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Modelling climate change impacts on the flood pulse in the Lower Mekong floodplains

K. Västilä, M. Kummu, C. Sangmanee and S. Chinvanno

ABSTRACT

The flood pulse is a key element characterizing the hydrology of the Mekong River and driving the high ecosystem productivity in the Lower Mekong floodplains, both in the Cambodian lowlands and the Mekong Delta in Vietnam. This paper assesses the impacts of climate change, both in terms of changed basin water balance and sea level rise, on the Lower Mekong flood pulse. The impacts were simulated by a three-dimensional hydrodynamic model using the projected changes in sea level and the Mekong mainstream discharge under the influence of climate change as boundary conditions. The model simulations projected that average and maximum water levels and flood duration increase in 2010–2049. The most consistent and notable changes occurred in the average and dry hydrological years. Sea level rise had the greatest effects in the Mekong Delta, whereas the impacts of changed basin water balance were more notable in the upper areas of the Mekong floodplains. The projected impacts were mostly opposite to those resulting from regional water infrastructure development. Higher and longer flooding could cause damage to crops, infrastructure and floodplain vegetation, and decrease the fertile land area. On the other hand, it might boost ecosystem productivity and enhance dry season water availability.

Key words | climate change, flood pulse, hydrology, impact assessment, mathematical modelling, the Mekong River

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ABBREVIATIONS

amsl	above mean sea level
BASIN	changed basin water balance scenario
DIVA	Dynamic Interactive Vulnerability Assessment tool
ECHAM4	a general circulation model developed by the Max Planck Institute for Meteorology
EIA 3D	a three-dimensional hydrodynamic model developed by the Environmental Impact Assessment Centre of Finland Ltd
GCM	General Circulation Model
IPCC	Intergovernmental Panel on Climate Change
MRCS	Mekong River Commission Secretariat
POM	Princeton Ocean Model
PRECIS	a regional climate model developed by the Hadley Centre for Climate Prediction and Research
RMSE	root mean square error
SEA	sea level rise scenario
SEA + BASIN	cumulative impact scenario
SEA START RC	Southeast Asia START Regional Center
SRES	Special Report on Emissions Scenarios
START	Global Change SysTem for Analysis, Research and Training network
TKK	Helsinki University of Technology
VIC	Variable Infiltration Capacity model
WUP-FIN	Lower Mekong Modelling Project

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INTRODUCTION

Annual flooding is an essential part of hydrology in many wetlands, including floodplains. Floodplains, which demonstrate significant seasonal changes in water level and flooded area are categorized as pulsing systems (Junk 1997). Pulsing systems are characterized by the regular flood pulse, which is assumed to be the key factor explaining their high ecological productivity (e.g. Junk *et al.* 1989; Lamberts 2001). Floodplains and other wetland ecosystems rely on the maintenance of their hydrological regime, such as the regular flood pulse, to survive and to support the various species dependent on them (Millennium Ecosystem Assessment 2005).

As the ecological and environmental importance of wetlands and floodplains is being recognized around the world, attempts to understand the hydrodynamics of floodplains and their sensitivity to future scenarios have increased (e.g. Whigham & Young 2001; Wolski *et al.* 2006; Wilson *et al.* 2007). Wetlands are degrading and disappearing more rapidly than other ecosystems due to, for example, construction of water infrastructure and increasing water withdrawals by humans (Millennium Ecosystem Assessment 2005). Further, the pressure on water resources will grow in the future, particularly in the developing countries (Alcamo *et al.* 2007). The hydrological regimes of wetlands and the patterns of flooding may also be altered by climate change.

