# The Cambodian Mekong floodplain under 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 –30% in wet season and +140% in dry season
- Hydropower developments alone reduce total flood extents by more than 20%
- Prey Veng and Takeo are the provinces most susceptible to climate change induced flood risks

1  **ABSTRACT**

2  Water infrastructure development is considered necessary to drive economic growth in the

3  Mekong region of mainland Southeast Asia. Yet the current understanding of hydrological

4  and flood pattern changes associated with infrastructural development still contain several

5  knowledge gaps, such as the interactions between multiple drivers, which may have serious

6  implications for water management, agricultural production, and ecosystem services. This

7  research attempts to conduct a cumulative assessment of basin-wide hydropower dam

8  construction and irrigation expansion, as well as climate change, implications on discharge

9  and flood changes in the Cambodian Mekong floodplain. These floodplains offer important

10  livelihoods for a considerable part of the 6.4 million people living on them, as they are among

11  the most productive ecosystems in the world – driven by the annual flood pulse. To assess

12  the potential future impacts, we used an innovative combination of three models: Mekong

13  basin-wide distributed hydrological model IWRM-VMod, whole Mekong delta 1D flood

14  propagation model MIKE-11 and 2D flood duration and extent model IWRM-Sub enabling

15  detail floodplain modelling. We then ran scenarios to approximate possible conditions

16  expected by around 2050. The scenarios approximate the conditions expected by around

17  2050. Our results show that the monthly and seasonal hydrological regimes (discharges,

18  water levels, and flood dynamics) will be subject to substantial alterations under future

19  development scenarios. Projected climate change impacts are expected to decrease dry season

20  flows and increase wet season flows, which is in opposition to the expected alterations under

21  development scenarios that consider both hydropower and irrigation. The likely impact of

22  decreasing water discharge in the early wet season (up to –30%) will pose a critical challenge

23  to rice production, whereas the likely increase in water discharge in the mid-dry season (up to

24  +140%) indicates improved water availability for coping with drought stresses and sustaining

25  environmental flows. At the same time, these changes would have drastic impacts on total

26  flood extent, which is projected to decline by around 20%, having potentially negative

27  impacts on floodplain productivity and aquaculture, whilst reducing the flood risk to more

28  densely populated areas. Our findings demonstrate the substantial changes that planned

29  infrastructural development will have on the area, potentially impacting important

30  ecosystems and people's livelihoods, calling for actions to mitigate these changes as well as

31  planning potential adaptation strategies.

1

34    **1. Introduction**

35    The Mekong River Basin is the largest river basin in the Southeast Asian mainland.

36    Historically, cyclones and severe tropical storms have generated the most significant Mekong

37    flooding events, the largest of which was recorded in 1966, when tropical storm Phyllis struck

38    the Upper Mekong Basin (Adamson et al., 2009). At the downstream end of the basin (Fig. 1),

39    severe floods have most commonly been recorded in the area around Stung Treng Province, at

40    the confluence of the Mekong and Tonle Sap rivers, and within the Vietnamese Mekong Delta.

41    The last severe flood occurred in 2011 and it is ranked among the highest discharge recorded

42    in the Lower Mekong Basin (LMB) (MRC, 2011).

43           Whilst flooding damages infrastructure, crops and floodplain vegetation, and the fertile

44    land, seasonal flooding is a vital hydrological characteristic of the Mekong River Basin, as it

45    improves water availability during the dry season, and maintains and increases the high

46    productivity of ecosystems and biodiversity (Arias et al., 2014; Arias et al., 2012; Boretti, 2020;

47    Kondolf et al., 2018; Kummu et al., 2010; Kummu and Sarkkula, 2008; Lamberts, 2008;

48    Schmitt et al., 2018; Schmitt et al., 2017; Västilä et al., 2010; Ziv et al., 2012). As part of the

49    annual flood cycle, floodwaters play an important role in the recharging of aquifers and

50    ensuring the hydrological connectivity of the floodplain, which is essential to maintaining

51    ground water resources for use during the dry season (Kazama et al., 2007; May et al., 2011).

52    Floodwaters also transport essential sediments and nutrients from the river channel into the

53    floodplain and distribute them across a wide area, which fertilizes agricultural lands and

54    enhances floodplain productivity (Arias et al., 2014; Kummu and Sarkkula, 2008; Lamberts,

55    2008). In addition, the wider the flood extent, the larger the area of interaction between aquatic

56    and terrestrial phases, which increases the potential transfer of floodplain terrestrial organic

57    matter into the aquatic phase. Under the combined impacts of hydropower infrastructure and

58    climate change, the flooded area in Cambodia's Tonle Sap Lake Basin is projected to decline

59    by up to 11% circa 2050, which may lead to a decline in the net sedimentation and the aquatic

60    net primary production of up to 59%, and 38% respectively (Arias et al., 2014; Lamberts,

61    2008).

62           Existing hydrological and flood regimes will likely be altered due to climate change

63    and infrastructure developments; but the degree of alterations vary with different drivers,

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64  location, and time (Piman et al., 2013; Try et al., 2020a). Hoang et al. (2016) project that the

65  Mekong's discharge under climate change conditions by 2050 under RCP 8.5 will decrease in

66  the wet season (up to –7% at Stung Treng) and increase in the dry season (up to +33% at Chiang

67  Saen), equivalent to an annual increase between +5% and +15%. Lauri et al. (2012) shows that

68  hydrological conditions of the Mekong River Basin were highly dependent upon the Global

69  Climate Model (GCM) being used, with projections of water discharge at Kratie station (Fig.

70  1), Cambodia, ranging from –11% to +15% for the wet season and from –10% to +13% for the

71  dry season for projections circa 2050. The study also concludes that the impact on water

72  discharge due to planned reservoirs was much larger than those simulated due to climate

73  change, with water discharge during the dry and early wet season being primarily determined

74  by reservoir operation. Hoang et al. (2019) find that for the same period under RCP 8.5

75  hydropower development plans in Mekong River Basin are expected to increase dry season

76  flows up to +133% and decrease wet season flows up to –16%. The future expansion of

77  irrigated lands in the wider Mekong region is expected to reduce river flows up to –9% in the

78  driest month (Hoang et al., 2019).

79      Changes to the Mekong mainstream flows will have direct impacts on flooding in the

80  LMB floodplains in Cambodia and Vietnam. Try et al. (2020a) considered the impact of future

81  climate change (circa 2100 under RCP 8.5) in isolation on the flood dynamics of the LMB,

82  projecting an increased flood extent area of 19–43%. Infrastructure development, in contrast,

83  is expected to cause a decline in the Tonle Sap's flood extent by up to 1,200 km$^2$ (Arias et al.,

84  2012), as dam development alone is expected to reduce flooded area in the Vietnamese Mekong

85  Delta by 6% in the wet year and by 3% in the dry year (Dang et al., 2018). Flood extent in the

86  Vietnamese Mekong Delta is projected to increase by 20% under the cumulative impacts of

87  climate change and infrastructure development, bringing prolonged submergences of 1–2

88  months (Triet et al., 2020).

