The Cambodian Mekong floodplain under ~~the~~ future development plans and climate change

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HIGHLIGHTS

- We study the impact of future scenarios on floods in the Cambodian Mekong floodplain
- The full combined development scenario alters flows up to ~~-34~~30% in wet season and +~~54~~140% in dry season
- ~~The full development causes a decrease in~~Hydropower developments alone reduce total flood ~~extent up to -18~~extents by more than 20%
- Prey Veng ~~is~~and Takêv are the provinces most ~~vulnerable province for the largest flooded area~~

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- ~~Climate~~susceptible to climate change ~~and hydropower mitigation exacerbate the degree of alterations~~induced flood risks

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ABSTRACT

Water infrastructure development is ~~crucial for driving~~considered necessary to drive economic growth in the ~~developing countries of the~~ Mekong~~.~~ region of mainland Southeast Asia. Yet ~~it may also alter existing hydrological and flood conditions, with serious implications for water management, agricultural production and ecosystem services, especially in the floodplain regions. Our~~ the current understanding of ~~the~~ hydrological and flood pattern changes associated with infrastructural development still contain several knowledge gaps, such as the ~~consideration of overlooked prospective drivers, and the~~ interactions between multiple drivers~~.~~, which may have serious implications for water management, agricultural production, and ecosystem services. This research attempts to conduct a cumulative ~~impact~~ assessment of multiple infrastructural developments and climate change implications on discharge and flood changes in the Cambodian ~~part of the~~ Mekong ~~floodplains~~floodplain. The developmental activity of ~~six central sectors (~~hydropower~~,~~, dam construction and irrigation~~, navigation, flood protection, agricultural land use and water use)~~ expansion, as well as climate change were considered in our innovative combination of three models: Mekong basin-wide distributed hydrological model IWRM-VMod, whole Mekong delta 1D flood propagation model MIKE-11 and 2D flood duration and extent model IWRM-Sub enabling detail floodplain modelling ~~analysis.~~. The scenarios approximate the conditions expected by around 2050. Our results show that the monthly~~, sub-seasonal,~~ and seasonal hydrological regimes (discharges, water levels, and flood dynamics) will be subject to ~~a~~ substantial alterations under ~~the 2020 planned~~future development ~~scenario, and even larger~~ scenarios. The degree of hydrological alterations under the ~~2040 planned~~combined development ~~scenario. The degree of hydrological alteration under the 2040 planned development is~~scenarios that consider both hydropower and irrigation impacts are somewhat counteracted by the effect of climate change~~, as well as the removal of mainstream dams in the Lower Mekong Basin and hydropower mitigation investments.~~. The likely impact of decreasing water discharge in the early wet season (up to ~~–34~~30%) will pose a critical challenge to rice production, whereas the likely increase in water discharge in the mid-dry season (up to +~~54~~140%) indicates improved water availability for coping with drought stresses and sustaining environmental ~~flow~~flows. At the same time, these changes would have drastic impacts on total flood extent, which is projected to decline ~~up to –18~~by around 20%, having potentially negative impacts on floodplain productivity and aquaculture, whilst ~~at the same time~~ reducing the flood risk to ~~the area.~~more densely populated areas. Our findings ~~urge~~

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~~the timely establishment~~highlight the hydrological complexity and heterogeneity of ~~adaptation and mitigation strategies to manage such future environmental alterations in a sustainable manner~~this region and demonstrate the substantial changes that planned infrastructural development will have on these ecologically fragile floodplains.

***Keywords*:**

Cambodian Mekong floodplain
, Climate change
, Cumulative impact assessment
, Hydrological alteration
, Hydropower dam
, IWRM model

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1. Introduction

The Mekong River Basin~~ (MRB)~~ is the largest river basin in the Southeast Asian mainland. Historically, cyclones and severe tropical storms have generated the most significant Mekong flooding events, the largest of which was recorded in 1966, when tropical storm Phyllis struck the Upper Mekong Basin (~~UMB) (Adamson et al., 2009). At the downstream end of the basin, severe floods have most commonly been recorded in the area around Stung Treng Province, Cambodia, at the confluence of the Mekong River, and within the~~Adamson et al., 2009). At the downstream end of the basin (Fig. 1), severe floods have most commonly been recorded in the area around Stung Treng Province, at the confluence of the Mekong and Tonle Sap rivers, and within the Vietnamese Mekong Delta. The last severe flood occurred in 2011 and it is ranked among the highest discharge recorded in the Lower Mekong Basin (LMB) ~~(MRC, 2011).~~(MRC, 2011).

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Whilst prolonged flooding damages infrastructure, crops and floodplain vegetation, and the fertile land; ~~annual~~seasonal flooding is a vital hydrological characteristic of the ~~MRB~~Mekong River Basin, as it improves water availability during the dry season, and maintains and increases the high productivity of ecosystems and biodiversity ~~(Arias et al., 2014; Arias et al., 2012; Boretti, 2020; Kondolf et al., 2018; Kummu et al., 2010; Kummu and Sarkkula, 2008; Lamberts, 2008; Schmitt et al., 2018; Schmitt et al., 2017; Västilä et al., 2010; Ziv et al., 2012).~~(Arias et al., 2014; Arias et al., 2012; Boretti, 2020; Kondolf et al., 2018; Kummu et al., 2010; Kummu and Sarkkula, 2008; Lamberts, 2008; Schmitt et al., 2018; Schmitt et al., 2017; Västilä et al., 2010; Ziv et al., 2012). As part of the annual flood cycle, floodwaters play an important role in the recharging of aquifers and ensuring the hydrological connectivity of the floodplain, which is essential to maintaining ground water resources for use during the dry season (Kazama et al., 2007; May et al., 2011). Floodwaters also transport essential sediments and nutrients from the river channel into the floodplain~~,~~ and distribute them across a wide area~~,~~; fertilizing agricultural lands and enhancing floodplain productivity ~~(Arias et al., 2014; Kummu and Sarkkula, 2008; Lamberts, 2008). Moreover~~(Arias et al., 2014; Kummu and Sarkkula, 2008; Lamberts, 2008). In addition, the wider the flood extent, the larger the area of interaction between aquatic and terrestrial phases, which increases the potential transfer of floodplain terrestrial organic matter ~~and energy~~ into the aquatic phase. Under the combined impacts of hydropower infrastructure and climate change, the flooded area in Cambodia's Tonle Sap Lake Basin is projected to decline by up to 11~~%,~~% circa 2050, which may lead to a decline in the net sedimentation and the aquatic net primary production of up to

59%, and 38% respectively ~~(Arias et al., 2014; Lamberts, 2008).~~(Arias et al., 2014; Lamberts, 2008).

Existing hydrological and flood regimes will likely be altered due to climate change and infrastructure developments; but the degree of alterations vary with different drivers, location, and time ~~(Hoang et al., 2016; Hoang et al., 2019; Lauri et al., 2012; Piman et al., 2013; Try et al., 2020a). Hoang et al. (2016) projected~~(Hoang et al., 2016; Hoang et al., 2019; Lauri et al., 2012; Piman et al., 2013; Try et al., 2020a). Hoang et al. (2016) project that the Mekong's discharge under climate change conditions by 2050 under RCP 8.5 will decrease in the wet season (up to –7~~%),~~%) and increase in the dry season (up to +33%), equivalent to an annual increase between +5% and +15%. ~~Lauri et al. (2012) pointed out~~Lauri et al. (2012) shows that hydrological conditions of the ~~MRB~~Mekong River Basin were highly dependent upon the Global Climate Model (GCM) being used, with projections of water discharge at Kratie station~~,~~ (Fig. 1), Cambodia, ranging from –11% to +15% for the wet season and from –10% to +13% for the dry season~~.~~ for projections circa 2050. The study also ~~concluded~~concludes that the impact on water discharge due to planned reservoirs was much larger than those simulated due to climate change, with water discharge during the dry and early wet season being primarily determined by reservoir operation. ~~Hoang et al. (2019) found~~Hoang et al. (2019) find that for the same period hydropower development plans in ~~MRB~~Mekong River Basin are expected to increase dry ~~seasons~~season flows up to +133% and decrease wet season flows up to –16%. ~~Acting in opposition to climate change, the~~The future expansion of irrigated lands in the wider Mekong region is expected to reduce river flows up to –9% in the driest month ~~(Hoang et al., 2019).~~(Hoang et al., 2019). These hydrological ~~alternations~~alterations are likely to intensify when considered cumulatively.

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Changes to the Mekong mainstream flows will have direct impacts on flooding in the LMB floodplains in Cambodia and Vietnam. ~~In the LMB part of Cambodia, Try et al. (2020a) projected an increased peak inundation area of 19–43% due to climate change. Infrastructure development, in contrast, is expected to cause a decline in the Tonle Sap's flood extent by up to 1,200 km~~^{2} ~~(Arias et al., 2012), as dam development alone is expected to reduce flooded area in the Mekong Delta by 6% in the wet year and by 3% in the dry year (Dang et al., 2018). Flood extent in the Vietnam's Mekong Delta is projected to increase by 20% under the cumulative impacts of climate change and infrastructure development, bringing prolonging submergences of 1–2 months (Triet et al., 2020).~~Try et al. (2020a) considered the impact of future climate change (circa 2100) in isolation on the flood dynamics of the LMB, projecting an increased flood extent area of 19–43%. Infrastructure development, in contrast, is expected to cause a decline in the Tonle Sap's flood extent by up to 1,200 km^2 (Arias et al., 2012), as dam development alone is expected to reduce flooded area in the Vietnamese Mekong Delta by 6% in the wet year and by 3% in the dry year (Dang et al., 2018). Flood extent in the Vietnamese Mekong Delta is projected to increase by 20% under the cumulative impacts of climate change and infrastructure development, bringing prolonged submergences of 1–2 months (Triet et al., 2020).

The impacts described above may eventually lead to a new hydrological and flood regime in the Mekong region, and would likely endanger the riverine ecology and endemic aquatic species of the Mekong floodplain ~~(Arias et al., 2012; Dang et al., 2018; Kummu and Sarkkula, 2008; Räsänen et al., 2012).~~(Arias et al., 2012; Dang et al., 2018; Kummu and Sarkkula, 2008; Räsänen et al., 2012). To effectively manage and overcome these pressures and challenges in any ~~particular~~ floodplain, there is an urgent need to evaluate the combined impacts of climate change and infrastructure operations basin-wide ~~(Hoang et al., 2019; Hoanh et al., 2010; Lauri et al., 2012; Västilä et al., 2010).~~(Hoang et al., 2019; Hoanh et al., 2010; Lauri et al., 2012; Västilä et al., 2010). However, the existing studies have focused either on the basin scale flow changes ~~(Dang et al., 2018; Hoang et al., 2016; Hoang et al., 2019; Hoanh et al., 2010; Lauri et al., 2012; Pokhrel et al., 2018; Try et al., 2020a)~~(Dang et al., 2018; Hoang et al., 2016; Hoang et al., 2019; Hoanh et al., 2010; Lauri et al., 2012; Pokhrel et al., 2018; Try et al., 2020a) or assessed the impacts on flooding either for the Tonle Sap ~~(Arias et al., 2012; Ji et al., 2018; Yu et al., 2019)~~(Arias et al., 2012; Chen et al., 2021; Ji et al., 2018; Yu et al., 2019) or the Vietnamese ~~parts of the~~ Mekong Delta ~~(Dang et al., 2018; Tran et al., 2018; Triet et al., 2020).~~(Dang et al., 2018; Tran et al., 2018; Triet et al., 2020). Very little is known how basin-wide development and climate change would impact Cambodian ~~floodplains~~Mekong floodplain other than the Tonle Sap (Fig. 1), despite them being important agricultural lands and home to more than 6.4 million people (2008 Population Census).

Therefore, we have attempted to quantify the cumulative impacts of water resources development plans and climate change on hydrological and flood conditions localised in the Cambodian Mekong floodplain (Fig. 1) by using an innovative combination of state-of-the-art hydrological and hydrodynamic models. In concentrating on the provincial level, using an extended time-series for the calibration period, validating the flood extent against satellite imagery, and incorporating a larger set of driving factors within our analysis, the present study is a novel ~~and important~~ contribution to the work being done to understand the potential for

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future changes to the complex hydrology of the floodplains in general, and specifically the Cambodian Mekong floodplain~~ in Cambodia~~. The results of this study ~~are crucial for proposing and~~may contribute to formulating adaptation and mitigation strategies to ~~the~~ flood-prone areas~~,~~ ~~identifying~~ that balance the ~~main drivers causing floods at the provincial level for better~~ need for flood ~~management,~~prevention and ~~supporting~~water resource allocation against the ecological functioning of the ~~government in meeting the national and global sustainable development goals~~floodplain.

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2. Materials and methods

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2.1. Study area

The study area is located in the downstream part of the Cambodian Mekong River Basin (excluding the Tonle Sap Lake region), also known as the “Cambodian Mekong floodplain” (Fig. 1). The area is about 27,760 km^2 and extends along the Mekong mainstream from Kratie province to the Cambodia-Vietnam border. It covers parts of 12 provinces in Cambodia and one province in Vietnam (Tay Ninh~~).~~), but does not extend into the Vietnamese Mekong Delta region (see division in Fig. 1).

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A major part of the Cambodian Mekong floodplain is characterized by a flat terrace and low-lying grounds with gentle slopes that contain many depressions and lakes, except for the upper parts of the Prek Thnot and Prek Chhlong tributaries, which contains steeper terrain. ~~Conditions~~Hydrological conditions within the area are dominated by the seasonality and year-to-year variability of the Mekong flow regimes. ~~During the flood~~The wet season runs from June to October, and the dry season runs from November to May. During the wet season, the characteristics of the floodplain and Tonle Sap Lake play a vital role in flood peak attenuation and regulation temporarily storing and later conveying water across the vast low-lying areas. During the wet season, water flows from the Mekong mainstream into the Tonle Sap Lake, but this flow is then reversed in the dry season. This illustrates the highly complex hydrological system at play throughout the region, and the ~~extreme~~ seasonal variations that characterize the ecological and agricultural landscape.

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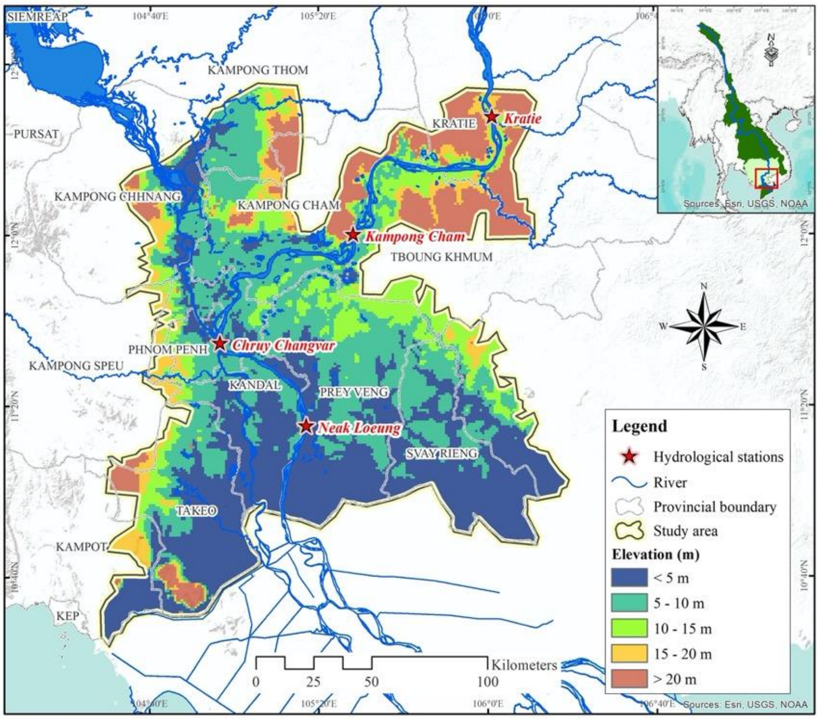
Within our historic baseline period of ~~1985–2008~~1971–2000, the ~~catchment~~ annual average temperature across the study area varies from ~~27.2~~26.9°C to 28.~~3~~2°C, with mean monthly temperatures between 30°C during the hottest months (April and/or May), and 26°C in the coldest month (January). Average annual rainfall ~~in~~across the ~~Cambodian Mekong~~

~~floodplain~~study area during the same period varies between 1,100 mm and 1,850 mm, with mean monthly rainfall ranging between 250 mm in the wettest months~~,~~ (May/June), and 10 mm in the driest~~.~~ (February).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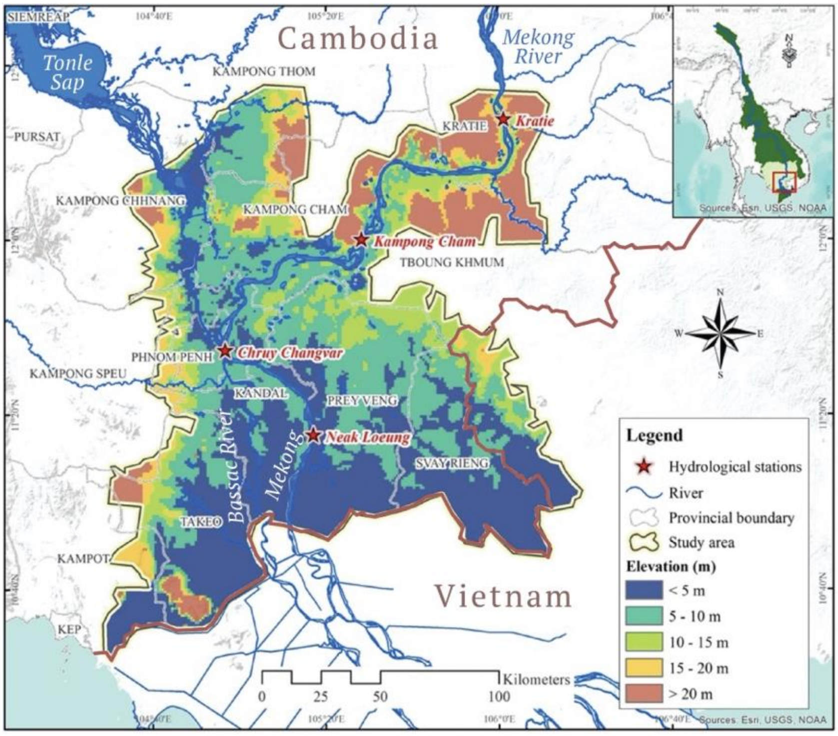