Climate change affects patterns of flooding by changing the basin water balance and raising sea level, which is a concern particularly in the river deltas. Changed basin water balance may alter the discharge hydrographs of rivers, and such alterations have been projected to cause significant changes in the flooding patterns of low latitude flood pulse systems (Mirza *et al.* 2003; Murray-Hudson *et al.* 2006; Veijalainen *et al.* 2007). Sea level rise is likely to aggravate seasonal flooding through backwater effects, as projected for instance in Bangladesh (Mohal *et al.* 2006). Sea level rise will displace millions of people and cause extensive damage to coastal ecosystems; the economic consequences will be particularly severe for many developing countries (Dasgupta *et al.* 2009).

The Mekong (Figure 1) is one of the largest monomodal (single-peaked) pulsing rivers in the world. Its average annual discharge of 475 km^3/a (15,000 m^3/s) (Mekong River Commission 2005) is the tenth greatest in the world, and its monthly discharges vary significantly between the wet and dry seasons. In the wet season, the annual monsoon floods inundate vast floodplains in the Lower Mekong Basin downstream of Kratie (see Figure 1). The timing of the floods is rather predictable, but their amplitude and duration vary according to the location and year. The Mekong River and its adjacent floodplains support fish and other natural resources, and provide water and fertile silt for agriculture. A large portion of the basin population depends on these water-related resources (Mekong River Commission 2003). The floodplains can be divided into three sub-areas according to their hydrological characteristics: the Tonle Sap lake–floodplain system, the Cambodian floodplains and the Mekong Delta (Figure 1).

The Tonle Sap lake–floodplain system is connected to the Mekong via the Tonle Sap River which flows towards Tonle Sap Lake in the dry season and towards the Mekong in the wet season (Figure 1). The Tonle Sap system is characterized by notable seasonal differences in water level and surface area (Kummu & Sarkkula 2008). It has been identified as one of the most productive freshwater ecosystems in the world (e.g. Bonheur 2001; Lamberts 2001), and its ecological productivity is widely attributed to the flood pulse from the Mekong River and the flooded gallery forests situated on the floodplain (Bonheur 2001; Lamberts 2001; Lamberts 2008; Nikula 2008). The timing of the flood pulse and monsoon rains is also crucial to rice farming since most of the rice cultivated in the Tonle Sap area is rainfed wet-season rice or floating rice (Heinonen 2006).

The hydrological conditions of the Cambodian floodplains are determined by both the seasonality of the Mekong discharge and the tides of the South China Sea. The tides have naturally the greatest impact in the Mekong Delta, which undergoes strong semi-diurnal and seasonal changes in water level. The hydrological regime of the Delta is strongly regulated by humans through flood control works and large-scale irrigation systems (Käkönen 2008). The intensively cultivated areas of the Delta are prone to damage caused by natural phenomena such as floods, droughts and saline water intrusion.