89      The impacts described above may eventually lead to a new hydrological and flood

90  regime in the Mekong region, and would likely endanger the riverine ecology and endemic

91  aquatic species of the Mekong floodplain (Arias et al., 2012; Dang et al., 2018; Kummu and

92  Sarkkula, 2008; Räsänen et al., 2012). To effectively manage and overcome these pressures

93  and challenges in any floodplain, there is an urgent need to evaluate the combined impacts of

94  climate change and infrastructure operations basin-wide (Hoang et al., 2019; Hoanh et al.,

95  2010; Lauri et al., 2012; Västilä et al., 2010). However, the existing studies have focused either

96  on the basin scale flow changes (Dang et al., 2018; Hoang et al., 2016; Hoang et al., 2019;

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97   Hoanh et al., 2010; Lauri et al., 2012; Pokhrel et al., 2018; Try et al., 2020a) or assessed the

98   impacts on flooding either for the Tonle Sap (Arias et al., 2012; Chen et al., 2021; Ji et al.,

99   2018; Yu et al., 2019) or the Vietnamese Mekong Delta (Dang et al., 2018; Tran et al., 2018;

100  Triet et al., 2020). Very little is known how basin-wide development and climate change would

101  impact Cambodian Mekong floodplain other than the Tonle Sap (Fig. 1), despite them being

102  important agricultural lands and home to more than 6.4 million people (2008 Population

103  Census).

104        Therefore, we have attempted to quantify the cumulative impacts of water resources

105  development plans and climate change on hydrological and flood conditions localised in the

106  Cambodian Mekong floodplain (Fig. 1) by using an innovative combination of state-of-the-art

107  hydrological and hydrodynamic models. In concentrating on the provincial level, using an

108  extended time-series for the calibration period, validating the flood extent against satellite

109  imagery, and incorporating a larger set of driving factors within our analysis, the present study

110  is a novel contribution to the work being done to understand the potential for future changes to

111  the complex hydrology of the floodplains in general, and specifically the Cambodian Mekong

112  floodplain. The results of this study may contribute to formulating adaptation and mitigation

113  strategies to flood-prone areas that balance the need for flood prevention and water resource

114  allocation against the ecological functioning of the floodplain.

115  **2. Materials and methods**

116  *2.1. Study area*

117  The study area is located in the downstream part of the Cambodian Mekong River Basin

118  (excluding the Tonle Sap Lake region), also known as the "Cambodian Mekong floodplain"

119  (Fig. 1). The area is about 27,760 km$^2$ and extends along the Mekong mainstream from Kratie

120  province to the Cambodia-Vietnam border. It covers parts of 12 provinces in Cambodia and

121  one province in Vietnam (Tay Ninh), but does not extend into the Vietnamese Mekong Delta

122  region (see division in Fig. 1).

123        A major part of the Cambodian Mekong floodplain is characterized by a flat terrace and

124  low-lying grounds with gentle slopes that contain many depressions and lakes, except for the

125  upper parts of the Prek Thnot and Prek Chhlong tributaries, which contains steeper terrain.

126  Hydrological conditions within the area are dominated by the seasonality and year-to-year

127  variability of the Mekong flow regimes. The wet season runs from June to October, and the dry

4

128 season runs from November to May. During the wet season, the characteristics of the floodplain
129 and Tonle Sap Lake play a vital role in flood peak attenuation and regulation temporarily
130 storing and later conveying water across the vast low-lying areas. During the wet season, water
131 flows from the Mekong mainstream into the Tonle Sap Lake, but this flow is then reversed in
132 the dry season. This illustrates the highly complex hydrological system at play throughout the
133 region, and the seasonal variations that characterize the ecological and agricultural landscape.

134 Within our historic baseline period of 1971–2000, the annual average temperature
135 across the study area varies from 26.9°C to 28.2°C, with mean monthly temperatures between
136 30°C during the hottest months (April and/or May), and 26°C in the coldest month (January).
137 Average annual rainfall across the study area during the same period varies between 1,100 mm
138 and 1,850 mm, with mean monthly rainfall ranging between 250 mm in the wettest months
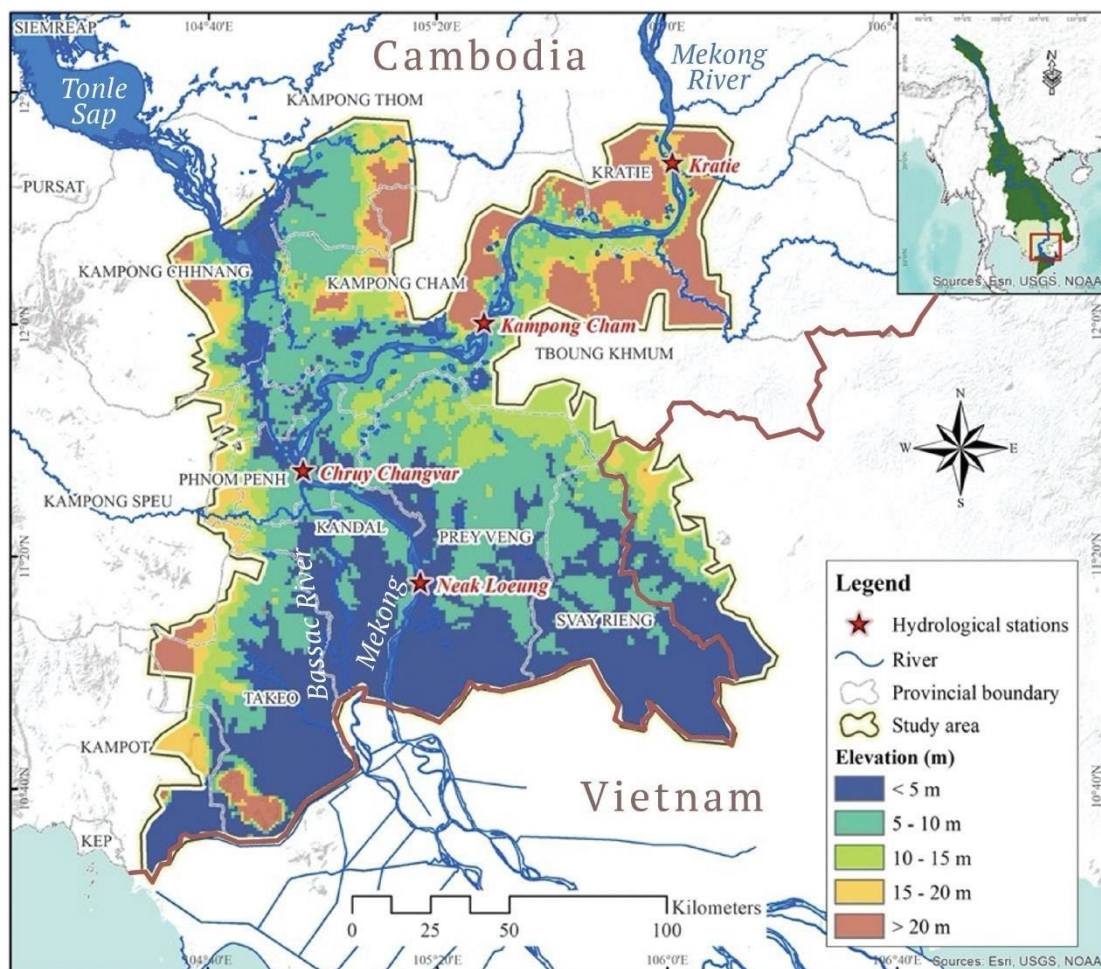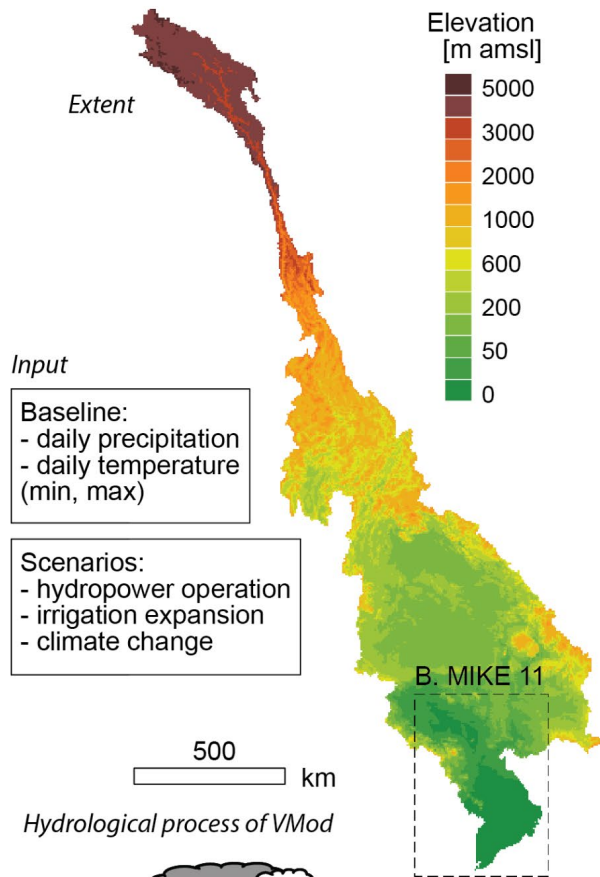139 (May/June), and 10 mm in the driest (February).