Fig. 1. *Map of the study area, the Cambodian Mekong floodplain. Elevation of 90-m grid cell was extracted from the SRTM database and river lines were obtained from the MRC database.*

2.2. ~~Datasets~~Modelling structure and datasets

We used a hydrological – floodplain model combination (Fig. 2), consisting of the distributed hydrological model IWRM-VMod (Lauri et al., 2006), the floodplain propagation model MIKE 11 (Dung et al., 2011), and the flood extent and duration model IWRM-Sub (MRC, 2018a) (Fig. 2). First, the IWRM-VMod model with resolution of 5 km x 5 km (see extent and hydrological processes in Fig. 2a) was used to simulate the entire Mekong basin's flow response to hydropower developments, irrigation expansion, and climate change impacts at around year 2050. We used the model runs, both baseline and scenarios, from Hoang et al. (2019). From the hydrological model we derived the boundary condition discharges that were used to drive the 1D flood propagation model MIKE 11 (as constructed and employed in Triet et al., 2017, 2020) in order to obtain the initial floodplain conditions, water levels, and fluctuating discharge of the Tonle Sap River. MIKE 11 model extends over the entire Mekong Delta down to the South China Sea, where sea level is used as another boundary

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The IWRM-Sub model was applied to Cambodian floodplains for the Mekong River Commission's (MRC) Council Study (MRC, 2018a). It is based on the SRTM 90-m topographical map (Jarvis et al., 2008), a soil types map (FAO, 2003), and a land use map (GLC2000, 2003), all aggregated to 1 km × 1 km resolution (Table 1). Geospatial data and river cross-section data were retrieved and added from the Mekong River Commission (MRC). The future climate scenarios are based on an ensemble of 5 GCM projections of precipitation and temperature taken from the CMIP5 suite of models (ACCESS, CCSM, CSIRO, HadGEM2, and MPI). Whilst the CMIP6 collection has now superseded the CMIP5 model results, an analysis of the differences between model collections shows consistent mean values for both precipitation and temperature across our study area for both wet and dry seasons (Table S1).

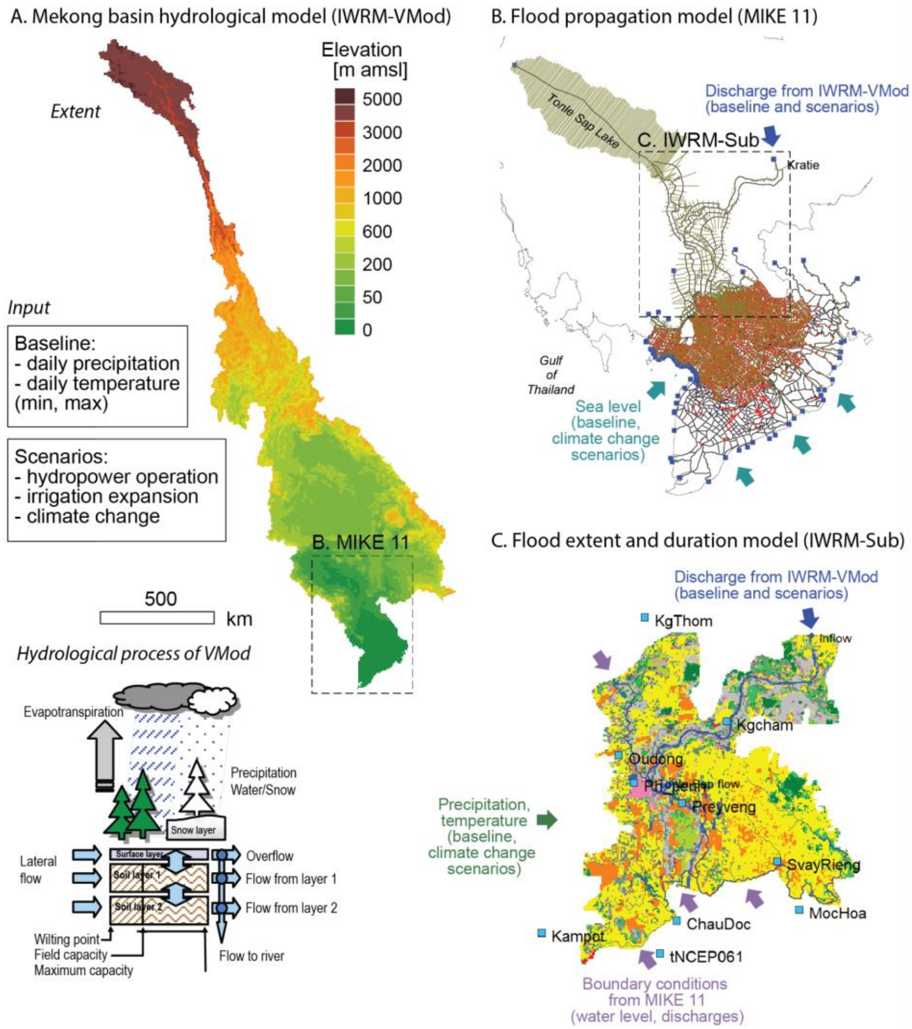

Fig. ~~We used an existing distributed hydrological – floodplain model combination, consisting of IWRM-VMod and the floodplain model IWRM-Sub (MRC, 2018a). Constructed for the MRC's Council Study by Jorma Koponen and his team, the models are based on the SRTM 90-m topographical map (Jarvis et al., 2008), soil types map (FAO, 2003), and land use map (GLC2000, 2003), all aggregated to 1 km × 1 km resolution. The daily meteorological and hydrological data for the period 1985–2008, geospatial data, and river cross-section data were retrieved from the Mekong River Commission (MRC). The satellite images of Landsat 5 were used to generate the flood extent maps based on a sophisticated water detection algorithm developed and optimized for the Lower Mekong region (Donchyts et al., 2016). The additional boundary conditions of Mekong River inflow at Kratie and Tonle Sap Great Lake were obtained from the MRC Decision Support Framework model comprising of the Soil and Water~~

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~~Assessment Tool (SWAT) and Integrated Quantity and Quality Model (IQQM). For the initial condition of the floodplain hydrodynamic model, flood points (water level) generated from the hydrodynamic model (ISIS) were also obtained from MRC. All model inputs and their brief description are presented in **Table 1**.~~

2. Schematic illustration of the modelling setup. A: Mekong basin hydrological model IWRM-VMod models the hydrology of the entire Mekong basin with 5 km x 5 km resolution (Hoang et al 2019). B: Flood propagation model MIKE 11 models the hydrodynamics of the entire Mekong floodplain using the discharges from IWRM-VMod and sea level in South China Sea as boundary conditions (Triet et al, 2017). C: Flood extent and duration model IWRM-Sub is a detailed 2D floodplain model using the output from two other models as an input.

Flood extent maps for calibration and validation were derived from Landsat images using a sophisticated water detection algorithm developed and optimized for the Lower Mekong region (Donchyts et al., 2016). All IWRM-Sub model inputs and their brief description are presented in Table 1, while input data for IWRM-VMod is detailed in Hoang et al (2019) and MIKE 11 in Triet et al. (2020).

Table 1. List and brief description of datasets for IWRM-Sub.

No.	Data type	Period	Resolution	Source
1	Topography (digital elevation model)	–	90 m	Shuttle Radar Topography Mission 2000
2	Land use map	2003	1 km	Global Land Cover 2000
3	Soil types map	2003	1 km	Food and Agriculture Organization
4	Meteorological data ~~•~~• Temperature ~~•~~• Rainfall	~~1985–2008~~1971–2000	Daily	~~Mekong River Commission~~Ensemble of 5 GCMs (ACCESS, CCSM, CSIRO, HadGEM2, and MPI)
5	~~Hydrological~~Historical discharge data ~~• Discharge~~ ~~• Inflow~~ ~~• Floodpoints~~	1985–~~2008~~2000	Daily	Mekong River Commission
6	~~Geospatial~~Historical water level data	~~–~~1985–2000	~~–~~Daily	Mekong River Commission
7	Hydropower dams and irrigation	–	–	Mekong River Commission
8	Climate change ~~(mean warmer & seasonal)~~projections of	~~1985–2008~~2036–2065	Daily	~~Mekong River Commission~~Ensemble of 5 GCMs (ACCESS, CCSM, CSIRO, HadGEM2, and MPI)

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	temperature and precipitation.			
9	Flood extent maps (satellite image)	1985–2008	30 m	SERVIR-Mekong
10	River cross-section	–	–	Mekong River Commission

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2.3. Modelling methodology

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We adapted and applied the existing IWRM-VMod (Hoang et al., 2019), MIKE11 (Triet et al., 2017), and IWRM-Sub (MRC, 2018a) models to assess the smaller scale cumulative impacts of future development plans and climate change on the Cambodian Mekong floodplain~~ (Hoang et al., 2019; ICEM and Alluvium, 2018; MRC, 2018a; Räsänen et al., 2012). Here we attempt to enhance~~. Here we enhanced the reliability of these existing models, particularly in the Cambodian Mekong floodplain, by advancing the predictive accuracy of the hydrology (recalibration), accounting for multiple calibration stations (four stations), and validating flood extents against satellite imagery~~;~~, as described below.

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Our initial model setup describes the current state of the floodplain for the historic baseline period of ~~1985–2008~~1971–2000, which we further calibrated and validated against observations of water discharge and water level taken at Kratie, Kampong Cham, ~~Chruy~~Chroy Changvar, and Neak Loeung hydrological stations (see locations in Fig. 1). The model performance was systematically quantified and evaluated based upon~~:~~ the Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), ratio of the root mean square error to the standard deviation of observed data (RSR), and coefficient of determination (R^2). ~~For the range adopted for performance rating see ASABE (2017).~~

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The use of 1971-2000 as our baseline represents well the hydrological state of the basin before major alterations were introduced (Soukhaphon et al., 2021). Including years after 2000 in our baseline would introduce significant hydrological and irrigation influences that would prohibit a thorough examination of these in isolation as part of our simulations.

Flood extent maps generated from the IWRM-Sub model were validated for the same period against satellite-based flood extent maps generated by the Surface Water Mapping Tool (SWMT). The SWMT is a Google Appspot based online application developed by Donchyts et al. (2016). A stack of Landsat (4 and 5) data were generated using SWMT from 1984 - 2000.

This stack of images was then used to generate a water index map using the Modified Normalized Difference Water Index (MNDWI) (Xu, 2006) to distinguish between water and non-water areas, which were then adjusted to account for dark vegetation and hill shadows using a Height Above Nearest Drainage (HAND) map (Rennó et al., 2008). Fig. ~~; see below for more information). To evaluate the model performance for flood inundation maps, we applied three indices: hit ratio (HR), true ratio (TR), and the normalized error (NE). HR evaluates how much of the flood derived from remote sensing images are identified by the simulation. TR evaluates how much of the simulated extent agrees with the remote sensing. NE evaluates the relative errors in the total area of flood extents. If both estimations overlap the area perfectly, both TR and HR become 1 and NE becomes 0~~S1 illustrates all procedures of the Surface Water Mapping Tool.

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To evaluate the model performance for flood inundation maps, we applied three indices: Recall, Precision, and the ratio between simulated and observed flood extent areas. Recall evaluates what proportion (0-1) of the flood derived from remote sensing images are identified by the simulation. Precision evaluates what proportion of the simulated extent agrees with the remote sensing data. If the simulated extent overlaps the observed extent area perfectly, recall, precision, and the ratio of extents become 1.

Once the IWRM-Sub model was successfully calibrated and validated, we modulated the inflow at Kratie and ~~Chruy Changvar stations~~at the confluence of the Tonle Sap River with the main Mekong channel to represent the upstream impacts of ~~various~~multiple development and climate change scenarios (see Section 2.4). We then simulated the Cambodian Mekong floodplain's hydrological and flood conditions (flood extent, flood depth, and flood duration) for each scenario. ~~The overall methodological framework adopted in this study is depicted in **Fig. S1**.~~

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~~For each time step, the Cambodian Mekong floodplain model (combination of IWRM-VMod and IWRM-Sub models) first interpolates meteorological data for each grid cell from observation point data using a height correction factor where required (ICEM and Alluvium, 2018). In addition, initial and boundary conditions (flood points and inflow) were incorporated into the model structure. To produce an initial flood extent map, we extracted flood points (water level) from the ISIS model.~~

~~The Surface Water Mapping Tool (SWMT) is a Google Appspot based online application developed by Donchyts et al. (2016) with the full support by the SERVIR-Mekong~~

~~project for the Mekong River Basin. A stack of Landsat 8 (also including 4, 5, and 7) data was generated using SWMT from the present period back to 1984. From this stack of images, two percentile maps were calculated, which represent two different situations: a permanent situation of the higher percentile (default value of 40) and a temporary situation of the lower percentile (default value of 8). Xu (2006) used the Modified Normalized Difference Water Index (MNDWI) to quantify the water index map from these percentile maps. Several spectral bands from the Landsat satellites were combined using the MNDWI, which are sensitive to the occurrence of water. Then the water and non-water areas can be classified from the threshold value applied to each pixel level. To improve the results, some corrections were performed to minimize errors associated with falsely classified water over dark vegetation and (hill) shadows. Dark vegetation is masked out using the Normalized Difference Vegetation Index (NDVI) and hill shadows are masked out using a Height Above Nearest Drainage (HAND) map (Rennó et al., 2008), derived from the Multi-Error-Removed Improved-Terrain (MERIT) Digital Elevation Model (DEM) (Yamazaki et al., 2017).~~ ~~**Fig. S2**~~ ~~illustrates all procedures of the Surface Water Mapping Tool.~~

2.4. Analytical scenario descriptions

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~~The scenario setups of this study are almost identical to scenarios from the MRC's Council Study consisting of three main water resource development scenarios. The baseline conditions represent year 2007 situation (BASE scenario). The medium-term development scenario is for the definite future of 2020 (Def2020). The long-term development scenario is for the planned development in 2040 (Pla2040). On top of these, there are three other sub-scenario setups, which are variations of the 2040 planned development (~~~~**Table**~~ The scenario setup that we adopted for our study is the same as that described in Hoang et al. (2019). The baseline (1971-2000) represents the Mekong basin at a time before significant alterations to the hydrological functioning of the catchment have occurred through infrastructural development. We then defined 11 development scenarios that cover each of the three main drivers of hydrological change in isolation (hydropower, irrigation, and climate change), as well as combinations of these together. For future scenarios, we used climate data from an ensemble of five GCMs (ACCESS, CCSM, CSIRO, HadGEM2, and MPI) for the years 2036-2065, and considered representative concentration pathway (RCP) levels 4.5 and 8.5. Our hydropower development scenario includes 126 dams on both mainstreams (N= 16) and tributaries (N= 110) of the Mekong, equivalent to a total active storage of 108 km^3, all of which are planned to be active between 2036 and 2065. We included two irrigation scenarios, a high and low expansion version, using the global projected irrigation expansion scenarios by Fischer et al. (2007) applied to the baseline irrigation extent taken from the MIRCA - ‘Global Dataset of Monthly Irrigated and Rain-fed Crop Areas around the Year 2000’ (Portmann et al., 2010). A list of scenarios and their notation are presented in Table 2, and a thorough description and justification for these scenarios can be found in Hoang et al. (2019).

Table 2. Summary of scenario names, driving climate data, and development inclusion descriptions.

