this is that the middle delta has a dense canal system which drains water easily, but this canal system also makes sea water easy to penetrate into the delta, and a sea level rise of 38 cm will impact 93% of the region. In the tidal region or the coastal part of the VMD, sea level rise will be the only driver of hydrological alterations.

Land subsidence at the rate up to 4 cm/year (Erban et al., 2014) causes significant increases in flood depths, but this phenomenon does not change baseline water levels. Land subsidence theoretically increases water retention capacity in various parts of the delta; however, because subsiding lands mostly occur in the tidal regions, land subsidence-induced water storage has little impact on water levels.

In addition to changes in water levels in terms of quantity and timing due to impacts of water infrastructure development, it is also important to consider the issue of water quality and fluvial geomorphology (Kondolf and Rubin, 2014; Chapman and Darby, 2016). Flooding in the wet season brings with its nutrients attached in alluvium-laden water (Kakonen, 2008). Dams, for example, would lessen sediment movement downstream (about 55–100% of the 160–200 × 10^6 ton/year; Pearse-Smith, 2012; Kondolf and Rubin, 2014); this could lead to a reduction of the sediment-bound nutrients delivered from the Mekong in the floodplains. Whether high dykes would offer poor farmers a significant improvement in livelihoods (Howie, 2011, Hoanh et al., 2014) or would only create short-term and negligible benefits (Chapman and Darby, 2016), it is clear that high dykes would change the availability of nutrients in protected areas. The effort to control water would result in increases in agrochemicals usage and may harm poor farmers who cannot afford them (fertilizers and flood prevention systems; Kakonen, 2008). Further interdisciplinary research is needed to address the complex relationships between water infrastructure development and social, economic, and environmental issues.

6. Conclusions

In this study, we demonstrated that the impacts of water infrastructure, sea level rise and land subsidence on water levels in the Mekong floodplains vary depending on the hydrological characteristics of each region. Thus, well planned, comprehensive water management strategies will be needed in each region.

In the Cambodian lowlands, which are mostly a river-dominated region, any alterations in hydrological regimes caused by the development of hydropower dams would have a direct effect on water levels. Hydropower reservoirs, which may impact on seasonal water levels, fluctuations and water levels' rising and falling rates, would need to be operated under regimes to minimize the impact on the region.

In the upper Vietnamese delta, the impact of delta-based water infrastructure on hydrological regimes is more significant than other factors in the wet season, but sea level rise will be the main driver in the dry season. In the wet season, dykes may not only affect water storage capacity but also water transfer capacity of the floodplains while efforts to widen the current canal systems to mitigate the impact of dykes would have limited effect in relieving impacts. Water storage areas should be maintained to reduce possible impact of localized water infrastructure development.

Finally, land subsidence and sea level rise will have the greatest effect on both the middle delta and coastal areas of the VMD, and the vulnerability of flooding in the delta would increase in the coming years. A combination of strategies, such as sea-dyke establishment, reductions in groundwater pumping and mangrove forests restoration, should be considered to alleviate water management issues in this large and important region.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ejrh.2017.12.002.

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