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

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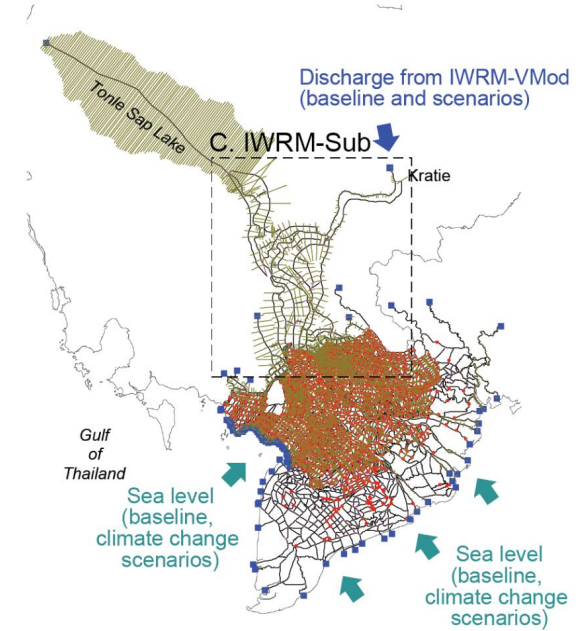143 *2.2. Modelling structure and datasets*

144 We used a hydrological – floodplain model combination (Fig. 2), consisting of the distributed

145 hydrological model IWRM-VMod (Lauri et al., 2006), the floodplain propagation model

146 MIKE 11 (Dung et al., 2011), and the flood extent and duration model IWRM-Sub (MRC,

147 2018a) (Fig. 2). First, the IWRM-VMod model with resolution of 5 km x 5 km (see extent

148 and hydrological processes in Fig. 2a) was used to simulate the entire Mekong basin's flow

149 response to hydropower developments, irrigation expansion, and climate change impacts at

150 around year 2050. We used the model runs, both baseline and scenarios, from Hoang et al.

151 (2019). From the hydrological model we derived the boundary condition discharges that were

152 used to drive the 1D flood propagation model MIKE 11 (as constructed and employed in

153 Triet et al., 2017, 2020) in order to obtain the initial floodplain conditions, water levels, and

154 fluctuating discharge of the Tonle Sap River. MIKE 11 model extends over the entire

155 Mekong Delta down to the South China Sea, where sea level is used as another boundary

156 condition. MIKE 11 also includes a detailed description of the channels, canals, and sluice

157 gates in the delta (Triet et al 2020). The results from MIKE 11 in turn were used as boundary

158 conditions to the detail scale (1 km x 1 km) floodplain hydrodynamic IWRM-Sub model. The

159 IWRM-Sub model is a flood model that also has hydrological processes (i.e., precipitation,

160 evaporation, etc) in it, making it ideal for large floodplain modelling in monsoon climate. It

161 uses the 2D depth averaged Navier Stokes, and St Venant equations to propagate a flood

162 wave out into the floodplain from the water level points passed as boundary conditions

163 (MRC, 2018a).

164 The IWRM-Sub model was applied to Cambodian floodplains for the Mekong River

165 Commission's (MRC) Council Study (MRC, 2018a). It is based on the SRTM 90-m

166 topographical map (Jarvis et al., 2008), a soil types map (FAO, 2003), and a land use map

167 (GLC2000, 2003), all aggregated to 1 km × 1 km resolution (Table 1). Geospatial data and

168 river cross-section data were retrieved and added from the Mekong River Commission

169 (MRC). The future climate scenarios are based on an ensemble of 5 GCM projections of

170 precipitation and temperature taken from the CMIP5 suite of models (ACCESS, CCSM,

171 CSIRO, HadGEM2, and MPI). Whilst the CMIP6 collection has now superseded the CMIP5

172 model results, an analysis of the differences between model collections shows consistent

173 mean values for both precipitation and temperature across our study area for both wet and dry
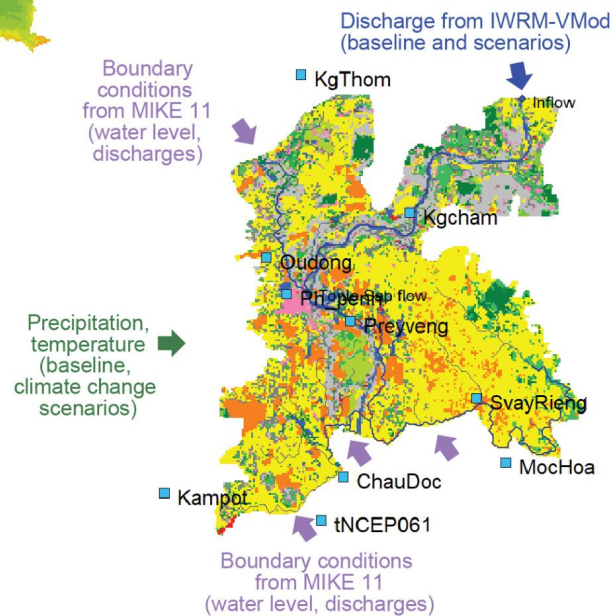
174 seasons (Table S1).

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Fig. 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

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185 presented in Table 1, while input data for IWRM-VMod is detailed in Hoang et al (2019) and

186 MIKE 11 in Triet et al. (2020).

187 **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<br>● Temperature<br>● Rainfall | 1971–2000 | Daily | Ensemble of 5 GCMs (ACCESS, CCSM, CSIRO, HadGEM2, and MPI) |
| 5 | Historical discharge data | 1985–2000 | Daily | Mekong River Commission |
| 6 | Historical water level data | 1985–2000 | Daily | Mekong River Commission |
| 7 | Hydropower dams and irrigation | – | – | Mekong River Commission |
| 8 | Climate change projections of temperature and precipitation. | 2036–2065 | Daily | Ensemble of 5 GCMs (ACCESS, CCSM, CSIRO, HadGEM2, and MPI) |
| 9 | Flood extent maps (satellite image) | 1985–2008 | 30 m | SERVIR-Mekong |
| 10 | River cross-section | – | – | Mekong River Commission |

188

189 *2.3. Modelling methodology*

190 We adapted and applied the existing IWRM-VMod (Hoang et al., 2019), MIKE11 (Triet et

191 al., 2017), and IWRM-Sub (MRC, 2018a) models to assess the smaller scale cumulative

192 impacts of future development plans and climate change on the Cambodian Mekong

193 floodplain. Here we enhanced the reliability of these existing models, particularly in the

194 Cambodian Mekong floodplain, by advancing the predictive accuracy of the hydrology

195 (recalibration), accounting for multiple calibration stations (four stations), and validating

196 flood extents against satellite imagery, as described below.