~~2). **Fig. S3** shows the overall list of employed hydropower dams within the Mekong basin (MRC, 2019). The hydropower development scenario consists of 126 dams on both mainstreams (16) and tributaries (110), according to the compiled database from ADB (2004) and the Mekong River Commission (MRC, 2009). Further information related to these hydropower dams' characteristics and names can be found in MRC (2016, 2018b).~~

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~~The BASE scenario includes 2007 LMB tributary and China mainstream hydropower dams (Manwan and Dachaoshan only), agricultural land use, irrigation schemes, water navigation, flood protection, as well as domestic and industrial water use. It represents the baseline conditions in the LMB used to compare against all other scenarios. The Pla2020 scenario (medium-term development) includes 2020 LMB tributary, LMB mainstream (Xayaburi and Don Sahong only) and China mainstream hydropower projects (11 dams), agricultural land use, irrigation schemes, water navigation, flood protection, as well as domestic and industrial water use. The Pla2040 scenario (long-term development) consists of LMB tributary, LMB mainstream (11 dams) and China mainstream hydropower projects (12 dams), as well as the aforementioned agricultural land use, etc. The Pla2040CC is the same development setup as Pla2040, but with climate change incorporated into the projection (IPSL-CM5A-MR under RCP4.5). Based on the IPCC's approach, the GCM selected for this study under the medium emission scenario represents the range of uncertainty inherent in the GCM climate change projections for the LMB (MRC, 2017), as it is characterized by an increased seasonal variability (wetter wet and drier dry seasons),and covers the monsoon seasonality (Her et al., 2019). There are then two additional sub-scenarios adapted from Pla2040; the Pla2040NoHPP scenario (2040 plans, LMB tributary and Chinese mainstream dams, but without LMB mainstream dams) and the Pla2040MiHPP scenario (2040 plans, mitigation measures and joint operation of key dams) (MRC, 2019). The mitigation measures and joint operation of key dams denote a good coordination among all mainstream hydropower dams; their operation is equipped with measures for navigation lock, fish passage, sediment flushing, environmental flow, and water quality maintenance (MRC, 2020). For more information related to hydropower development and irrigation scenarios see Hoang et al. (2019).~~

~~**Table 2.** Summary of scenario considerations.~~

Scenario name	~~Level of development for water-related sectors*~~Scenario description			~~Climate~~	~~Floodplain settlement~~					
	~~ALU~~Climate data	~~DIW~~Hydropower	~~FPF~~Irrigation	~~HPP~~	~~IRR~~	~~NAV~~				
~~BASE~~S1_Baseline	Baseline (1971 - 2000)	~~2007~~Circa 2000	~~2007~~Circa 2000	~~2007~~	~~2007~~	~~2007~~	~~2007~~	~~1985 – 2008~~	~~2007~~	
~~Def2020~~S2_Hydropower	~~Definite future scenario 2020~~Baseline (1971 - 2000)	~~2020~~Future development	~~2020~~Circa 2000	~~2020~~	~~2020~~	~~2020~~	~~2020~~	~~1985 – 2008~~	~~2020~~	
S3_Irrigation_High	Baseline (1971 - 2000)	Circa 2000	HIGH irrigation expansion							
S4_Irrigation_Low	Baseline (1971 - 2000)	Circa 2000	LOW irrigation expansion							
S5_CC_RCP45	Future (2036 - 2065) RCP 4.5	Circa 2000	Circa 2000							
S6_CC_RCP85	Future (2036 - 2065) RCP 8.5	Circa 2000	Circa 2000							
~~Pla2040~~S7_HP_RCP45	Future (2036 - 2065) RCP 4.5	~~Planned~~Future development ~~scenario 2040, no climate change~~	~~2040~~Circa 2000	~~2040~~	~~2040~~	~~2040~~	~~2040~~	~~2040~~	~~1985 – 2008~~	~~2040~~
~~Pla2040CC~~S8_HP_RCP85	Future (2036 - 2065) RCP 8.5	~~Planned~~Future development ~~scenario 2040 with~~	~~2040~~Circa 2000	~~2040~~	~~2040~~	~~2040~~	~~2040~~	~~2040~~	~~Mean warmer &~~	~~2040~~

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		~~climate change~~							~~wetter~~	
~~Pla2040NoHPP~~S9_LI_HP_RCP45	Future (2036 - 2065) RCP 4.5	~~Planned~~Future development ~~2040 without mainstream HPP~~	~~2040~~LOW irrigation expansion	~~2040~~	~~2040~~	~~Only tributary 2040~~	~~2040~~	~~2040~~	~~1985–2008~~	~~2040~~
~~Pla2040MiHPP~~S10_LI_HP_RCP85	Future (2036 - 2065) RCP 8.5	~~Planned~~Future development ~~2040 with HPP mitigation investments~~	~~2040~~LOW irrigation expansion	~~2040~~	~~2040~~	~~2040~~	~~2040~~	~~2040~~	~~1985–2008~~	~~2040~~
S11_HI_HP_RCP45	Future (2036 - 2065) RCP 4.5	Future development	HIGH irrigation expansion							
S12_HI_HP_RCP85	Future (2036 - 2065) RCP 8.5	Future development	HIGH irrigation expansion							

~~*ALU = Agriculture/Land use change; DIW = Domestic and Industrial Water Use; FPF = Flood Protection Infrastructure; HPP = Hydropower; IRR = Irrigation; and NAV = Navigation~~

3. Results

3.1. Predictive accuracy of the models

The Mekong basin wide IWRM-VMod hydrological model was calibrated and validated against discharges in various stations, with very good performance: validation period NSE at Nakhon Phanom station of 0.74, and at Stung Treng station of 0.64 (Hoang et al., 2019). MIKE 11 model application to the entire Mekong delta was, in turn, validated against two flood events in 2000 and 2011 in Triet et al (2017) also with good correspondence to the observations achieving NSE to observed water levels of between 0.72 and 0.97 across 19 different gauging stations.

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Here we validated the IWRM-Sub model for Cambodian Mekong floodplain against water levels and discharge in four stations and flood extent based on Landsat imagery (see Methods). Based on the validation measures (Table 3), a good model performance is obtained at all stations (both water discharge and water level) with the values of NSE between 0.~~62~~69 and 0.~~96~~87, PBIAS between ~~–3.68~~14.4% and +~~20.66~~9.8%, RSR between 0.~~19~~37 and 0.~~45~~55, and R^2 between 0.89 and 0.~~97~~93. It should be noted that the statistical model performance with NSE and R^2 greater than 0.5, PBIAS between ±25%, and RSR less than 0.7 is indicated as decision guidelines for hydrologic model studies ~~(Benaman et al., 2005; Setegn et al., 2010).~~(Benaman et al., 2005; Setegn et al., 2010). A time series comparison between the simulated and observed water discharge and water level (1985–~~2008~~2000) at four hydrological stations can be found in Fig. ~~**S4**~~S2 and Fig. S3. It is apparent that the simulated water discharge among these stations is well in line with the observed data throughout the ~~24-year study period; however, three stations, namely Kampong Cham, Chruy Changvar, and Neak Loeung overestimate the peak water discharge and water level. The model consistently overestimates the medium and high water discharges at Neak Loeung station, and the overall predictive accuracy at this station is also lower than at the other three stations (**Table 3**). This could be due to the complex flow system between the Mekong and Tonle Sap River which cannot be fully captured by the model, especially for stations in the Lower Mekong River downstream of the Phnom Penh junction~~15-year hydrological record available for comparison.

Results of the flood extent ~~map from the Cambodian floodplain~~comparison between IWRM-Sub model and SWMT ~~(Landsat 5)~~ observations over the time horizon 1985–~~2008~~2000 show equally a ~~very~~ good agreement. ~~However, the~~The model ~~does overestimate~~underestimates the total flooded area by ~~about 14%, with the~~ just 0.1% as the ratio of simulated to observed flooded extent areas is 0.99. However, the overlapping flooded area ~~being about 11,640 km² (73% of the IWRM-Sub model area and 84~~only constituted 71% of the ~~SWMT area~~observed (SWMT) extent (which constitutes the recall), and 72% of the simulated (IWRM-sub) extent (which is the precision) (Fig. ~~**2**). The overestimation could~~3). Part of this discrepancy may be ~~attributed to the use of a large spatial resolution~~accounted for by the ~~model (1 km × 1 km) while the satellite data is at a 30-m spatial resolution. Moreover, a lot of scattering~~inclusion of rivers and lakes in the ~~flood~~ extent ~~is noticeable from~~of the simulation, yet not in the ~~generated satellite image. Nevertheless, both results look very promising as indicated by the three evaluation indices (HR = 0.84, TR = 0.73, and NE = 0.14).~~SWMT derived extents.

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Table 3. Statistical model performance at four hydrological stations (1985–~~2008). See station locations in **Fig. 1.**~~ 2000). See station locations in Fig. 1. Note: the statistical model performance with Nash Sutcliffe Efficiency (NSE) and the coefficient of determination (R^2) greater than 0.5, percentage bias (PBIAS) between ±25%, and the ratio of the root mean square error to the standard deviation (RSR) less than 0.7 is indicated as decision guidelines for hydrologic model studies (Benaman et al., 2005; Setegn et al., 2010).

Station	Water discharge				Water level			
	NSE	PBIAS (%)	RSR	R^2	NSE	PBIAS (%)	RSR	R^2
Kratie	0.~~96~~79	~~8.37~~0.9	0.~~19~~45	0.~~97~~89	0.~~96~~69	–~~3.68~~14.4	0.~~20~~55	0.~~97~~93
Kampong Cham	0.~~96~~80	4.5~~.70~~	0.~~19~~45	0.~~97~~90	0.~~92~~87	~~0.02~~-1.4	0.~~28~~37	0.~~92~~93
~~Chruy~~Chroy Changvar	0.~~88~~80	~~20.66~~9.8	0.~~34~~45	0.~~93~~91	0.~~92~~86	~~0.32~~-3.4	0.~~31~~37	0.~~92~~93
Neak Loeung	0.~~62~~81	~~19.38~~-5.6	0.~~45~~44	0.~~89~~91	0.85	~~10.23~~3.8	0.~~34~~38	0.~~91~~93

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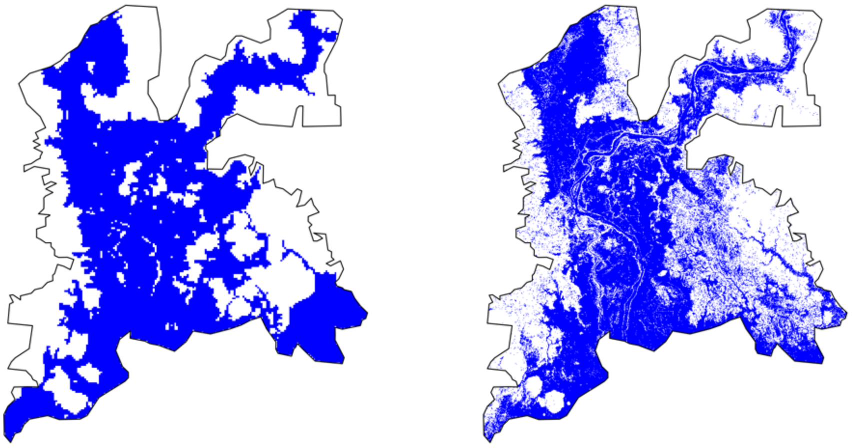

(a) simuluated flood extent

(b) satellite-based flood extent

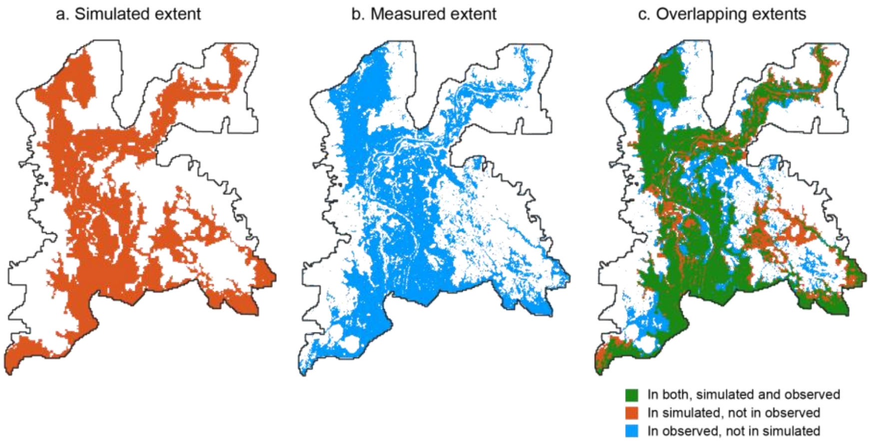

Fig. ~~2~~3. Comparison of maximum flood extent ~~resulted~~resulting from the model and measured from satellite images.

3.2. Impacts on hydrological conditions

Having run the model for each of the development scenarios (~~BASE, Pla2020, Pla2040, Pla2040CC, Pla2040NoHPP, Pla2040MiHPP~~S1-S12; see Table 2), we obtained the corresponding daily time series of water discharge and water level at each station~~,~~ and compared them with the baseline scenario ~~(Fig. S5)~~. We then calculated the ~~flow duration~~

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~~curves for each scenario at each station (**Fig. S6**), and the~~ mean monthly water discharge and water level across the study period~~ (.*Fig.* S7).~~ Finally, we computed the percentage change in mean monthly water discharge and water level for each scenario at each station~~ (~~. The results at Kratie, Kampong Cham, and Chroy Changvar were virtually indistinguishable from one another, so to avoid unnecessary repetition, we have presented results from only Kampong Cham (as the midway station) and Neak Loeung, which differs significantly from the other stations for being downstream of the Tonle Sap River confluence (Fig. 1), and the Bassac River distributary (Fig. 4~~Fig. 3~~).

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All scenarios that contain an element of hydropower development follow the same ~~generic~~ pattern of increasing both water discharge and water level during the dry season (Nov–~~Apr~~May), whilst reducing water discharge and water level during the early and mid- wet season (~~May–Aug~~Jun–Sep) (Fig. 4). The ~~late wet season (Sep–Oct)~~impact of climate change appears to fluctuate during the months of January to June between Kampong Cham (and Kratie and Chruy Changvar) and Neak Loeung, as there is ~~characterized by~~ a ~~mixed pattern of changes (increasing and decreasing). The degree of alteration to these hydrological indicators is most pronounced~~ slight increase in discharge and water levels at the upstream ~~area of Kratie station and diminishes~~ stations, yet a slight decrease at the downstream ~~towards Neak Loeung~~ station~~. February and March display~~, though the ~~highest~~ magnitude of ~~alterations to the wet season water~~any alteration is only small. From July to December, however, the climate change impact is much stronger and increases discharge and water ~~level increases, while June displays~~levels at all stations. The larger magnitude of the climate change impacts during the wetter months counteracts the impact of hydropower and irrigation (which slightly reduces flows and water levels in all months), which can be seen in the difference between scenario S2 (hydropower solo) and scenarios S7-S12 that incorporate multiple drivers (Fig. 4; scenario description in Table 2). This is most evident at Kampong Cham station in October, where climate change impacts are large enough to offset hydropower impacts, so that only those scenarios that incorporate the additional impact of irrigation are strong enough to reduce flows and water levels. Whilst the largest ~~decrease in~~ magnitude impacts are in the wetter months of July to September, the proportional impacts are far larger in the dry season~~ flows and water levels~~, where the impact of hydropower development dominate the flow regime and increase water levels up to 150% in April at Kampong Cham, compared to a maximum decrease of <25% in July.

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Comparing results from upstream stations with those at Neak Loeung, we see that the magnitude of climate change impacts are larger downstream both absolutely and proportionally. This is evident in the greater differences between the solo hydropower scenario (S2) and the combined hydropower and climate change scenarios (S7-S12) here than observed at the upstream stations. Nevertheless, hydropower impacts still dominate the flow regime, especially during the drier months where discharges increase >100% in April.

Our results suggest that planned hydropower developments will drastically alter the hydrology of the Mekong main channel and far outweigh the effects of irrigation or climate change impacts in either counteracting or enhancing these alterations.

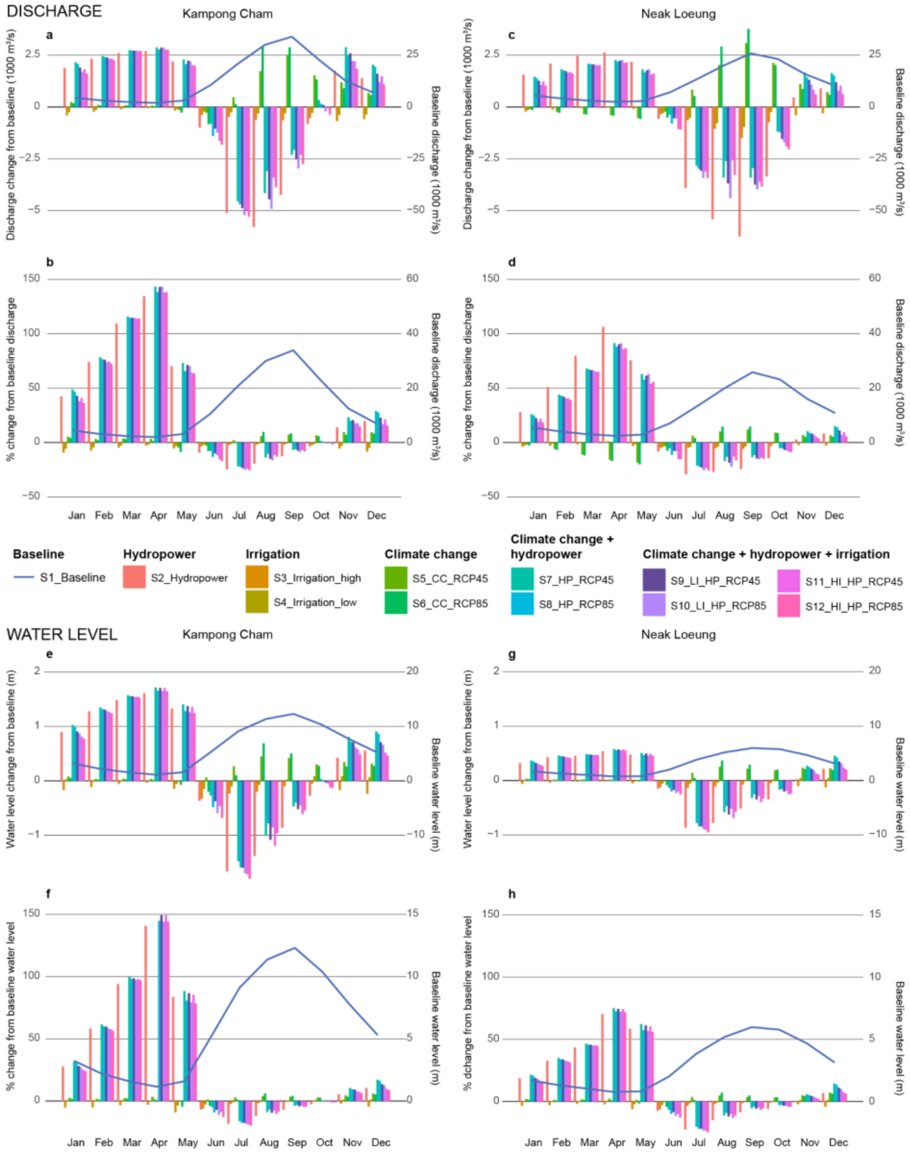

Fig. ~~Comparing scenarios Pla2020 and Pla2040 illustrates the incremental impact of future planned developments throughout the Mekong independently of climate variability, as the same climate data was used for both scenarios. Across all four stations, and throughout the years, the proportional impact of Pla2040 is significantly larger than for Pla2020, especially in the wet and early dry season months (May-Dec). This demonstrates that the planned~~

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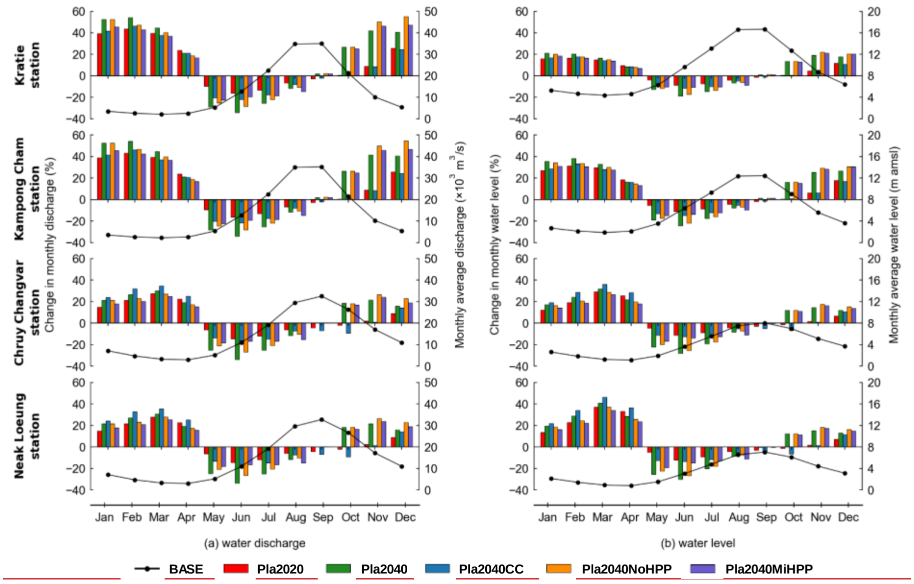
~~development for the 2020–2040 period will severely impact the hydrological functioning of the Mekong main channel, raising the dry season flows and reducing the wet season flows to slightly homogenise the river's hydrograph. The expected mean dry season flows increase by up to +50% (in January and February) at upstream stations, and reduce wet season flows by more than −30% (in June) at all stations. The incorporation of climate change into the Pla2040CC scenario reverses the magnitude of these developmental impacts between May and December, as the warmer dry season months and wetter wet season months compensate for the anthropogenic flow alterations. Between January and April, the climate change impact is less consistent, showing opposing trends at Kratie and Kampong Cham (upstream stations) compared to Chruy Changvar and Neak Loeung (downstream stations). Though this may in part be due to model overestimation at downstream stations (**Fig. S4**).~~

~~Of all the scenarios, Pla2040NoHPP shows the largest proportional changes at the onset of the dry season (Nov–Dec), slightly intensifying the proportional impact of developments compared to Pla2040. However, for the rest of the months (during Jan–Oct) both Pla2040NoHPP and to a greater extent Pla2040MiHPP show a reduction in the proportional change in both water discharge and water level compared to Pla2040. The difference between the changes shown in Pla2040 compared to Pla2040NoHPP can be interpreted as the impact of developing mainstream dams in isolation; and comparing Pla2040MiHPP with Pla2040 shows the impact of mitigation measures in isolation. Our results suggest that development that excludes mainstream dams with the incorporation of mitigation investments would be the most sustainable in terms of minimising hydrological alterations, which will be aided in this respect by the influence of climate change.~~



~~**Fig. 3**~~4. *Changes in monthly water discharge and water level at* ~~four monitoring stations; the black~~*Kampong Cham (left hand side) and Neak Loeung (right hand side); the blue line* ~~with markers~~ *indicates the baseline monthly* ~~water~~ *discharge and water level*~~;~~*, and the colour bar* ~~chart indicates~~*charts indicate both the magnitude (a, c,e,g) and the percentage (b, d, f, h) change under different scenarios in comparison with the baseline (*~~1985–2008).~~*1971–2000). (See location of stations in Fig. 1).*

3.3. Impacts on flood conditions

Here we present the quantitative results together with the spatial analysis of flood conditions throughout the entire study area. The comparisons between each scenario and their justifications are described in the analysis at the provincial level because of the similarity in patterns. Under the baseline scenario (~~BASE~~S1), the modelling results between ~~1985~~1971 and ~~2008~~2000 show that the ~~total~~yearly flooded area ranges from ~~5,611~~7,785 to ~~12,634~~11,525 km^2. Its mean annual value is estimated at 9,~~477~~370 km^2, about 34% of the whole study area.

~~The impact of planned development up until 2020 (Pla2020 scenario) is to reduce the total flooded area from the baseline period in all years, with an average reduction of −6.3% (**Fig. 4**). This reduction is exacerbated by the planned development of 2020–2040 (Pla2040) further reducing the total flooded area to an average of −7.9% compared to the baseline period. However, the inclusion of climate change in the Pla2040 scenario (Pla2040CC) counteracts the anthropogenic impact so that years that see reductions are lessened (mean = −5.3%), and some years see substantial increases in the total flooded area (mean = +13.8%), with the average~~

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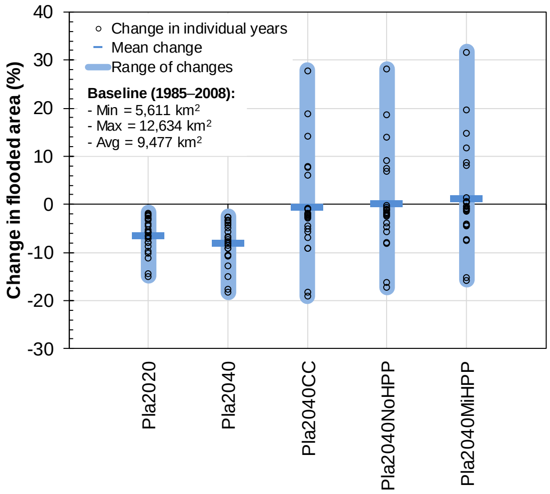
~~reduction across the entire study period being just −0.5% (**Fig. 4**). We see a similar pattern for development scenarios that exclude the mainstream dams without accounting for climate change (Pla2040NoHPP), and include mitigation measures without accounting for climate change (Pla2040MiHPP), where the years that see reductions in the total flooded area are less reduced (means of −4.3% and −4.6% respectively), and some years see substantial increases (means of +14.1% and +9.8% respectively) with average changes in total flooded area of +0.3% and +1.4% compared to the baseline period. If the impact of the mitigation measures incorporated into the development scenario of Pla2040MiHPP were to combine with the impact of climate change evident in scenario Pla2040CC, then the total flooded area might be expected to increase more substantially.~~



We compared year to year the impact of each development scenario against the S1_baseline (1971-2000) on the total flooded area across the study area (Fig. 5). Scenarios S2-S4 use the same driving climate data as the baseline scenario (S1), and so the variability in the impact shown is significantly reduced to produce consistent impacts for all years. Whereas scenarios S5-S12 are driven by future climate data projections, so that the variability in comparing year to year is significant. Nevertheless, there is a clear pattern that emerges once again showing the dominance of hydropower development in significantly reducing the yearly flooded area. The impacts of both irrigation development scenarios (S3 and S4) also reduce the yearly flooded area, though to a lesser extent. Climate change impacts in isolation (S5 and S6) increase the flooded area overall, though there are some years in which the area is reduced compared to the baseline. The proportional magnitude of these effects is most evident in the solo hydropower development with a median reduction of >20% year on year, yet the combined impact of irrigation, hydropower, and climate change did reduce flooded areas by up to 40% in some years (Fig. 5).

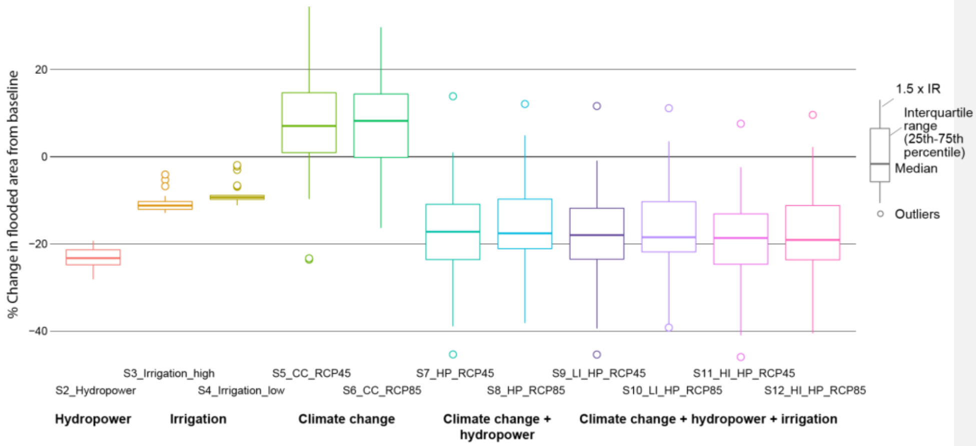


Fig. ~~4~~*5. Changes in total flooded area* ~~over~~*compared to the baseline period* ~~1985–2008~~*1971–2000; the graph shows the range of changes due to interannual variation (*~~rounded vertical bar~~*box and whiskers), the* ~~value for mean~~*median change (horizontal line) and* ~~the values for change in individual~~*outliers that were exceptional years (circles).*

The spatial distribution of flood inundation and depth across the Cambodian Mekong floodplain varies greatly between scenarios of planned developments and climate change (Fig. ~~5 and Fig. S8~~6). The floodplain is characterized spatially by a high fluctuation of flood depth and flood duration alteration of over ±~~50% in all scenarios (Pla2020, Pla2040, Pla2040CC, Pla2040NoHPP, and Pla2040MiHPP), especially in the Southeast and the Southwest. Whilst the magnitude of these fluctuations is large across all scenarios, it is most evident in scenarios Pla2020 and Pla2040, and less so in scenarios Pla2040CC, Pla2040NoHPP, and Pla2040MiHPP. Outside the hotspot areas (Southeast and the Southwest), the flood depth alteration varies between −20% and 0% under scenarios Pla2020 and Pla2040, and between −10% and +50% under scenarios Pla2040CC, Pla2040NoHPP, and Pla2040MiHPP. Our results suggest that hydropower dams would lower the flood depth, but the effect of climate change under wetter conditions would cause an increase in most areas which are currently prone to flooding. In addition, the planned developments under Pla2020 and Pla2040 would likely~~

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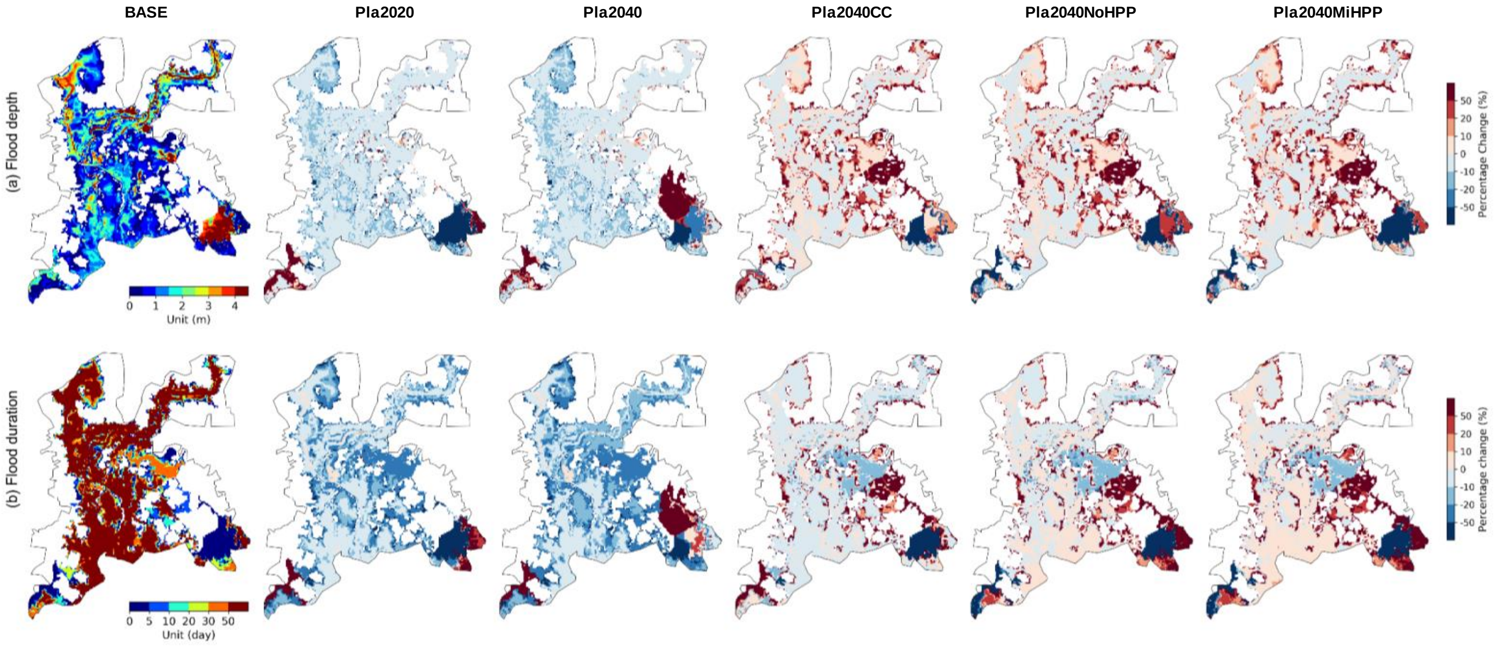
~~reduce the flood duration between 10% and 20% in most areas, which might be seen as a benefit for flood protection measures in the region. By contrast, the scenarios Pla2040CC, Pla2040NoHPP and Pla2040MiHPP show a slight shift in the flood duration either increasing or decreasing by 10% across the majority of the study area, mainly in the low-lying areas along the Mekong River and its main tributaries. In summary, the planned developments of 2020–2040 will reduce both the flood depth and duration across most of the floodplain, whilst the exclusion of mainstream dams, mitigation measures and climate change will have the opposite effect of increasing flood depths and durations, though these impacts are spatially heterogenic and highly variable~~100% in almost all scenarios, especially in the Southeast and the Southwest part of the study area. Whilst the magnitude of these fluctuations is large across all scenarios, it is most evident in hydropower (S2) (reductions of depth and duration) and climate change RCP 8.5 (S6) scenarios (increase in depth and duration). Though even in these most extreme cases, there are areas that run contrary to the general pattern of change, highlighting the hydrological complexity of the region. The low irrigation scenario (S4) has the least impact (Fig. 6), though even this level of development may significantly impact the lower lying regions in the southwest and southeast where much of the rice cultivation is concentrated. Our results suggest that all scenarios will cause heterogeneous impacts across the region that may effectively shift flood impacts from one area to another rather than completely dispel the associated risks.