8

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

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

208　　　　Flood extent maps generated from the IWRM-Sub model were validated for the same
209　　period against satellite-based flood extent maps generated by the Surface Water Mapping Tool
210　　(SWMT). The SWMT is a Google Appspot based online application developed by Donchyts
211　　et al. (2016). A stack of Landsat (4 and 5) data were generated using SWMT from 1984 - 2000.
212　　This stack of images was then used to generate a water index map using the Modified
213　　Normalized Difference Water Index (MNDWI) (Xu, 2006) to distinguish between water and
214　　non-water areas, which were then adjusted to account for dark vegetation and hill shadows
215　　using a Height Above Nearest Drainage (HAND) map (Rennó et al., 2008). Fig. S1 illustrates
216　　all procedures of the Surface Water Mapping Tool.

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

223　　　　Once the IWRM-Sub model was successfully calibrated and validated, we modulated
224　　the inflow at Kratie and at the confluence of the Tonle Sap River with the main Mekong channel
225　　to represent the upstream impacts of multiple development and climate change scenarios (see
226　　Section 2.4). We then simulated the Cambodian Mekong floodplain's hydrological and flood
227　　conditions (flood extent, flood depth, and flood duration) for each scenario.

*2.4. Analytical scenario descriptions*

229 The scenario setup that we adopted for our study is the same as that described in Hoang et al.

230 (2019). The baseline (1971-2000) represents the Mekong basin at a time before significant

231 alterations to the hydrological functioning of the catchment have occurred through

232 infrastructural development. We then defined 11 development scenarios that cover each of the

233 three main drivers of hydrological change in isolation (hydropower, irrigation, and climate

234 change), as well as combinations of these together. For future scenarios, we used climate data

235 from an ensemble of five GCMs (ACCESS, CCSM, CSIRO, HadGEM2, and MPI) for the

236 years 2036-2065, and considered representative concentration pathway (RCP) levels 4.5 and

237 8.5. These GCMs were selected based on their performance in reproducing historic

238 temperature, seasonal precipitation, and climate extremes in the Mekong region. The GCM

239 data were downscaled using bilinear interpolation and statistically bias corrected using a

240 quantile mapping method. For full details see Hoang et al (2016; 2019). The seal level boundary

241 condition was adjusted by 43 cm for future scenarios to account for the combined effects of

242 sea level rise and deltaic subsidence, taken as the average of the range estimated by Manh et al

243 (2015) i.e., 22-63 cm. This value was used for both RCP4.5 and RCP8.5 as the climate change

244 component of sea level rise for our study period taken from IPCC (2014) is relatively consistent

245 across RCP scenarios (RCP4.5: 19-33 cm; RCP8.5: 22-38 cm). Our hydropower development

246 scenario includes 126 dams on both mainstreams (N= 16) and tributaries (N= 110) of the

247 Mekong, equivalent to a total active storage of 108 km$^3$, all of which are planned to be active

248 between 2036 and 2065. Dam simulation was based on the optimisation scheme developed by

249 Lauri et al. (2012), which calculates each dam's operating rules separately in a cascade, aiming

250 to maximise productive outflows (i.e., outflows through the turbines), thus maximising hydro-

251 power production. The optimised dam operation rules were later validated against observations

252 by Räsänen et al (2017). We also included two irrigation scenarios, a high and low expansion

253 version, using the global projected irrigation expansion scenarios by Fischer et al. (2007)

254 applied to the baseline irrigation extent taken from the MIRCA - 'Global Dataset of Monthly

255 Irrigated and Rain-fed Crop Areas around the Year 2000' (Portmann et al., 2010). A list of

256 scenarios and their notation are presented in Table 2, and a thorough description and

257 justification for these scenarios can be found in Hoang et al. (2019).

258 **Table 2.** Summary of scenario names, driving climate data, and development inclusion
259 descriptions. See Section 2.4 for data description.

| Scenario name | Scenario description |
| --- | --- |

| | Climate data | Hydropower | Irrigation |
|---|---|---|---|
| S1_Baseline | Baseline (1971 - 2000) | Circa 2000 | Circa 2000 |
| S2_Hydropower | Baseline (1971 - 2000) | Future development | Circa 2000 |
| 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 |
| S7_HP_RCP45 | Future (2036 - 2065) RCP 4.5 | Future development | Circa 2000 |
| S8_HP_RCP85 | Future (2036 - 2065) RCP 8.5 | Future development | Circa 2000 |
| S9_LI_HP_RCP45 | Future (2036 - 2065) RCP 4.5 | Future development | LOW irrigation expansion |
| S10_LI_HP_RCP85 | Future (2036 - 2065) RCP 8.5 | Future development | LOW irrigation expansion |
| 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 |

260

## 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

268 achieving NSE to observed water levels of between 0.72 and 0.97 across 19 different gauging
269 stations.

270      Here we validated the IWRM-Sub model for Cambodian Mekong floodplain against
271 water levels and discharge in four stations and flood extent based on Landsat imagery (see
272 Methods). Based on the validation measures (Table 3), a good model performance is obtained
273 at all stations (both water discharge and water level) with the values of NSE between 0.69 and
274 0.87, PBIAS between –14.4% and +9.8%, RSR between 0.37 and 0.55, and $R^2$ between 0.89
275 and 0.93. It should be noted that the statistical model performance with NSE and $R^2$ greater
276 than 0.5, PBIAS between ±25%, and RSR less than 0.7 is indicated as decision guidelines for
277 hydrologic model studies (Benaman et al., 2005; Setegn et al., 2010). A time series comparison
278 between the simulated and observed water discharge and water level (1985–2000) at four
279 hydrological stations can be found in Fig. S2 and Fig. S3. It is apparent that the simulated water
280 discharge among these stations is well in line with the observed data throughout the 15-year
281 hydrological record available for comparison.

282      Results of the flood extent comparison between IWRM-Sub model and SWMT
283 observations over the time horizon 1985–2000 show equally a good agreement. The model
284 underestimates the total flooded area by just 0.1% as the ratio of simulated to observed flooded
285 extent areas is 0.99. However, the overlapping flooded area only constituted 71% of the
286 observed (SWMT) extent (which constitutes the recall), and 72% of the simulated (IWRM-
287 sub) extent (which is the precision) (Fig. 3). Part of this discrepancy may be accounted for by
288 the inclusion of rivers and lakes in the extent of the simulation, yet not in the SWMT derived
289 extents. Using multiple models in succession can have the negative effect of compounding
290 errors, however these results demonstrate that this has not unduly impacted our methodology
291 as our estimations closely match the observations of flood extent.

292

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

| Station | Water discharge | | | | | Water level | | | |
|---|---|---|---|---|---|---|---|---|---|
| | NSE | PBIAS (%) | RSR | $R^2$ | | NSE | PBIAS (%) | RSR | $R^2$ |