BASE Pla2020 Pla2040 Pla2040CC Pla2040NoHPP Pla2040MiHPP

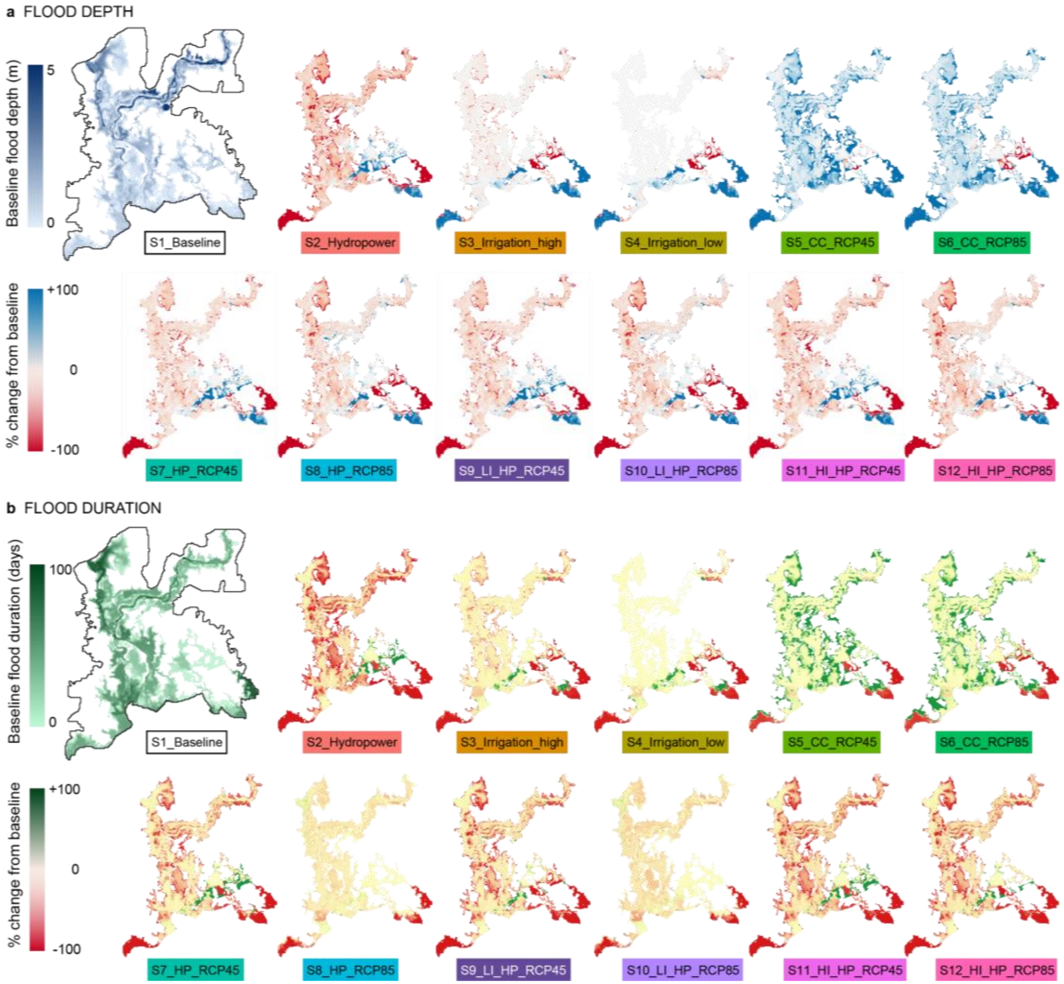

a FLOOD DEPTH
Baseline flood depth (m)
5
0
S1_Baseline
S2_Hydropower
S3_Irrigation_high
S4_Irrigation_low
S5_CC_RCP45
S6_CC_RCP85
% change from baseline
+100
0
-100
S7_HP_RCP45
S8_HP_RCP85
S9_LI_HP_RCP45
S10_LI_HP_RCP85
S11_HI_HP_RCP45
S12_HI_HP_RCP85
b FLOOD DURATION
Baseline flood duration (days)
100
0
S1_Baseline
S2_Hydropower
S3_Irrigation_high
S4_Irrigation_low
S5_CC_RCP45
S6_CC_RCP85
% change from baseline
+100
0
-100
S7_HP_RCP45
S8_HP_RCP85
S9_LI_HP_RCP45
S10_LI_HP_RCP85
S11_HI_HP_RCP45
S12_HI_HP_RCP85

***Fig.** ~~5~~6.* *Spatial distribution of changes in flood depth ~~(upper row)~~ and duration. a: food depth; b: flood duration ~~(lower row)~~. Results are shown over the baseline period ~~1985–2008~~1971-2000, and all scenarios~~.~~ (see description in **Table 2**).*

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3.4. Provincial level analysis

~~As the Cambodian Mekong floodplain covers only~~We examined the change in flooded area, flood depth and flood duration for 10 provinces that have a ~~little~~considerable part of their area within the study area (Kampong Speu and Kampot province, and Tay Ninh province ~~is~~ in Vietnam, ~~we did~~were not ~~present results for these regions. For the remaining 10 provinces, we examined the change in flooded area, flood depth and flood duration for each~~included; see Fig. 1). Each scenario was compared to the baseline period at the provincial level (Fig. ~~6). Here we present only the key results, with the detailed analysis being given in the Supplementary.~~7). Under the baseline scenario (~~BASE~~S1), the modelling results show that the average flooded area ranges from a minimum of ~~184~~188 km^2 in ~~Svay Rieng~~Phnom Penh province to a maximum of 2,~~251~~308 km^2 in Prey Veng province, which represents 43% of the provincial territory. Whilst the average flood depth ranges from ~~1.1~~0.54 m in Svay Rieng province to 2.4~~.9~~ m in Krâchéh (Kratie) province, and the average flood duration ranges from ~~6~~10 days in Svay Rieng province to ~~85~~79 days in Kâmpóng Chhnang province.

Except for the Svay Rieng region, which appears anomalous, Kâmpóng Chhnang and Krâchéh are least affected by the impacts of climate change, whilst Prey Veng and Takêv are most affected (Fig. 7). The development scenarios have least effect in ~~Kandal province. As a whole, Kampong Thom province receives the largest~~Prey Veng, where flood ~~protection benefit from the planned developments between 2020 and 2040, with reductions under the Pla2040 scenario of −10.5% for flooded area, −6.0% for flood depth, and −14.1% for~~ area and depths are almost unaffected in comparison to the other provinces.

Svay Rieng displays an extreme reduction in flood duration~~. Kampong Chhnang province receives the least benefit from such developments in terms of flooded area (only −3.1% under Pla2040) and flood~~ for all scenarios, including climate change scenarios, which is also true of the flooded area except for the RCP 4.5 climate impact scenario (S5). Depths, however, increase in all scenarios suggesting that flooding in this province is reduced in extent and duration ~~(only −4.3% under Pla2040), while Kampong Cham province receives the least benefit in terms of flood depths, only −2.5% under Pla2040.~~ to a shorter more intense (and so deep) flood event.

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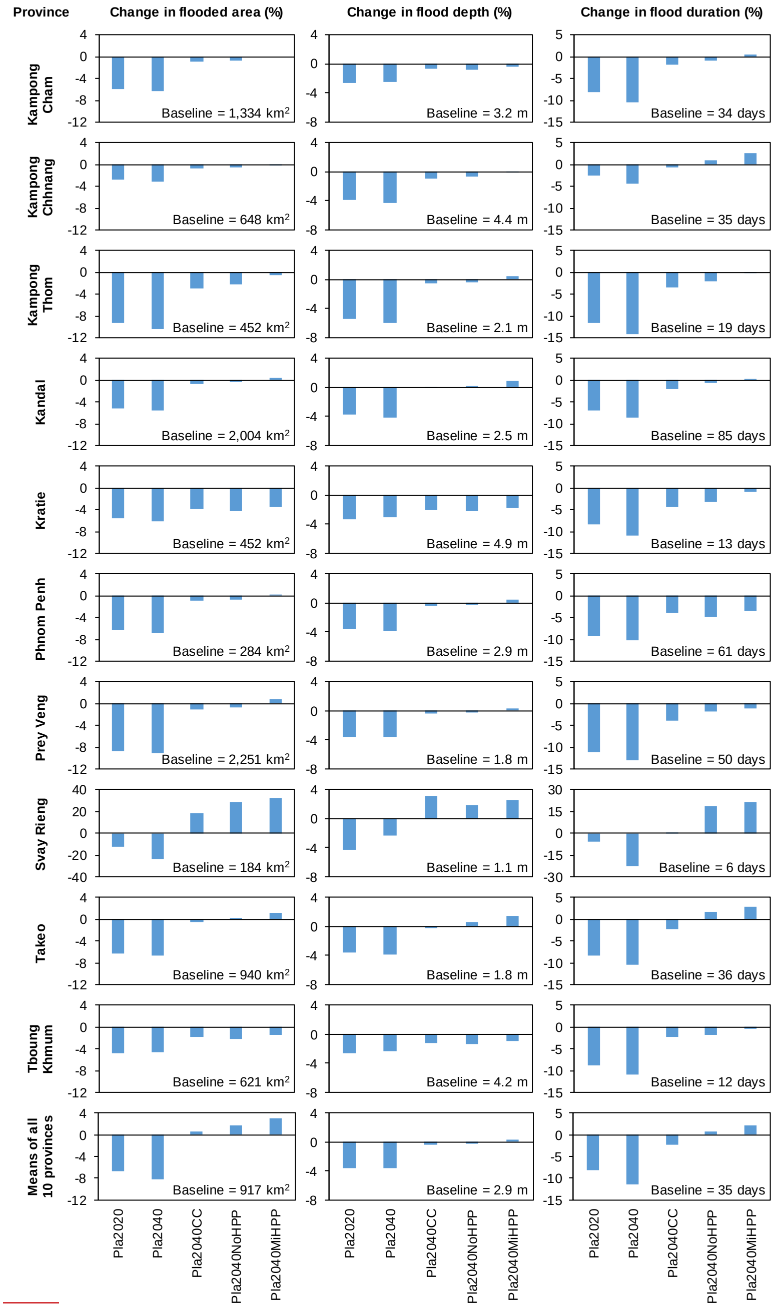
Province
Change in flooded area (%)
Change in flood depth (%)
Change in flood duration (%)
Kampong Cham
Baseline = 1,334 km^2
Baseline = 3.2 m
Baseline = 34 days
Kampong Chhnang
Baseline = 648 km^2
Baseline = 4.4 m
Baseline = 35 days
Kampong Thom
Baseline = 452 km^2
Baseline = 2.1 m
Baseline = 19 days
Kandal
Baseline = 2,004 km^2
Baseline = 2.5 m
Baseline = 85 days
Kratie
Baseline = 452 km^2
Baseline = 4.9 m
Baseline = 13 days
Phnom Penh
Baseline = 284 km^2
Baseline = 2.9 m
Baseline = 61 days
Prey Veng
Baseline = 2,251 km^2
Baseline = 1.8 m
Baseline = 50 days
Svay Rieng
Baseline = 184 km^2
Baseline = 1.1 m
Baseline = 6 days
Takeo
Baseline = 940 km^2
Baseline = 1.8 m
Baseline = 36 days
Tboung Khmum
Baseline = 621 km^2
Baseline = 4.2 m
Baseline = 12 days
Means of all 10 provinces
Baseline = 917 km^2
Baseline = 2.9 m
Baseline = 35 days
4
0
-4
-8
-12
5
-5
-10
-15
40
20
-20
-40
30
15
-30
Pla2020
Pla2040
Pla2040CC
Pla2040NoHPP
Pla2040MiHPP

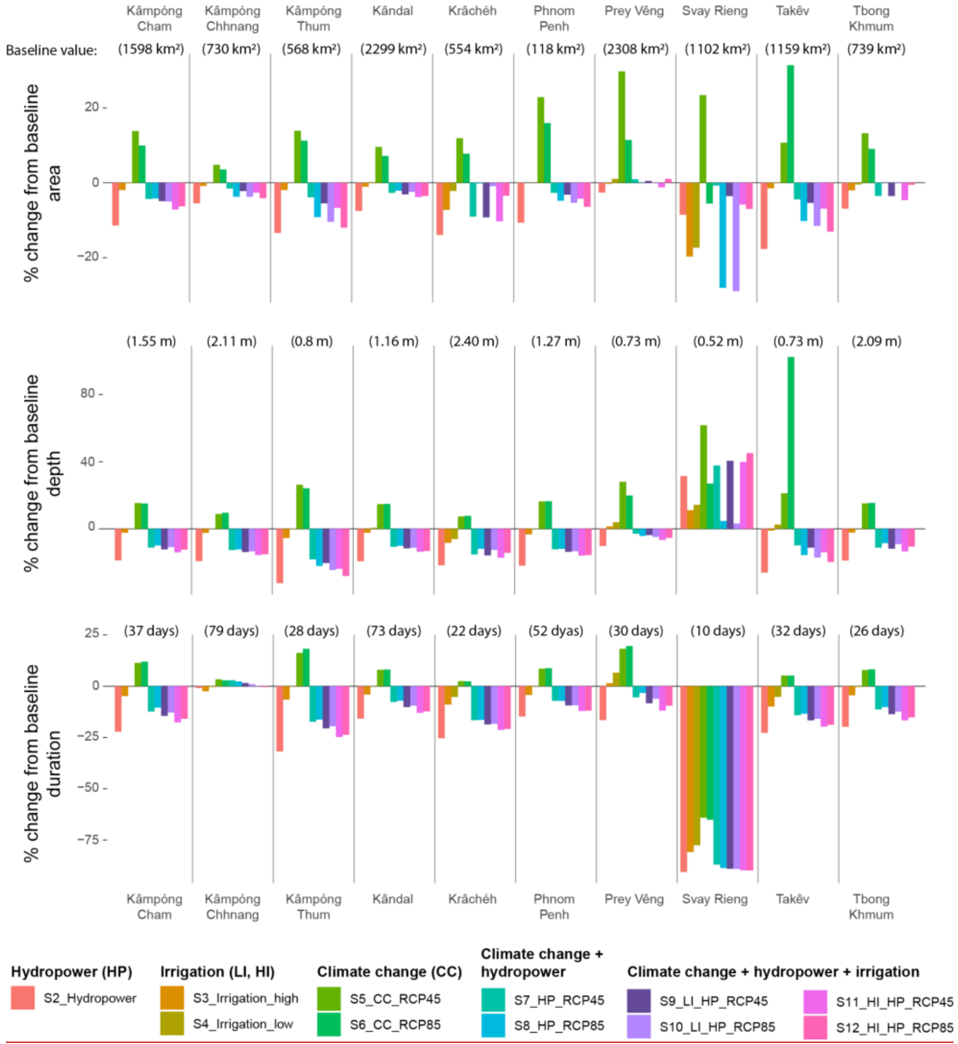

***Fig.* ~~6~~*7.* *Changes in annual mean flooded area, flood depth, and flood duration* ~~*over*~~*compared to the baseline period* ~~1985–2008~~*(1971–2000) for all scenarios at the provincial level.* ~~For Svay Rieng province, the scale of vertical axis is different from other provinces. For scenarios Pla2040CC, Pla2040NoHPP and Pla2040MiHPP, means of all 10 provinces are strongly controlled the large increases in Svay Rieng province.~~ *See province location in Fig. 1.*

4. Discussion

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4.1. Key findings

~~Our~~ The model performance metrics achieved by our hydrological simulation ~~accuracy~~ of water discharge and water level for the baseline period of ~~1985–2008~~1971–2000 at all four monitoring stations (Kratie, Kampong Cham, ~~Chruy~~Chroy Changvar and Neak Loeung) ~~exceeds~~exceed existing studies within the same region ~~(Hoang et al., 2016; Hoang et al., 2019; Västilä et al., 2010),~~(Hoang et al., 2016; Hoang et al., 2019; Västilä et al., 2010), with the ~~possible~~ exception of ~~Dang et al. (2018),~~Dang et al. (2018), who recorded an NSE value of 0.98 compared to our value of 0.~~92~~80 at Kampong Cham station. ~~Nevertheless, the relative success of our baseline simulations allows us to have great confidence in our future projections of hydrological responses within the bounds of error inherent within the GCM predations of future climate change.~~

Whilst there are ~~individual~~ studies of flood extent within our study ~~region~~ area that only focus on a single event rather than a multi-year analysis that slightly surpass our own in terms of ~~accuracy when focusing on a single event (Fujii et al., 2003),~~performance metrics (Fujii et al., 2003), our continual analysis of annual flood patterns comprising a ~~24~~30-year time horizon is comparable to, and often exceeds, ~~the accuracy of~~ other such multi-year analyses done in the region ~~(Try et al., 2020a; Try et al., 2020b). This conformation~~(Try et al., 2020a; Try et al., 2020b). The relative success of our ~~initial~~ baseline simulations ~~of flood extent again suggests that we might~~allows us to have a high degree of confidence in our future projections of the Cambodian Mekong floodplain's hydrological response to planned infrastructural development and future climate changes ~~in the flood hydrograph.~~

~~The~~. All future projections of ~~all of the~~ scenarios containing multiple drivers that we considered within our analysis~~,~~ followed the same generic pattern of alterations to both the expected ~~water~~ discharge and river water level, increasing during the dry season (Nov–~~Apr~~May), and decreasing during the early- and mid- wet season (~~May–Aug~~Jun–Sep). Such a general pattern of alteration is due to the ~~combined impacts of multiple drivers and the compensation between them. However, the late wet season (Sep–Oct) is characterized by a mixed pattern of changes (increasing and decreasing), which may be due to the uncertainty inherent in climate change simulations, and the effect of extreme flood events where inflow exceeds the flood storage capacity of reservoirs.~~overwhelming dominance of the hydropower development impacts, that overcome any counteraction that might be applied by either irrigation development schemes (counteracts in dry season) or climate change impacts.

These general trends are in line with the majority of previous ~~researches in the region (Dang et al., 2018; Hoang et al., 2016; Hoang et al., 2019; Lauri et al., 2012; Piman et al., 2013;~~

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~~Räsänen et al., 2012; Västilä et al., 2010).~~research in the region (Dang et al., 2018; Hoang et al., 2016; Hoang et al., 2019; Kallio and Kummu, 2021; Lauri et al., 2012; Piman et al., 2013; Räsänen et al., 2012; Västilä et al., 2010). The degree of alteration to these hydrological indicators is most pronounced in the upstream ~~area~~areas of Kratie ~~station~~, Kampong Cham, and Chroy Changvar stations and diminishes downstream of the confluence with the Tonle Sap River towards Neak Loeung station, which is also consistent with earlier findings ~~(Dang et al., 2018; Lauri et al., 2012).~~(Dang et al., 2018).

Our findings clearly demonstrate ~~that the degree of hydrological alteration expected under the full development (Pla2040) scenario is diminished by the effect of climate change, and further reduced by the absence of mainstream dams in the Lower Mekong Basin and hydropower mitigation investments. During the wet and early dry season (May–Dec), climate change would play the most important role in reducing the developmental impacts on hydrology, while during the mid- and late dry season (Jan–Apr), hydropower mitigation investments would be the most important driver counteracting developmental impacts. These findings support previous evidence that climate change may act in opposition to the impact of planned developments along the Mekong (Hoang et al., 2019).~~the homogenizing effect that the planned hydropower developments would have on the Mekong River’s hydrograph, which would go far beyond simply contracting the impacts of other drivers and would reshape the expected flow regime, massively increasing dry season low flows and significantly reducing wet season high flows.

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~~The exclusion of LMB mainstream dams, by contrast, may contribute only slightly to counteracting developmental impacts, as the proposed LMB mainstream dams are mostly run-of-the-river types, with low height and little storage capacity, which maintains the natural flow of the rivers to the benefit of ecosystem productivity but to the detriment of flood prevention efforts. Moreover, having its outlet upstream of Kratie station, the 3S basin contributes a large fraction of the Mekong’s annual flows (20%) and consists of 42 dams in total (on-going and future development). The full development of these 42 dams will lead to substantially increasing dry season flows (63%) and decreasing wet season flows (22%) (Piman et al., 2013). Such considerable impacts may already dominate downstream flow alternations, further reducing the potential impact of planned LMB mainstream dams.~~

~~Our future projections of~~ The future projections of flood conditions suggest that most provinces will see ~~a decline~~an increase in depth, duration, and area~~,~~ under climate change scenarios, but that these alterations are counteracted by the combined development scenarios reflecting the flood prevention benefit afforded by ~~the Pla2040 scenario. However, as with the~~

~~water discharge and water level results, the impact of planned developments on flood prevention measures is counteracted to a large degree by the effect of climate change, absent mainstream dams in the Lower Mekong Basin, and hydropower mitigation investments. These findings~~ irrigation and hydropower scenarios. These findings are supported by ~~our earlier results and previous~~other studies that ~~have concentrated on similar areas and~~look at the impact of isolated drivers ~~(Fujii et al., 2003; Pokhrel et al., 2018; Try et al., 2020a; Try et al., 2020b).~~of hydrological change in the region (Fujii et al., 2003; Try et al., 2020a), and studies that look at multiple drivers in nearby regions (Hoanh, et al., 2010; Pokhrel et al., 2018;).

Our provincial level assessment shows that Prey Veng province is most vulnerable to the largest flooded area~~,~~ (Fig. 7), as its large territory is entirely located in the low-lying area adjacent to the Mekong River. Kampong Thom province receives the largest flood prevention benefit provided by the planned hydropower developments ~~of 2020 and 2040.~~, whilst Kampong Chhnang ~~province~~ receives the least ~~benefit from such developments~~ in terms of flooded area and flood duration, most likely because the flood regime is strongly controlled by the Tonle Sap Lake System and receives ~~only a minor~~less influence from the upstream flow alterations. ~~Meanwhile, in terms of flood depth, Kampong Cham province receives the least benefit from such developments, as it mainly functions as a transfer zone of the Mekong flood flow from upstream to the floodplain and delta.~~ Svay Rieng province is ~~designated as the most vulnerable to the effect of climate change, as well as the province most effected~~drastically impacted by ~~the reduction in flood protection benefit provided by the exclusion of LMB mainstream dams, and the adverse impact of mitigation investments.~~all the scenarios. This is most likely due to the extremely low ground surface elevation (majority less than 8 m~~).~~) meaning that slight alterations have proportionally large impacts. The region may also be affected by changes to the hydrological conditions on the Vietnamese Mekong Delta, some of which were represented in this study by means of the boundary conditions supplied by Triet et al (2020) that considered the whole delta region.

4.2. Implications of hydrological and flood condition changes

Changes in hydrological and flood conditions in the Cambodian Mekong floodplain could imply both positive and negative consequences to various sectors such as water resource management, agricultural productions, and ecosystem services ~~(Arias et al., 2012; Kummu and Sarkkula, 2008).~~(Arias et al., 2012; Kummu and Sarkkula, 2008). In addition, the direction, magnitude, and frequency of impacts will be varied from one location to another.

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The beneficial consequences associated with the impact of planned developments are derived from increased water availability in the dry season, and reduced flood prevalence in the wet season. The reduction in flood risk due to the decline in the wet season flows and water levels would be a large socio-economic benefit of these development plans, potentially reducing the duration and extent of affected regions by more than 20~~%.~~% (Fig. 5). In addition, increased dry season flow would greatly enhance agricultural productivity, enhance water security, and minimize conflicts between consumers. Environmental flow could also be secured which may help some aspects of ecosystem productivity. Increases in water levels might also reduce energy costs associated with water pumping, and better facilitate dry season navigation.

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However, there are many negative consequences to the reduction in flood extent and duration associated with the planned ~~developments of 2020–2040.~~development scenarios. Hydropower projects in the Mekong are projected to trap considerable parts of the sediments and the nutrients it contains in the reservoir behind the dam wall, reducing their transportation downstream and subsequent distribution across the floodplain ~~(Kondolf et al., 2018; Kummu et al., 2010; Schmitt et al., 2018; Schmitt et al., 2017).~~(Kondolf et al., 2018; Kummu et al., 2010; Schmitt et al., 2018; Schmitt et al., 2017). The reduction in sediment transport rates associated with reduced wet season flows and sediment trapping upstream inevitably leads to sediment-starved water flow downstream. This in turn leads to increased rates of channel incision and accelerating riverbank erosion as river waters gain in-situ material for transportation up to carrying capacity ~~(Darby et al., 2013; Morris, 2014).~~(Darby et al., 2013; Morris, 2014). The drop in soil fertility (nutrient bound to sediment) throughout the downstream floodplains would result in a great challenge for ecosystem productivity ~~(Arias et al., 2014), rice production (Boretti, 2020) and the sustainability of flooded forests (rich habitats for fish and other species) (Arias et al., 2014).~~(Arias et al., 2014), rice production (Boretti, 2020) and the sustainability of flooded forests (rich habitats for fish and other species) (Arias et al., 2014). Dams also act as barriers disturbing fish migration between upstream and downstream sections essential for feeding and breeding, resulting in fisheries losses ~~(Ziv et al., 2012).~~(Ziv et al., 2012). In addition, the increasing dry season water levels will disturb various river works - for instance, the low water level condition is favourable to river channel ~~maintenances~~maintenance (dredging) and constructions of water infrastructure, usually started and very active during the dry season months.

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Whilst higher economic damages from flood disasters are proportional to extended flooded areas, intensifying flood depths, and prolonging flood durations, there are counteracting positive impacts associated with floods, including the transport of nutrients and increased fisheries productivity. Increasing flood extents widen the coverage of fertile agricultural land ~~(Lamberts, 2008),~~(Lamberts, 2008), which implies a more extensive production of rice - the most important agricultural activity in the Cambodian Mekong floodplain. In contrast, a substantial reduction in flooded area would lead to a fall in flooded forest, a rich habitat for fish and other species ~~(Arias et al., 2014; Kummu and Sarkkula, 2008),~~(Arias et al., 2014; Kummu and Sarkkula, 2008), leading to a decline in fisheries and ~~other~~ ecosystem ~~productivities~~productivity in general. These benefits from an extended flood extent need to be balanced against the detrimental impacts of deep flood depths and long flood durations, which can be catastrophic to crop yields across the floodplains. Therefore, suitable flood conditions should be well determined for a better trade-off with the developmental impacts.

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4.3. Limitations and perspectives for future research

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Several studies have been conducted to understand hydrologic processes within the Cambodian Mekong ~~floodplains including parts of Cambodia~~floodplain, Tonle Sap Lake Basin, and Vietnamese Mekong Delta. Different considerations have been taken into account for the analysis in previous ~~researches~~research; they include but are not limited to (1) water infrastructure development, (2) climate change, (3) sea level rise, (4) land use and land cover change, (5) population growth, and (6) climatic related phenomena. However, the present study is targeted to gain insight into how the combination of ~~water infrastructure~~upstream hydropower development, irrigation expansion, and climate change will affect the Cambodian Mekong floodplain in terms of hydrological and flood patterns. Under climate change scenarios, the future rainfall and temperature were assumed respectively to be wetter and warmer~~, while the land use change was considered unchanged in the future. The effect of sea level rise and tides was also excluded in this study, but any tidal effects would have a minor influence on the water level fluctuations at hydrological stations in the Cambodian Mekong River (Dang et al., 2018). Another limitation of this study is our inclusion of just one GCM and one RCP. Whilst there is a large degree of variation between GCMs in the region, the general trends are consistent (wetter wet seasons, and dryer dry seasons), and our choice of GCM represents the median magnitude of these directional changes (MRC, 2017). Nevertheless, the future inclusion of multiple GCMs and RCPs could lead to uncover (1) the lower/upper bounds or extreme events of projected climate, (2) dissimilar degrees of change and impact to different sectors, and (3) a plausible range of future change and impacts.~~.

~~The impact of dam operations will be opposing those of irrigation, as they may lower hydrological conditions during the dry season, which are expected to be increased by the dam~~

~~operations (Lauri et al., 2012). Therefore, to minimise uncertainties in terms of future directions and magnitudes of changes resulting from these key drivers, reliable and up-to-date data, and detailed information of key drivers should be well considered. Future research should employ finer resolution climate models, and more GCMs and CMIP-6 scenarios in combination with a small-scale decision support tool set-up; as well as satellite-based image analysis to assist in evaluating a comprehensive study of the flood vulnerability or Water-Energy-Food Nexus in the Cambodian Mekong floodplain for the present and future conditions.~~

Future research should employ finer resolution climate models and newer CMIP-6 scenarios, although according to our analysis of basin-wide mean precipitation and temperature do not differ greatly between these two climate change modelling phases (Table S1). In addition, a small-scale decision support tool set-up; as well as satellite-based image analysis to assist in evaluating a comprehensive study of the flood vulnerability in the Cambodian Mekong floodplain or the wider implications for the Water-Energy-Food Nexus for present and future conditions.

Another relevant research direction is the prediction of future land use and river morphological changes. This could generate a key input for a more realistic assessment of hydrological and flood ~~alteration~~alterations. River sand mining has been very active in the Cambodian Mekong River and its main tributaries as rapid and on-going urbanization requires a massive amount of sand, which is an important material not only for construction but also for backfill ~~(Boretti, 2020; Hackney et al., 2020). River bank~~(Boretti, 2020; Hackney et al., 2020). Riverbank collapses, directly or indirectly associated with excessive sand extraction, have been very severe. Moreover, many floodplains and wetlands have been filled~~ up~~ by sand and transformed into urban areas, resulting in a critical change in river morphology and landscape along the river channels and throughout the floodplains. More importantly, these alterations are still being perpetuated without the full impact of their occurrence being understood or accounted for.

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Floods are an essential component of the landscape for both the people and the ecosystem of the Mekong Basin, but they also pose significant hazards and losses when the magnitude is too great to handle effectively. As the development of water infrastructure could cause a decrease in flood conditions and climate change may reverse such impacts, it is still unknown what the desired flood water level and flood duration should be. This has led to a great difficulty in proposing optimum flood protection measures while maximizing dam benefits. Therefore, another potential research topic is the determination of the ideal flood conditions for ~~a ~~maximum productivity from both the agricultural and ecosystem perspectives.

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The intended purpose of these future ~~researches~~research is to provide valuable information and assist governments, policymakers, and water resources engineers to foresee future threats of different intensities. Moreover, their results would be helpful in formulating better water resources management strategies, and in elevating all living things' resilience to the future challenges for the sustainability of resources within the floodplain.

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5. Conclusions

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By combining the effects of development activities and climate change, this research ~~performs~~uses a ~~cumulative impact assessment~~novel setup of three different models to assess the ~~hydrological regime changes in the Cambodian Mekong River and flood condition alterations within its floodplains. We integrated the planned~~potential impacts of hydropower development ~~activity of six central sectors throughout the Mekong River Basin: hydropower~~, irrigation ~~, navigation, flood protection, agricultural land use, and water use. The study also attempts to isolate the individual impacts of~~ expansion, and climate change ~~, mainstream dams in the Lower Mekong Basin, and hydropower mitigation investments. The modelling results~~ on the Cambodian Mekong floodplain. We show ~~high sensitivity of hydrological and flood condition responses to the drivers considered as part of our analysis, highlighting~~through model validation that the developed modelling setup performs well in the study area and could therefore potentially be used for future studies in the Mekong, as well as in the floodplains of other large rivers. Our findings contribute to the delivery of more precise information about the expected changes to flooding regimes in the area and highlight the importance of properly characterising the directions and magnitudes of these changes. ~~This study will contribute to the delivery of more precise information about the expected hydrology and flood behaviours resulting from future development activities and climate change, and assist in strategic plan formulation and decision making processes in the dynamic Mekong region.~~

~~The key results from this research demonstrate that the monthly, sub-seasonal and seasonal hydrological regimes in the Cambodian Mekong River will be subject to substantial alterations under the 2020 development scenario, and even larger alterations under the 2040 development scenario. Both~~The combined development scenarios ~~exhibit~~that we analysed exhibited the same ~~generic~~ pattern of decreasing hydrological conditions during the ~~early~~ wet season ~~months~~, whilst increasing water discharge and water levels in the dry season ~~months~~. The degree of hydrological alteration under ~~the full~~hydropower development ~~scenario (2040)~~and irrigation expansion is counteracted to a limited degree by the ~~effect~~impact of future climate change, which is projected to intensify the onset of wet season months and exacerbate water deficiencies in the dry season months. ~~The removal of mainstream dams along the Lower Mekong Basin and the implementation of hydropower mitigation investments also counteract the impact of the 2040 planned developments, diminishing the reduction in wet season flows and the increase in dry season flows across all regions. The planned 2040 developmental impact on flood characteristics is to significantly reduce extent, duration, and depth throughout all provinces, with the largest reductions being in Kampong Thom province of 10.5% for area and 14.1% for duration. Again, these reductions in flood characteristics are counteracted by both climate change and mitigation measures, in some provinces to such an extent that they display slight increases in flood extent, depth, and duration, most notably in Svay Rieng.~~

Our findings assist in strategic plan formulation and decision-making processes in the dynamic Mekong region. The positive and negative implications of developmental impacts on water availability, flow alterations, and particularly flood regime alterations should be carefully considered when determining the level of investment to place in counteracting measures. Reduced flooding during the wet season ~~flows and the associated reduction in flood extent, depth, and duration have demonstrable~~has flood protection benefits ~~that reduce the socio-economic impact of damage to infrastructure, crop yields and land, and hazards to public health~~, whereas increases in dry season flows have the benefit of increased water availability for irrigation~~, consumption, and maintaining environmental flow.~~. However, ~~there are~~the negative ~~consequences to the~~ impacts ~~of the planned 2040 development including~~should also be considered: a reduction in fisheries productivity, sediment trapping and a decline in nutrient supply to the floodplain, and a reduction in floodplain ecosystem productivity ~~including flooded forests.~~. Balancing these trade-offs will be an essential component of any successful floodplain management strategy put in place to address future climate change and uncertainty in a sustainable manner. A timely preparedness will be essential to avoid future economic and environmental damages, as well as safeguarding the wellbeing of vulnerable communities living throughout the ~~Lower~~Cambodian Mekong ~~floodplains.~~floodplain.

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Supplementary material

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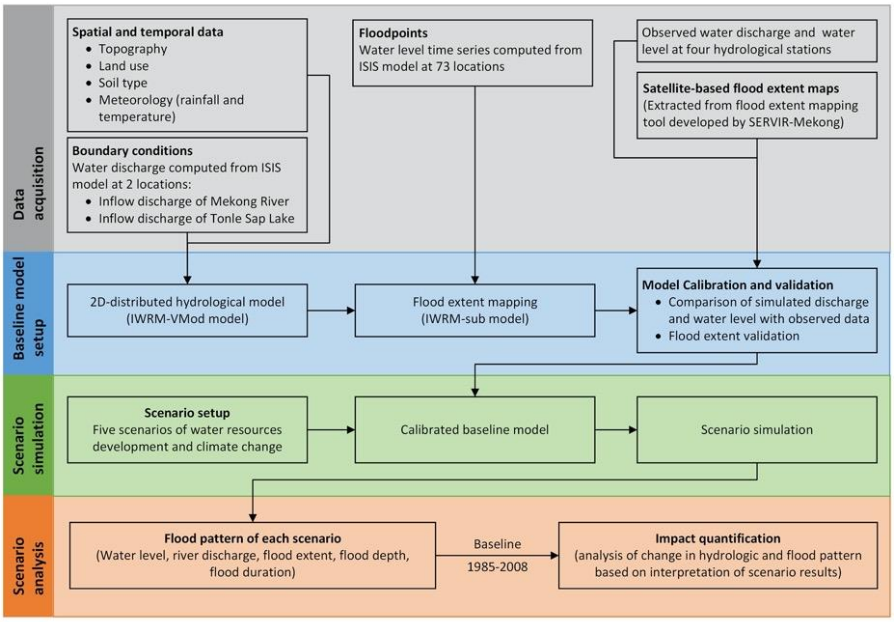