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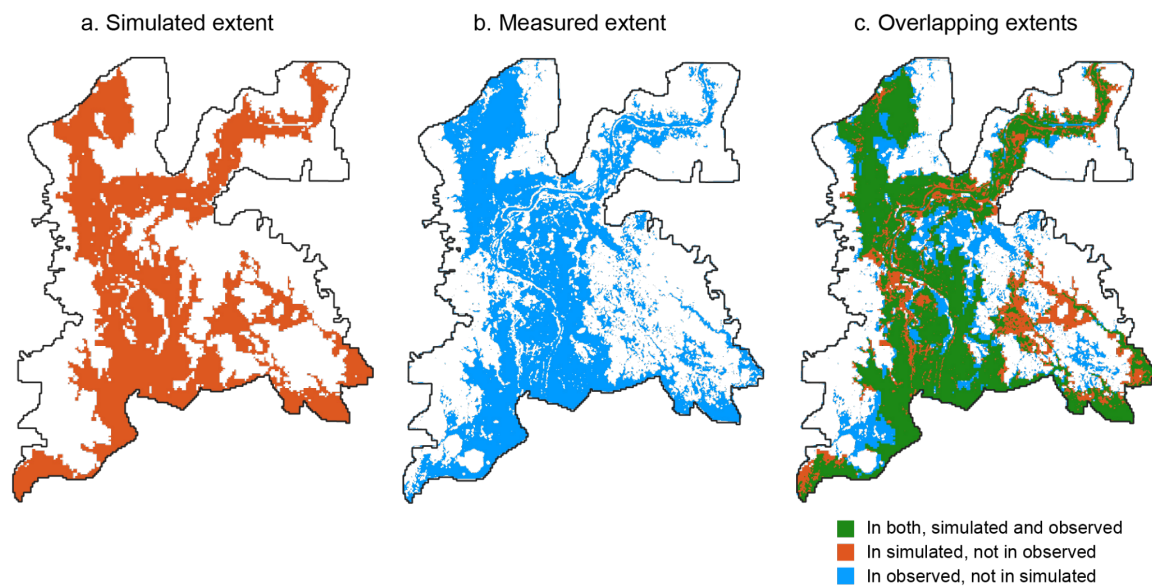| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Kratie | 0.79 | 0.9 | 0.45 | 0.89 | 0.69 | −14.4 | 0.55 | 0.93 |
| Kampong Cham | 0.80 | 4.5 | 0.45 | 0.90 | 0.87 | -1.4 | 0.37 | 0.93 |
| Chroy Changvar | 0.80 | 9.8 | 0.45 | 0.91 | 0.86 | -3.4 | 0.37 | 0.93 |
| Neak Loeung | 0.81 | -5.6 | 0.44 | 0.91 | 0.85 | 3.8 | 0.38 | 0.93 |

299

300



*Fig. 3. Comparison of maximum flood extent 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 (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. We then calculated the mean monthly water discharge and water level across the study period. 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).

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314       All scenarios that contain an element of hydropower development follow the same
315    pattern of increasing both water discharge and water level during the dry season (Nov–May),
316    whilst reducing water discharge and water level during the early and mid- wet season (Jun–
317    Sep) (Fig. 4). The impact of climate change appears to fluctuate during the months of January
318    to June between Kampong Cham (and Kratie and Chruy Changvar) and Neak Loeung, as there
319    is a slight increase in discharge and water levels at the upstream stations, yet a slight decrease
320    at the downstream station, though the magnitude of any alteration is only small. From July to
321    December, however, the climate change impact is much stronger and increases discharge and
322    water levels at all stations. The larger magnitude of the climate change impacts during the
323    wetter months counteracts the impact of hydropower and irrigation (which slightly reduces
324    flows and water levels in all months), which can be seen in the difference between scenario S2
325    (hydropower solo) and scenarios S7-S12 that incorporate multiple drivers (Fig. 4; scenario
326    description in Table 2). This is most evident at Kampong Cham station in October, where
327    climate change impacts are large enough to offset hydropower impacts, so that only those
328    scenarios that incorporate the additional impact of irrigation are strong enough to reduce flows
329    and water levels. Whilst the largest magnitude impacts are in the wetter months of July to
330    September, the proportional impacts are far larger in the dry season, where the impact of
331    hydropower development dominate the flow regime and increase water levels up to 150% in
332    April at Kampong Cham, compared to a maximum decrease of <25% in July.

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

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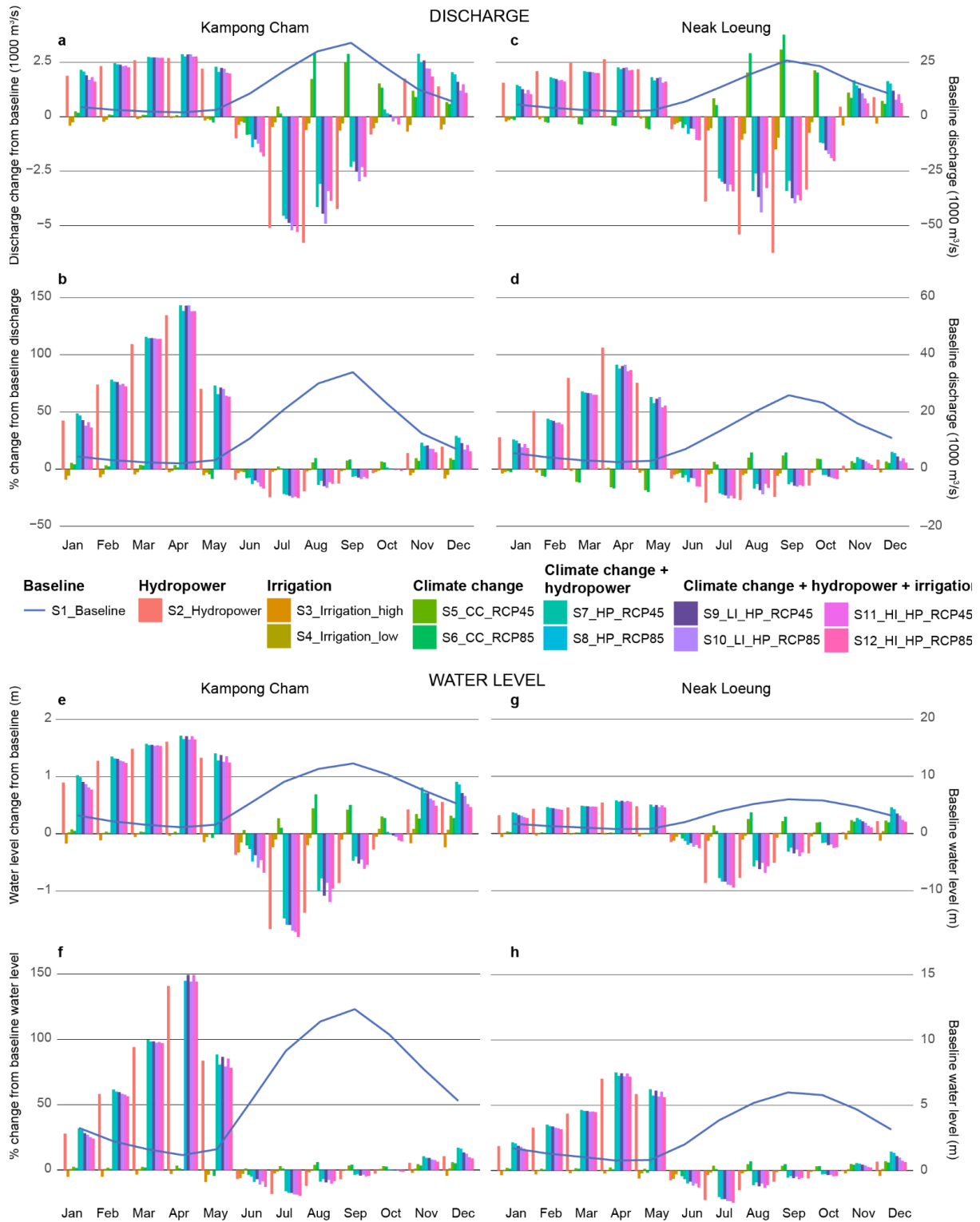341    change impacts in either counteracting or enhancing these alterations.

342

**Fig. 4.** *Changes in monthly water discharge and water level at Kampong Cham (left hand side) and Neak Loeung (right hand side); the blue line indicates the baseline monthly discharge and water level, and the colour bar 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 (1971–2000). (See location of stations in Fig. 1).*

15

348 *3.3. Impacts on flood conditions*

349 Here we present the quantitative results together with the spatial analysis of flood conditions

350 throughout the entire study area. The comparisons between each scenario and their

351 justifications are described in the analysis at the provincial level because of the similarity in

352 patterns. Under the baseline scenario (S1), the modelling results between 1971 and 2000 show

353 that the yearly flooded area ranges from 7,785 to 11,525 km$^2$. Its mean annual value is

354 estimated at 9,370 km$^2$, about 34% of the whole study area.

355 We compared year to year the impact of each development scenario against the

356 S1_baseline (1971-2000) on the total flooded area across the study area (Fig. 5). Scenarios S2-

357 S4 use the same driving climate data as the baseline scenario (S1), and so the variability in the

358 impact shown is significantly reduced to produce consistent impacts for all years. Whereas

359 scenarios S5-S12 are driven by future climate data projections, so that the variability in

360 comparing year to year is significant. Nevertheless, there is a clear pattern that emerges once

361 again showing the dominance of hydropower development in significantly reducing the yearly

362 flooded area. The impacts of both irrigation development scenarios (S3 and S4) also reduce the

363 yearly flooded area, though to a lesser extent. Climate change impacts in isolation (S5 and S6)

364 increase the flooded area overall, though there are some years in which the area is reduced

365 compared to the baseline. The proportional magnitude of these effects is most evident in the

366 solo hydropower development with a median reduction of >20% year on year, yet the combined

367 impact of irrigation, hydropower, and climate change did reduce flooded areas by up to 40%
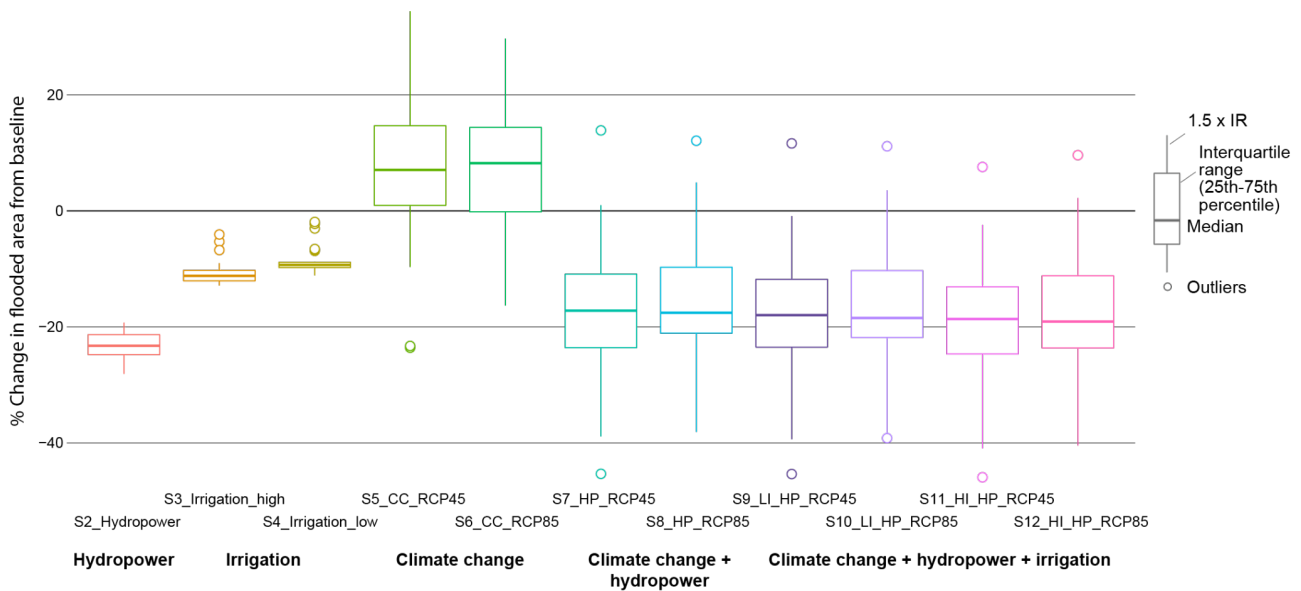
368 in some years (Fig. 5).

369

The spatial distribution of flood inundation and depth across the Cambodian Mekong floodplain varies greatly between scenarios of planned developments and climate change (Fig. 6). The floodplain is characterized spatially by a high fluctuation of flood depth and flood duration alteration of over ±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.
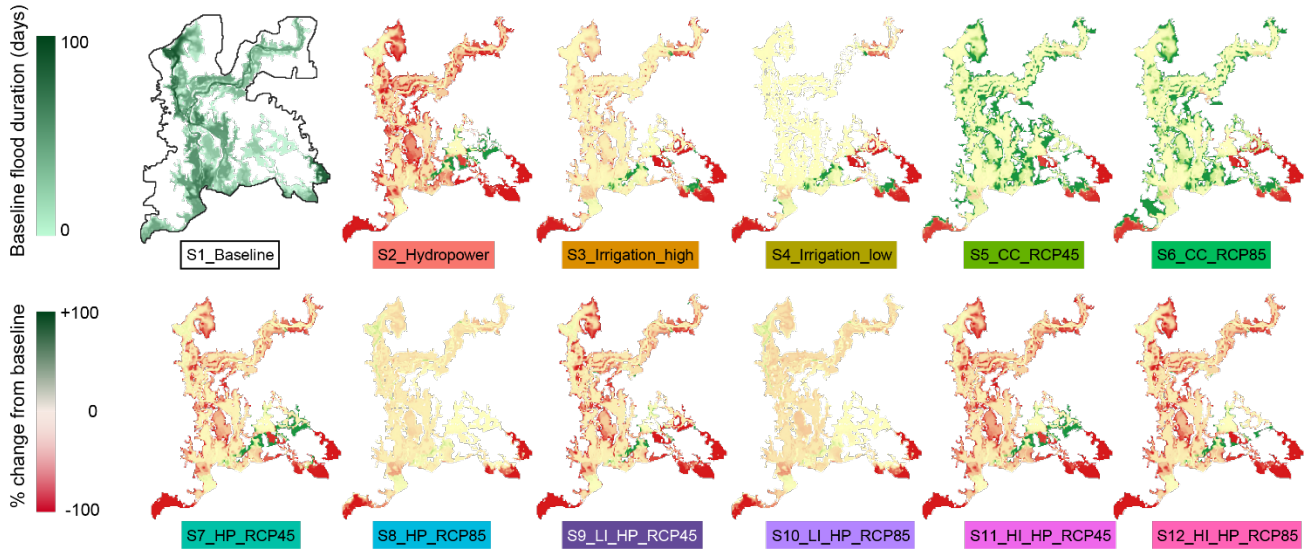
17
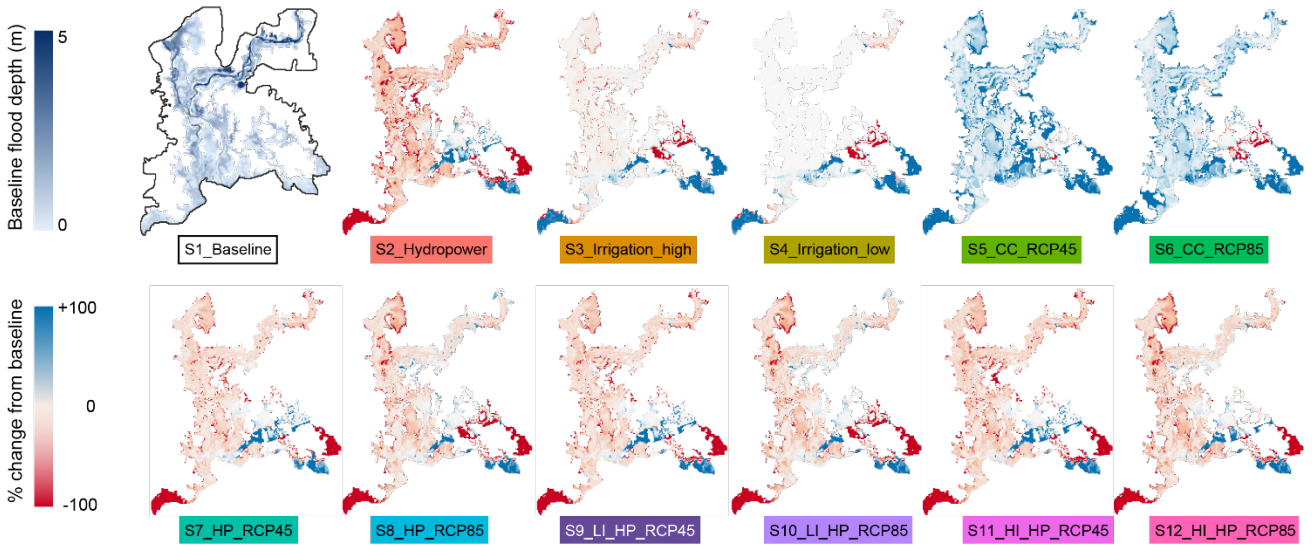
a FLOOD DEPTH