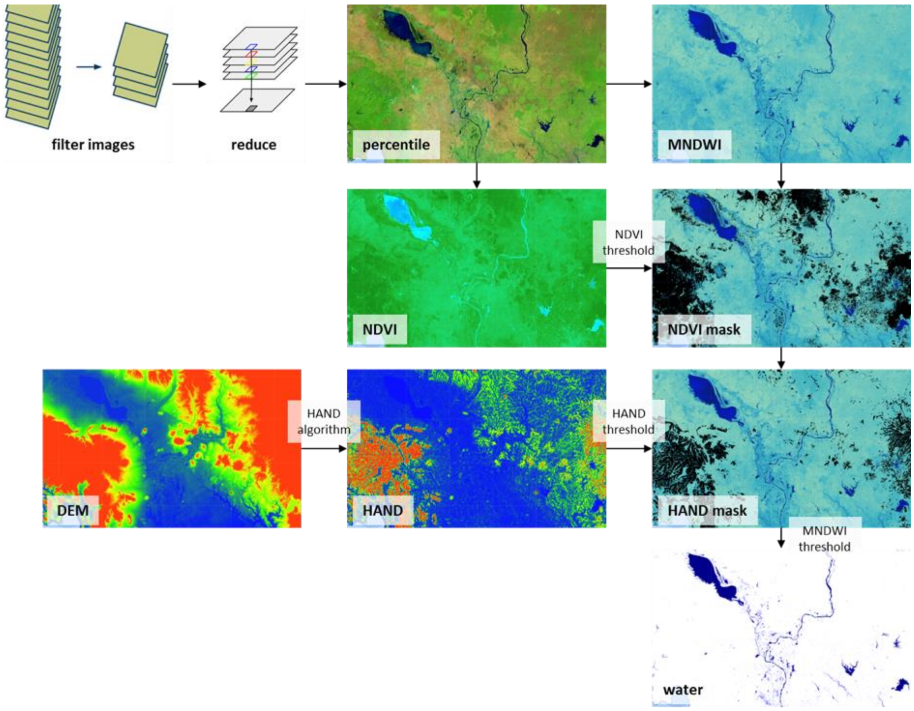

Fig. S1. ~~Overall framework of methodology.~~

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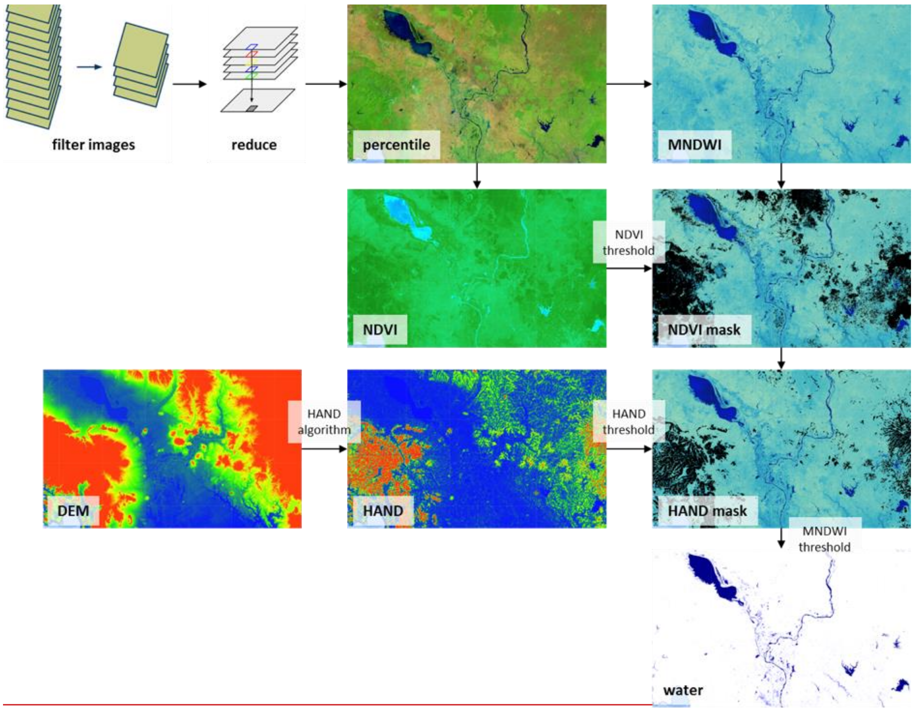

~~**Fig. S2.**~~ *Schematic processes in generating floodwater coverage from satellite images. MNDWI is the Modified Normalized Difference Water Index, NDVI is the Normalised Difference Vegetation Index, and HAND is the Height Above Nearest Drainage.*

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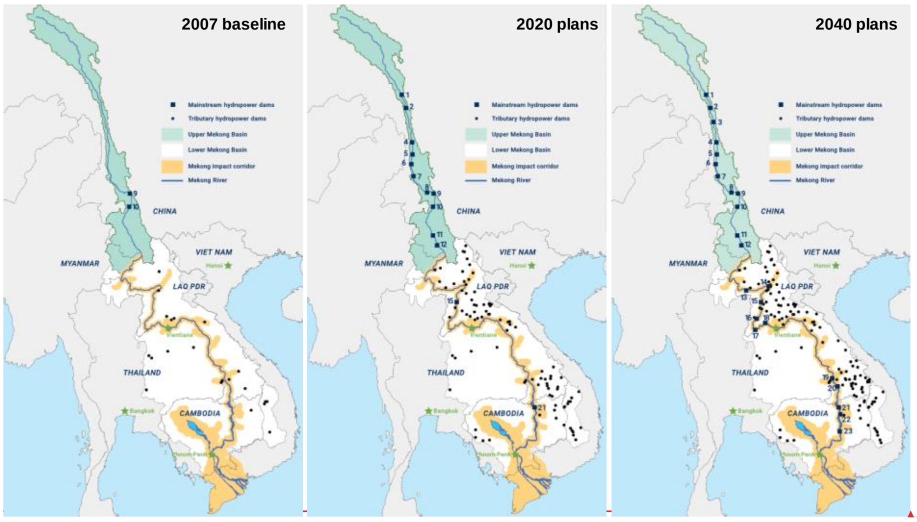

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~~*Fig. S3.* Location map of hydropower dams considered in this study (MRC, 2019). The mainstream dams are (1) Wunonglong, (2) Lidi, (3) Tuoba, (4) Huangdeng, (5) Dahuaqiao, (6) Miaowei, (7) Gongguoqiao, (8) Xiaowan, (9) Manwan, (10) Sachaoshan, (11) Nuozhadu, (12) Jinghong and Lower Mekong's mainstream dams are (13) Pak Beng, (14) Luang Prabang, (15) Xayaburi, (16) Pak Lay, (17) Sanakham, (18) Pak Chom, (19) Ban Koum, (20) Lat Sua/Phou Ngoy, (21) Don Sahong, (22) Stung Treng, (23) Sambo.~~

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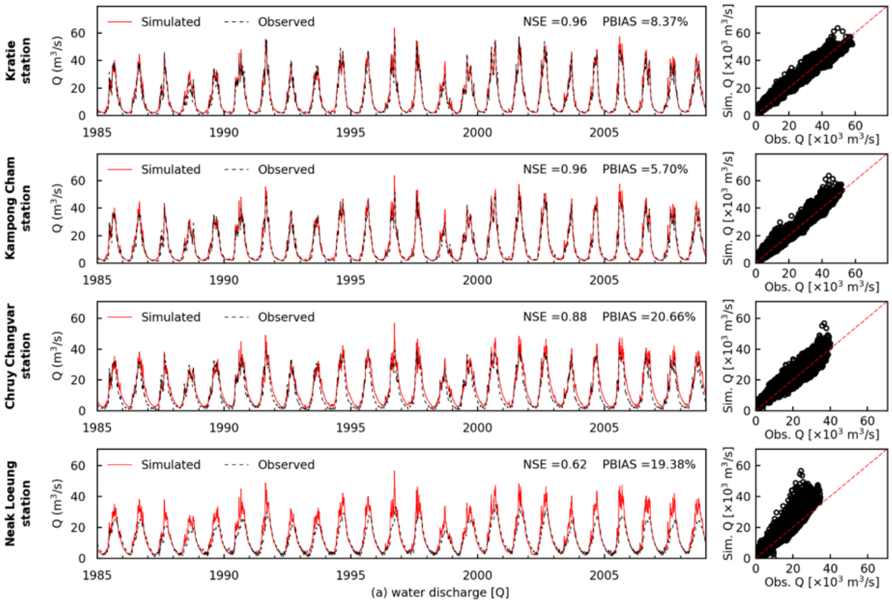
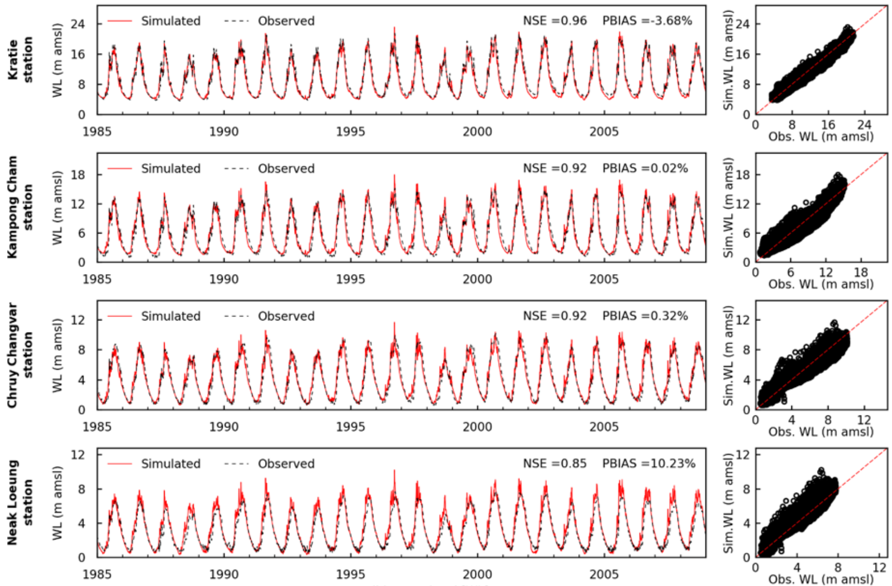


(a) water discharge [Q]



(b) water level [WL]

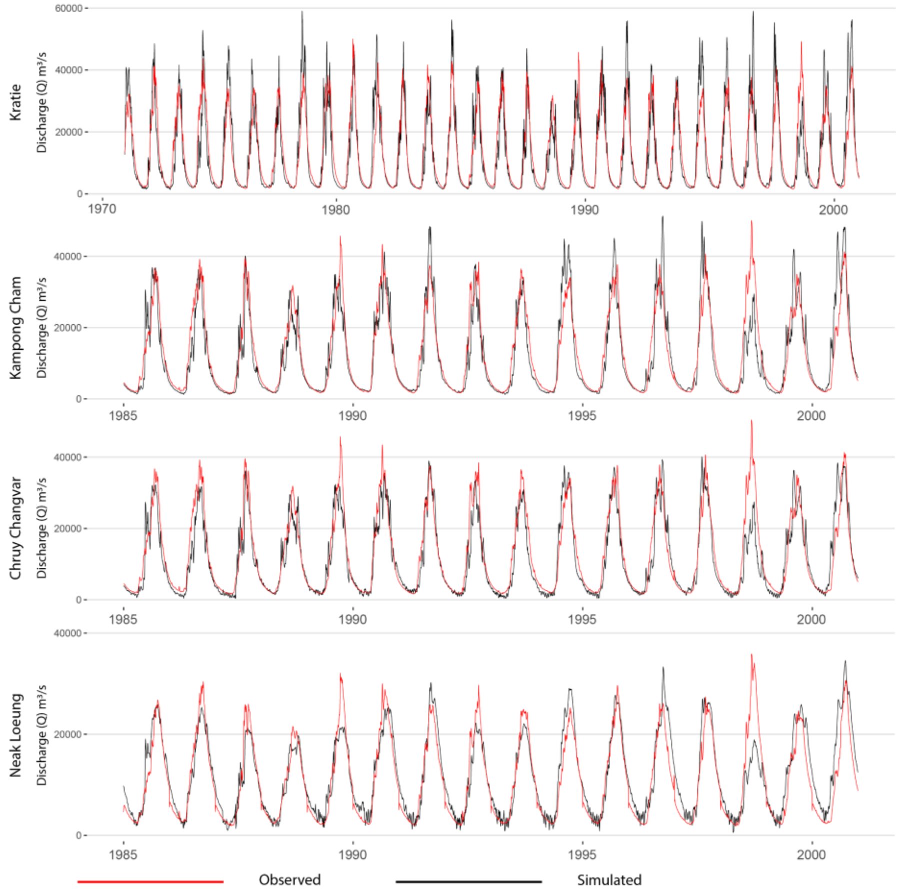


Fig. ~~S4~~*S2. Time series comparison* ~~and scatter plot~~ *between the observed and simulated water discharge [Q]* ~~and water level [WL].~~ *at each gauging station. See location of the stations in* ***Fig. 1****.*

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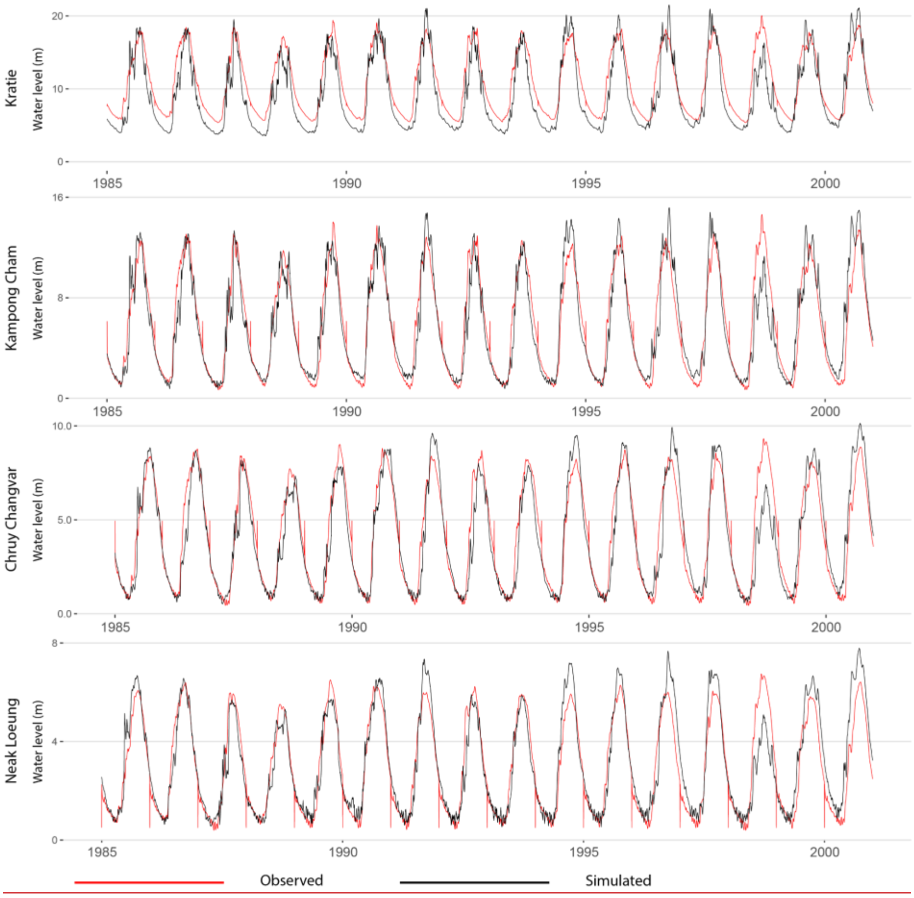
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Water level (m)
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10
0
1985
1990
1995
2000
Kampong Cham
Water level (m)
16
8
0
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1990
1995
2000
Chruy Changvar
Water level (m)
10.0
5.0
0.0
1985
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Neak Loeung
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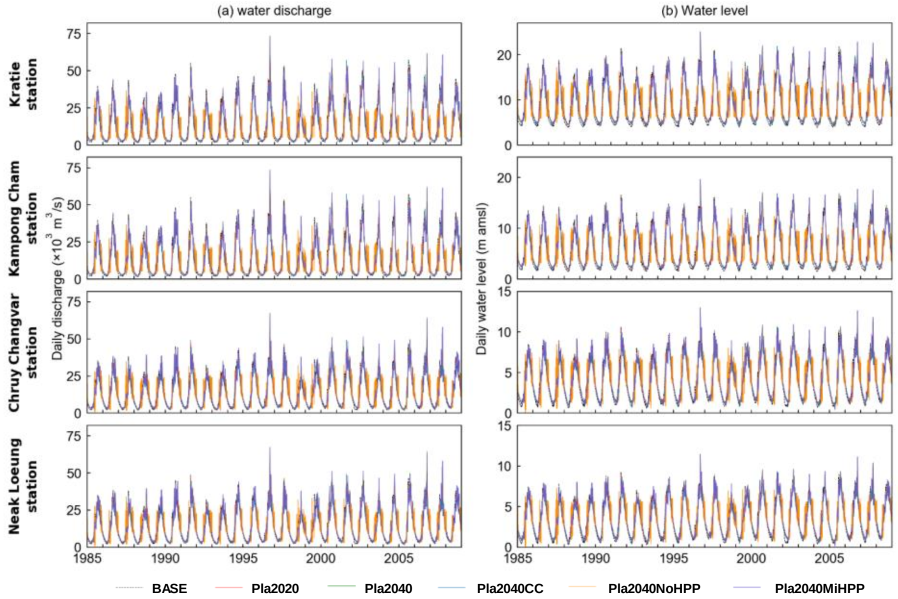
Fig. S3.