b FLOOD DURATION

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

*3.4. Provincial level analysis*

We examined the change in flooded area, flood depth and flood duration for 10 provinces that have a considerable part of their area within the study area (Kampong Speu and Kampot province, and Tay Ninh province in Vietnam, were not included; see Fig. 1). Each scenario was compared to the baseline period at the provincial level (Fig. 7). Under the baseline scenario (S1), the modelling results show that the average flooded area ranges from a minimum of 188 $km^2$ in Phnom Penh province to a maximum of 2,308 $km^2$ in Prey Veng province, which represents 43% of the provincial territory. Whilst the average flood depth ranges from 0.54 m

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400     in Svay Rieng province to 2.4 m in Kratie province, and the average flood duration ranges from

401     10 days in Svay Rieng province to 79 days in Kampong Chhnang province.

402     Except for the Svay Rieng region, which appears anomalous, Kampong Chhnang and

403     Kratie are least affected by the impacts of climate change, whilst Prey Veng and Takeo are

404     most affected (Fig. 7). The development scenarios have least effect in Prey Veng, where flood

405     area and depths are almost unaffected in comparison to the other provinces.

406     Svay Rieng displays an extreme reduction in flood duration for all scenarios, including

407     climate change scenarios, which is also true of the flooded area except for the RCP 4.5 climate

408     impact scenario (S5). Depths, however, increase in all scenarios suggesting that flooding in this

409     province is reduced in extent and duration to a shorter more intense (and so deep) flood event.
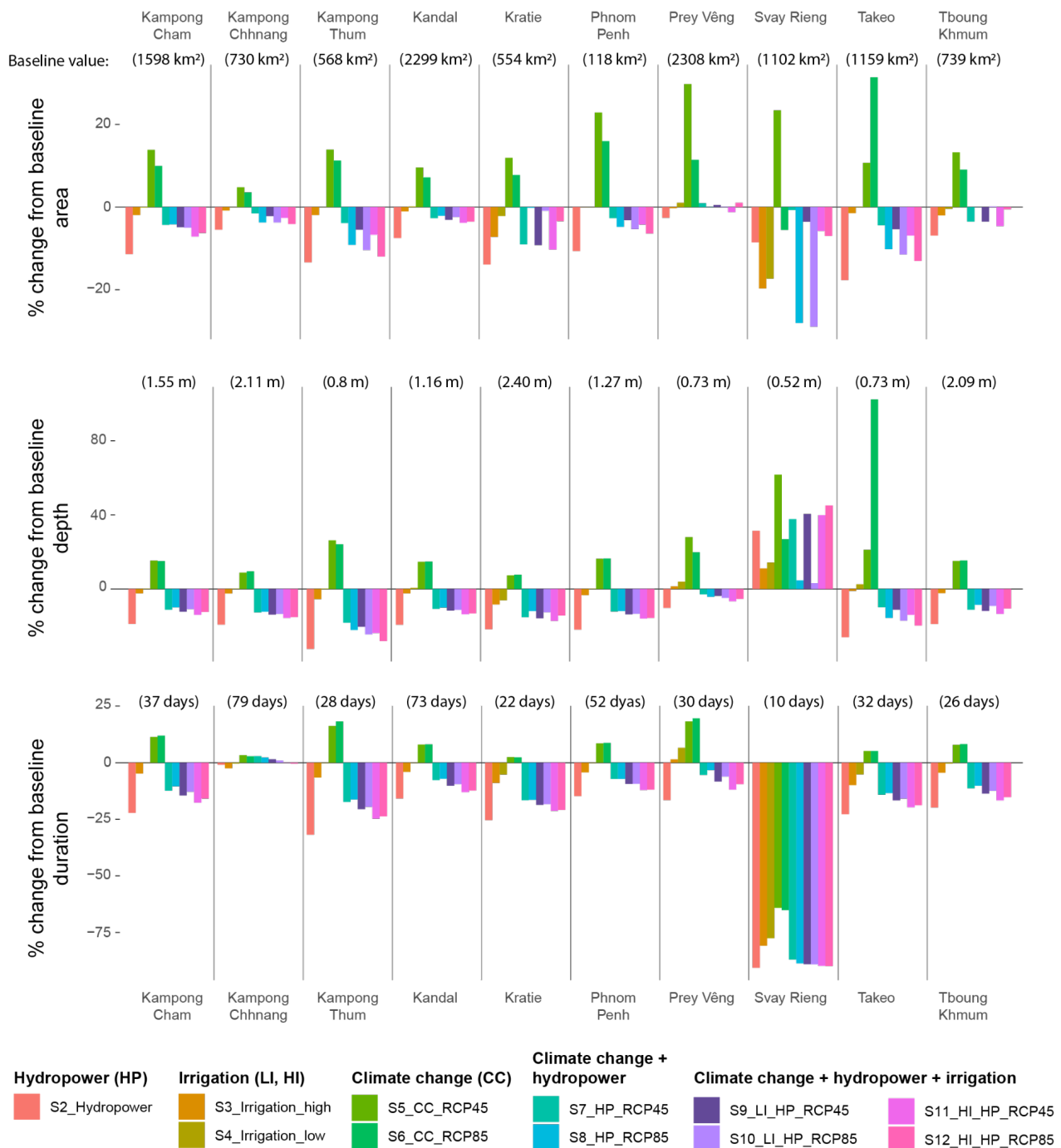
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**Fig. 7.** *Changes in annual mean flooded area, flood depth, and flood duration compared to the baseline period (1971–2000) for all scenarios at the provincial level. See province location in Fig. 1.*

## 4. Discussion

### 4.1. Key findings

The model performance metrics achieved by our hydrological simulation of water discharge and water level for the baseline period of 1971–2000 at all four monitoring stations (Kratie,

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418    Kampong Cham, Chroy Changvar and Neak Loeung) exceed existing studies within the same

419    region (Västilä et al., 2010), with the exception of Dang et al. (2018), who recorded an NSE

420    value of 0.98 compared to our value of 0.80 at Kampong Cham station. Whilst there are studies

421    of flood extent within our study area that only focus on a single event rather than a multi-year

422    analysis that slightly surpass our own in terms of performance metrics (Fujii et al., 2003), our

423    continual analysis of annual flood patterns comprising a 30-year time horizon is comparable

424    to, and often exceeds, other such multi-year analyses done in the region (Try et al., 2020a; Try

425    et al., 2020b). The relative success of our baseline simulations allows us to have a high degree

426    of confidence in our future projections of the Cambodian Mekong floodplain's hydrological

427    response to planned infrastructural development and future climate changes. All future

428    projections of scenarios containing multiple drivers that we considered within our analysis

429    followed the same generic pattern of alterations to both the expected discharge and river water

430    level, increasing during the dry season (Nov–May), and decreasing during the early- and mid-

431    wet season (Jun–Sep). Such a general pattern of alteration is due to the overwhelming

432    dominance of the hydropower development impacts, that overcome any counteraction that

433    might be applied by either irrigation development schemes (counteracts in dry season) or

434    climate change impacts.