~~*Fig.* S5.~~ *Time series comparison* ~~of water discharge and water level under different scenarios~~*between the observed and simulated water levels [WL] at each gauging station.*

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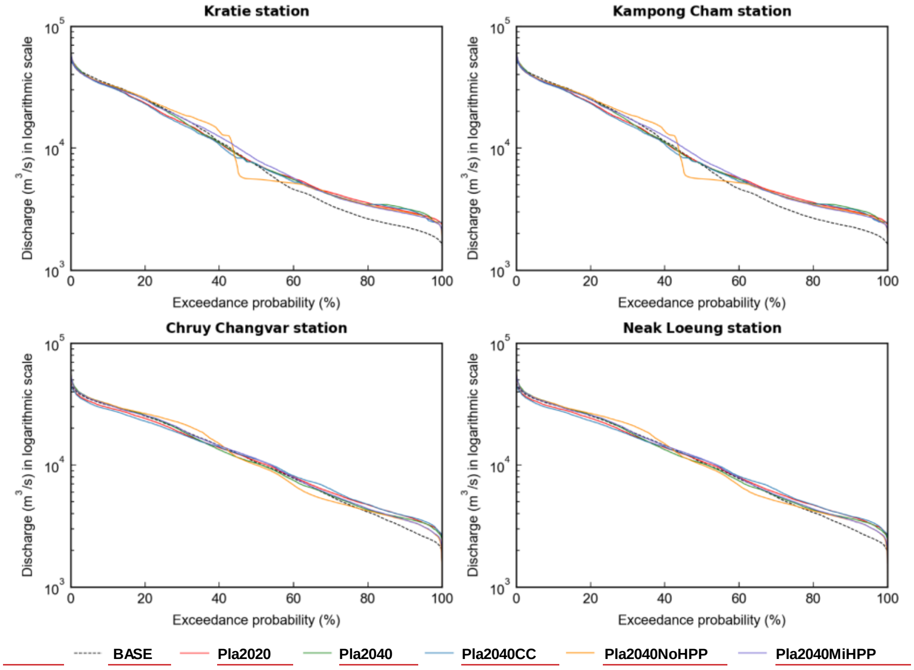
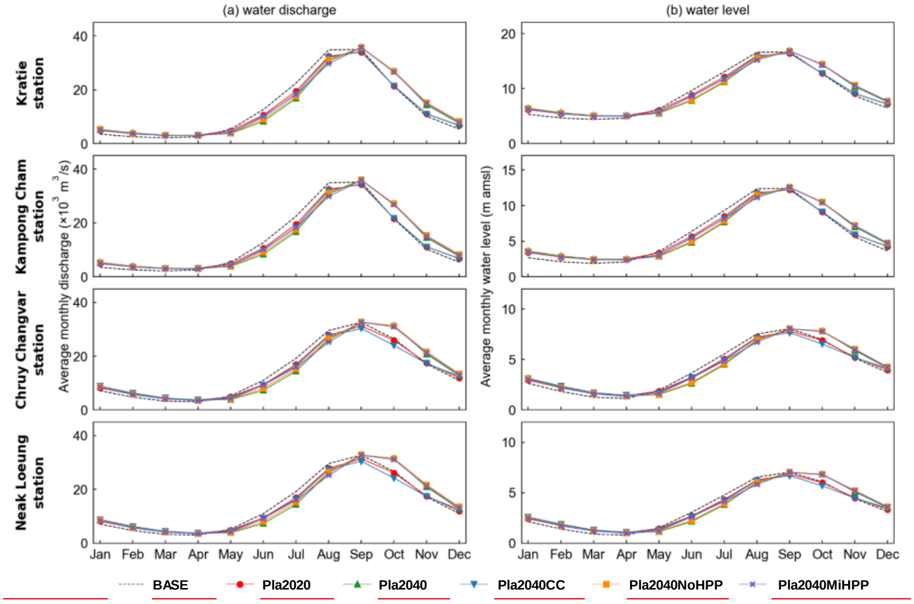
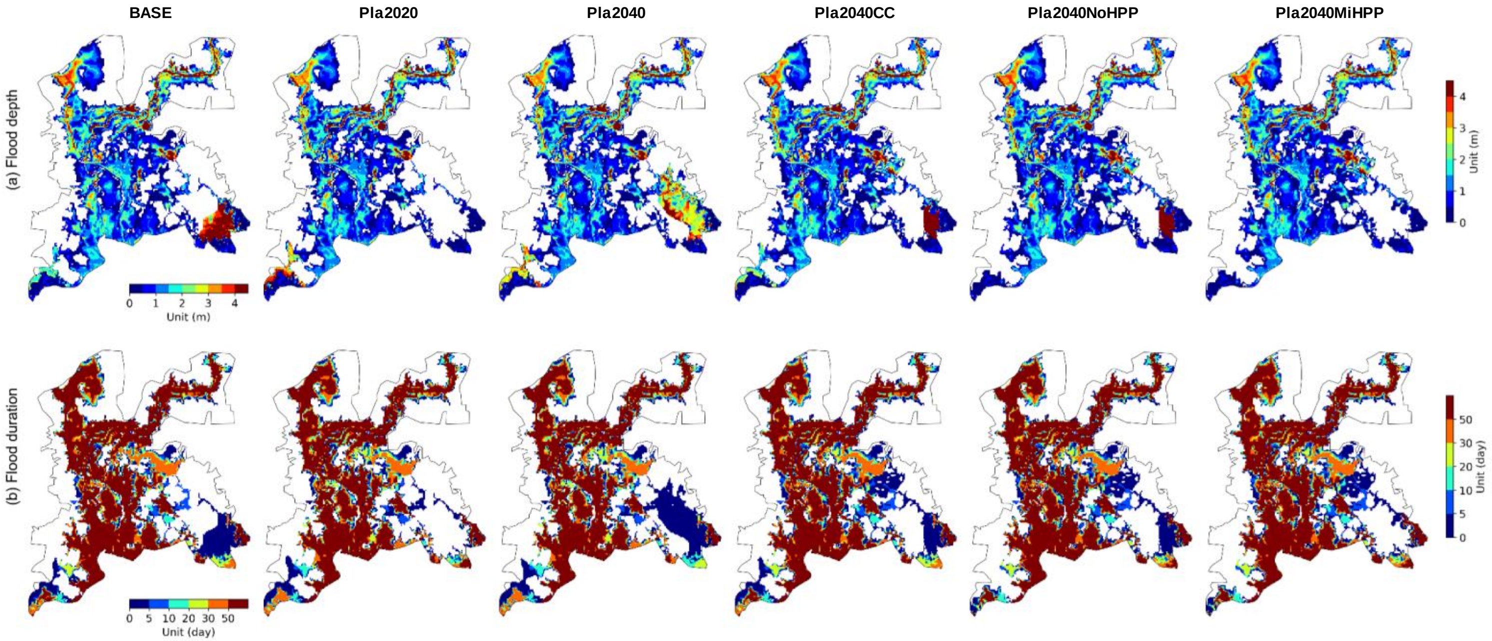


~~**Fig. S6.** Comparison of flow duration curves under different scenarios. Vertical axis is log-scale.~~



~~**Fig. S7.** Comparison of monthly water discharge and water level under different scenarios.~~



~~**Fig. S8.** Spatial distribution of mean annual flood depth and flood duration.~~

~~**Table S1**~~

~~Changes in flooded area, flood depth, and flood duration over the baseline period 1985–2008 at provincial level.~~

Table S1. Comparison of GCM ensemble means for precipitation and temperature across the wet (May - Oct) and dry (Nov - Apr) seasons between CMIP-5 and CMIP-6. Analysis is based on the ensemble median of six GCMs that are equivalent between CMIP5 and CMIP6 generations. Data with resolution of 5 arc-min from www.worldclim.com were used.

~~Province~~	~~Change in flooded area (%)~~					
	~~Pla2020~~	~~Pla2040~~	~~Pla2040CC~~	~~Pla2040NoHPP~~		~~Pla2040MiHPP~~
~~Kampong Cham~~	~~-5.9~~	~~-6.3~~	~~-0.8~~	~~-0.8~~		~~0.0~~
~~Kampong Chhnang~~	~~-2.7~~	~~-3.1~~	~~-0.7~~	~~-0.5~~		~~-0.1~~
~~Kampong Thom~~	~~-9.3~~	~~-10~~RCP 4.5	~~-2.9~~	~~-2.3~~		~~-0~~RCP 8.5
		CMIP5		CMIP6	CMIP5	CMIP6
~~Kandal~~	~~-5.2~~Precipitation - wet season (mm / 5 months)	~~-5.6~~1102		~~-0.7~~1086	~~-0.4~~1149	~~0.4~~1090
~~Kratie~~	~~-5.6~~	~~-6.2~~	~~-3.9~~	~~-4.3~~		~~-3.6~~
~~Phnom Penh~~	~~-6.3~~	~~-6.9~~	~~-1.0~~	~~-0.7~~		~~0.2~~
~~Prey Veng~~	~~-8.7~~Precipitation - dry season (mm / 7 months)	~~-9.2~~338	~~-1.1~~328	~~-0.7~~332		~~0.7~~333
~~Svay Rieng~~	~~-12.2~~	~~-23.4~~	~~18.5~~	~~28.2~~		~~32.3~~
~~Takeo~~Temperature - wet season (°C)	~~-6.3~~	~~-6~~23.6	~~-0~~23.6	24.0~~.3~~	24.1~~.2~~	
~~Tboung Khmum~~Temperature - dry season (°C)	~~-4~~19.7	~~-~~19.4~~.7~~	~~-1.8~~20.0	~~-2.2~~19.9		~~-1.4~~
~~Means of all 10 provinces~~	~~-6.7~~	~~-8.2~~	~~0.5~~	~~1.7~~		~~2.9~~

~~Province~~	~~Change in flood depth (%)~~				
	~~Pla2020~~	~~Pla2040~~	~~Pla2040CC~~	~~Pla2040NoHPP~~	~~Pla2040MiHPP~~
~~Kampong Cham~~	~~-2.6~~	~~-2.5~~	~~-0.7~~	~~-0.9~~	~~-0.4~~
~~Kampong Chhnang~~	~~-3.9~~	~~-4.3~~	~~-1.0~~	~~-0.7~~	~~0.0~~
~~Kampong Thom~~	~~-5.4~~	~~-6.0~~	~~-0.6~~	~~-0.4~~	~~0.5~~
~~Kandal~~	~~-3.8~~	~~-4.1~~	~~-0.1~~	~~0.1~~	~~0.8~~
~~Kratie~~	~~-3.3~~	~~-3.0~~	~~-2.0~~	~~-2.2~~	~~-1.7~~
~~Phnom Penh~~	~~-3.6~~	~~-3.9~~	~~-0.4~~	~~-0.3~~	~~0.5~~
~~Prey Veng~~	~~-3.6~~	~~-3.6~~	~~-0.4~~	~~-0.2~~	~~0.3~~
~~Svay Rieng~~	~~-4.2~~	~~-2.3~~	~~3.1~~	~~1.9~~	~~2.5~~
~~Takeo~~	~~-3.5~~	~~-3.9~~	~~-0.2~~	~~0.6~~	~~1.4~~
~~Tboung Khmum~~	~~-2.6~~	~~-2.4~~	~~-1.2~~	~~-1.3~~	~~-1.0~~
~~Means of all 10 provinces~~	~~-3.7~~	~~-3.6~~	~~-0.3~~	~~-0.3~~	~~0.3~~

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~~Province~~	~~Change in flood duration (%)~~				
	~~Pla2020~~	~~Pla2040~~	~~Pla2040CC~~	~~Pla2040NoHPP~~	~~Pla2040MiHPP~~
~~Kampong Cham~~	~~-8.2~~	~~-10.4~~	~~-1.9~~	~~-1.0~~	~~0.5~~
~~Kampong Chhnang~~	~~-2.6~~	~~-4.3~~	~~-0.7~~	~~1.0~~	~~2.6~~
~~Kampong Thom~~	~~-11.6~~	~~-14.1~~	~~-3.5~~	~~-2.0~~	~~-0.2~~
~~Kandal~~	~~-6.9~~	~~-8.6~~	~~-2.1~~	~~-0.7~~	~~0.3~~
~~Kratie~~	~~-8.3~~	~~-10.9~~	~~-4.3~~	~~-3.2~~	~~-0.9~~
~~Phnom Penh~~	~~-9.2~~	~~-10.2~~	~~-4.0~~	~~-4.9~~	~~-3.5~~
~~Prey Veng~~	~~-11.2~~	~~-13.0~~	~~-3.8~~	~~-1.8~~	~~-1.2~~
~~Svay Rieng~~	~~-5.8~~	~~-22.7~~	~~0.5~~	~~18.5~~	~~21.5~~
~~Takeo~~	~~-8.3~~	~~-10.4~~	~~-2.3~~	~~1.7~~	~~2.9~~
~~Tboung Khmum~~	~~-8.8~~	~~-10.9~~	~~-2.4~~	~~-1.8~~	~~-0.3~~
~~Means of all 10 provinces~~	~~-8.1~~	~~-11.5~~	~~-2.5~~	~~0.6~~	~~2.2~~

~~**Analysis of flood alterations at provincial level**~~

~~As the Cambodian Mekong floodplain covers only a little part of Kampong Speu and Kampot province, and Tay Ninh province is in Vietnam, we did not present results for these regions. For the remaining 10 provinces, we examined the change in flooded area, flood depth and flood duration for each scenario compared to the baseline period at the provincial level (**Fig. 6** and **Table S1**). Under the baseline scenario (BASE), the modelling results show that the average flooded area ranges from a minimum of 184 km^2 in Svay Rieng province to a maximum of 2,251 km^2 in Prey Veng province, which represents 43% of the provincial territory. Whilst the average flood depth ranges from 1.1 m in Svay Rieng province to 4.9 m in Kratie province, and the average flood duration ranges from 6 days in Svay Rieng province to 85 days in Kandal province.~~

~~Results from all scenarios predominantly show decreasing flood conditions in most provinces. The degree of alteration at provincial level is generally less than 10% in comparison with the baseline. Both scenarios Pla2020 and Pla2040 show reductions to flooded area, depth, and duration in all provinces, with the reductions for Pla2040 being slightly larger than for Pla2020. The largest reductions displayed by Pla2040 are located in Svay Rieng province in terms of area (-23.4%), Kampong Thom province in terms of depth (-6.0%), and Kampong Thom province for duration (-22.7%). This signifies the benefit to flood prevention efforts afforded by the planned developments in 2020 and 2040.~~

~~In comparison with Pla2040, the incorporation of climate change into the Pla2040CC scenario reverses the magnitude of these developmental impacts, as the warmer dry season months and wetter wet season months compensate for the anthropogenic flow alterations. As a result, the Pla2040CC scenario is in a much closer alignment with the baseline, so that reductions to the flood extent, depth, and duration are much smaller than for the Pla2040 scenario, whilst one province displayed increases in flood extent and depth. The largest reductions displayed by Pla2040CC are all located in Kratie province (area –3.9%, depth –2.0%, duration –4.3%). However, the province of Svay Rieng, which displayed the largest reductions under scenario Pla2040, displays overall increases in flooded area (+18.5%), depth (+3.1%) and duration (+0.5%) under scenario Pla2040CC. This illustrates that the impact of climate change works in opposition to the impact of planned developments, diminishing both the negative environmental implications of the dams, and the negative flood implications of climate change.~~

~~Under the Pla2040NoHPP scenario, a reduction in flood conditions is observed in most provinces, except Svay Rieng and Takeo province which are characterized by increases to all three measurements of flooding. Moreover, in Kampong Chhnang and Kandal provinces, at least one of the three measurements increase whilst the others reduce ever so slightly. The magnitude of the reductions is again much smaller than for Pla2040 and more in line with the Pla2040CC results. This reflects the reduction in anthropogenic flow alternations introduced by mainstream dam operations. The largest reductions of flood extent and depth are found in Kratie province (–4.3% and –2.2%), and Phnom Penh city in terms of duration (–4.9%). The largest increases for all measurements are again found in Svay Rieng province (area +28.2%, depth +1.9%, duration +18.5%).~~

~~The Pla2040MiHPP scenario is more varied still, displaying reductions smaller than Pla2040NoHPP and more increases across the measurements and provinces. The change in flooded area ranges from –3.6% in Kratie province to +32.3% in Svay Rieng province, the change in flood depth ranges from –1.7% in Kratie province to +2.5% in Svay Rieng province, and the change in flood duration ranges from –3.5% in Phnom Penh city to +21.5% in Svay Rieng province. In comparison with Pla2040, the mitigation measures and joint operation of key dams (Pla2040MiHPP scenario) not only significantly lessen the reducing impact of dams on flood conditions, but also transform some provinces from a reducing impact to an increasing impact on flood measures. Such mitigation investments are introduced generally to optimize the dam benefits while maintaining the natural flow in rivers and thus benefiting ecosystem~~

~~productivity. However, installing run-of-the-river style dams along the mainstream reduces the active storage capacity and seriously compromises the dam’s ability to act as flood prevention, forsaking the opportunity to counteract the increasing flood potential of climate change.~~

~~The majority of provinces are characterized by a reduction in flood conditions under all scenarios. The provincial flood conditions show a decreasing rate of flooded area between −23.4% and −0.1%, between −6.0% and −0.03% for flood depth, and between −22.7% and −0.2% for flood duration. Although a few provinces did exhibit an increasing pattern under the Pla2040CC, Pla2040NoHPP and Pla2040MiHPP scenario (up to +32.3% for flooded area, +3.1% for flood depth and +21.5% for flood duration). Under Pla2040CC, Svay Rieng was the sole province characterized by an increase in flood conditions, and it also displayed the largest increasing trends under Pla2040NoHPP, and Pla2040MiHPP, suggesting that Svay Rieng province is the most sensitive and vulnerable to the effect of climate change and LMB mainstream dam operations. Svay Rieng province is located in the lowland area and far from the mainstream (poor flood drainage system), indicating a significant impact of the widespread and prolonged flood condition.~~

~~Overall Prey Veng is the province most vulnerable to the largest flooded area of about 2,056 km^2 under Pla2020 and 2,045 km^2 under Pla2040, or respectively 47% and 43% of the provincial territory. Kampong Thom province receives the largest flood protection benefit from the planned developments between 2020 and 2040, with reductions under the Pla2040 scenario of −10.5% for flooded area, −6.0% for flood depth, and −14.1% for flood duration. Kampong Chhnang province receives the least benefit from such developments in terms of flooded area (only −3.1% under Pla2040) and flood duration (only −4.3% under Pla2040), while Kampong Cham province receives the least benefit in terms of flood depths, only −2.5% under Pla2040.~~

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