435        These general trends are in line with the majority of previous research in the region

436    (Dang et al., 2018; Kallio and Kummu, 2021; Lauri et al., 2012; Piman et al., 2013; Räsänen

437    et al., 2012; Västilä et al., 2010). The degree of alteration to these hydrological indicators is

438    most pronounced in the upstream areas of Kratie, Kampong Cham, and Chroy Changvar

439    stations and diminishes downstream of the confluence with the Tonle Sap River towards Neak

440    Loeung station, which is also consistent with earlier findings (Dang et al., 2018).

441        Our findings clearly demonstrate the homogenizing effect that the planned hydropower

442    developments would have on the Mekong River's hydrograph, which would go far beyond

443    simply contracting the impacts of other drivers and would reshape the expected flow regime,

444    massively increasing dry season low flows and significantly reducing wet season high flows.

445        The future projections of flood conditions suggest that most provinces will see an

446    increase in depth, duration, and area under climate change scenarios, but that these alterations

447    are counteracted by the combined development scenarios reflecting the flood prevention

448    benefit afforded by irrigation and hydropower scenarios. These findings are supported by other

449    studies that look at the impact of isolated drivers of hydrological change in the region (Fujii et

450 al., 2003; Try et al., 2020a), and studies that look at multiple drivers in nearby regions (Hoanh,
451 et al., 2010; Pokhrel et al., 2018;).

452       Our provincial level assessment shows that Prey Veng province is most vulnerable to
453 the largest flooded area (Fig. 7), as its large territory is entirely located in the low-lying area
454 adjacent to the Mekong River. Kampong Thom province receives the largest flood prevention
455 benefit provided by the planned hydropower developments, whilst Kampong Chhnang receives
456 the least in terms of flooded area and flood duration, most likely because the flood regime is
457 strongly controlled by the Tonle Sap Lake System and receives less influence from the
458 upstream flow alterations. Svay Rieng province is drastically impacted by all the scenarios.
459 This is most likely due to the extremely low ground surface elevation (majority less than 8 m)
460 meaning that slight alterations have proportionally large impacts. The region may also be
461 affected by changes to the hydrological conditions on the Vietnamese Mekong Delta, some of
462 which were represented in this study by means of the boundary conditions supplied by Triet et
463 al (2020) that considered the whole delta region.

464 *4.2. Implications of hydrological and flood condition changes*

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

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

479       However, there are many negative consequences to the reduction in flood extent and
480 duration associated with the planned development scenarios. Hydropower projects in the
481 Mekong are projected to trap considerable parts of the sediments and the nutrients it contains

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482 in the reservoir behind the dam wall, reducing their transportation downstream and subsequent
483 distribution across the floodplain (Kondolf et al., 2018; Kummu et al., 2010; Schmitt et al.,
484 2018; Schmitt et al., 2017). The reduction in sediment transport rates associated with reduced
485 wet season flows and sediment trapping upstream inevitably leads to sediment-starved water
486 flow downstream. This in turn leads to increased rates of channel incision and accelerating
487 riverbank erosion as river waters gain in-situ material for transportation up to carrying capacity
488 (Darby et al., 2013; Morris, 2014). The drop in soil fertility (nutrient bound to sediment)
489 throughout the downstream floodplains would result in a great challenge for ecosystem
490 productivity (Arias et al., 2014), rice production (Boretti, 2020) and the sustainability of
491 flooded forests (rich habitats for fish and other species) (Arias et al., 2014). Dams also act as
492 barriers disturbing fish migration between upstream and downstream sections essential for
493 feeding and breeding, resulting in fisheries losses (Ziv et al., 2012). In addition, the increasing
494 dry season water levels will disturb various river works - for instance, the low water level
495 condition is favourable to river channel maintenance (dredging) and constructions of water
496 infrastructure, usually started and very active during the dry season months.

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

510 *4.3. Limitations and perspectives for future research*

511 Several studies have been conducted to understand hydrologic processes within the Cambodian
512 Mekong floodplain, Tonle Sap Lake Basin, and Vietnamese Mekong Delta. Different
513 considerations have been taken into account for the analysis in previous research; they include

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514  but are not limited to (1) water infrastructure development, (2) climate change, (3) sea level
515  rise, (4) land use and land cover change, (5) population growth, and (6) climatic related
516  phenomena. However, the present study is targeted to gain insight into how the combination of
517  upstream hydropower development, irrigation expansion, and climate change will affect the
518  Cambodian Mekong floodplain in terms of hydrological and flood patterns. Under climate
519  change scenarios, the future rainfall and temperature were assumed respectively to be wetter
520  and warmer.

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

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

539  Floods are an essential component of the landscape for both the people and the
540  ecosystem of the Mekong Basin, but they also pose significant hazards and losses when the
541  magnitude is too great to handle effectively.  As the development of water infrastructure could
542  cause a decrease in flood conditions and climate change may reverse such impacts, it is still
543  unknown what the desired flood water level and flood duration should be. This has led to a
544  great difficulty in proposing optimum flood protection measures while maximizing dam

545 benefits. Therefore, another potential research topic is the determination of the ideal flood
546 conditions for maximum productivity from both the agricultural and ecosystem perspectives.

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

**5. Conclusions**

553 By combining the effects of development activities and climate change, this research
554 uses a novel setup of three different models to assess the potential impacts of hydropower
555 development, irrigation expansion, and climate change on the Cambodian Mekong floodplain.
556 We show through model validation that the developed modelling setup performs well in the
557 study area and could therefore potentially be used for future studies in the Mekong, as well as
558 in the floodplains of other large rivers. Our findings contribute to the delivery of more precise
559 information about the expected changes to flooding regimes in the area and highlight the
560 importance of properly characterising the directions and magnitudes of these changes. The
561 combined development scenarios that we analysed exhibited the same pattern of decreasing
562 hydrological conditions during the wet season, whilst increasing water discharge and water
563 levels in the dry season. The degree of hydrological alteration under hydropower development
564 and irrigation expansion is counteracted to a limited degree by the impact of future climate
565 change, which is projected to intensify the onset of wet season months and exacerbate water
566 deficiencies in the dry season months.

567 Our findings assist in strategic plan formulation and decision-making processes in the
568 dynamic Mekong region. The positive and negative implications of developmental impacts on
569 water availability, flow alterations, and particularly flood regime alterations should be carefully
570 considered when determining the level of investment to place in counteracting measures.
571 Reduced flooding during the wet season has flood protection benefits, whereas increases in dry
572 season flows have the benefit of increased water availability for irrigation. However, the
573 negative impacts should also be considered: a reduction in fisheries productivity, sediment
574 trapping and a decline in nutrient supply to the floodplain, and a reduction in floodplain
575 ecosystem productivity. Balancing these trade-offs will be an essential component of any
576 successful floodplain management strategy put in place to address future climate change and

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577 uncertainty in a sustainable manner. A timely preparedness will be essential to avoid future
578 economic and environmental damages, as well as safeguarding the wellbeing of vulnerable
579 communities living throughout the Cambodian Mekong floodplain.

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