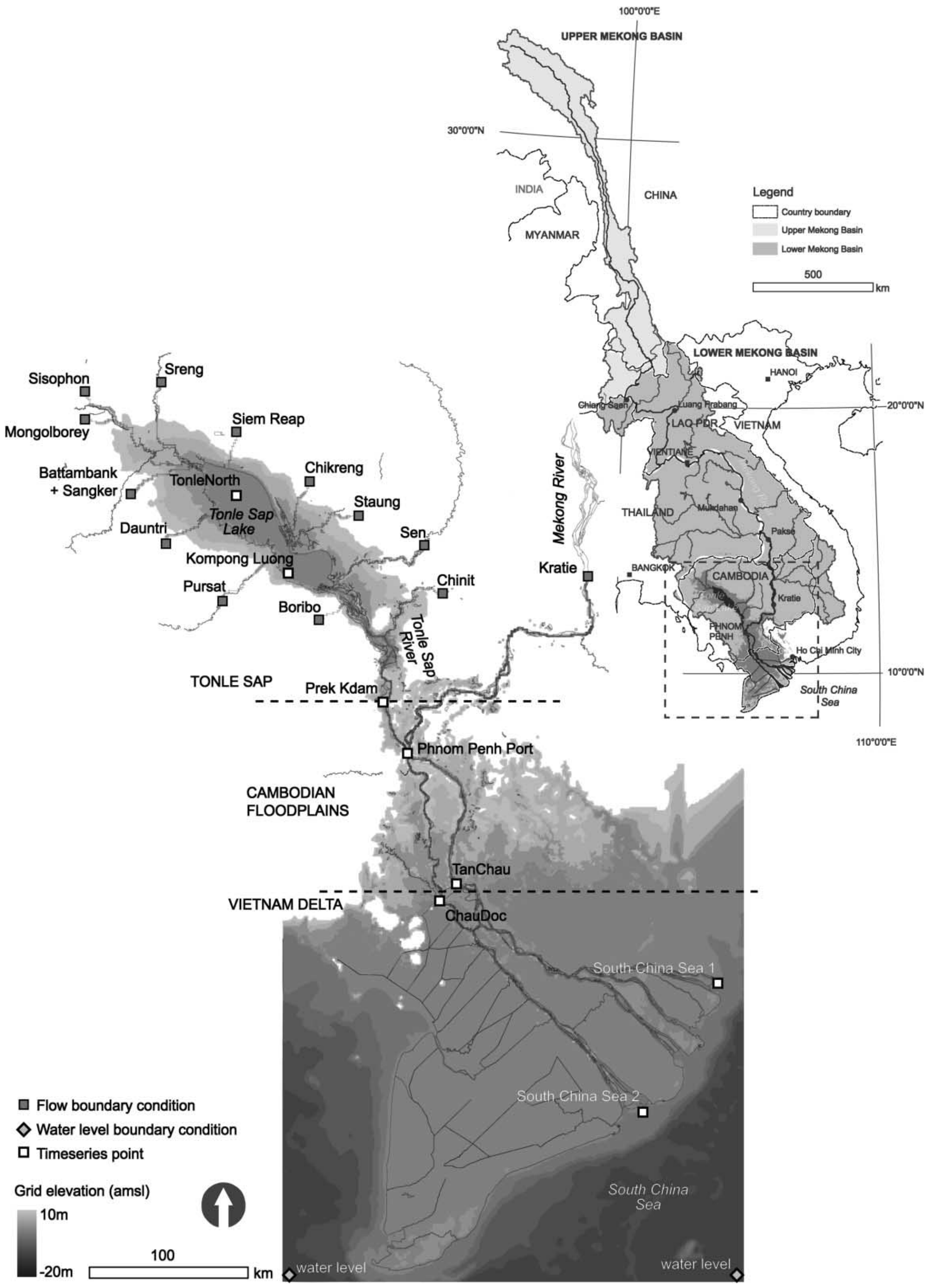

Figure 1 | The Mekong Basin (upper) and the EIA 3D model area with grid elevations, and boundary condition and time series points.

The Mekong River and its extensive wetlands are facing increasing pressure from water infrastructure development projects (see e.g. King *et al.* 2007; Kummu & Sarkkula 2008) and climate change (see e.g. Eastham *et al.* 2008; Penny 2008; TKK & SEA START RC 2009). Climate change is likely to affect the Lower Mekong floodplains through both the changing basin water balance, due to the large upstream basin area, and sea level rise, due to the proximity of the South China Sea. Before this study, the combined effects of changing basin water balance and sea level rise on the Lower Mekong flood pulse had not been thoroughly assessed.

The study presented in this article formed a part of a multidisciplinary research project looking at the interconnections between water and climate change in the Lower Mekong Basin (TKK & SEA START RC 2009; Keskinen *et al.* 2010; Nuorteva *et al.* 2010). The aim of this study was to estimate how climate change will alter the flood pulse characteristics in the Lower Mekong floodplains in the first half of the 21st century. The impacts of three scenarios were assessed: climate-change induced alterations in basin water balance, sea level rise and their cumulative impacts. The paper puts the impacts into the larger context by comparing them to those caused by water infrastructure development and to the overall uncertainty in climate modelling, and by describing some of their potential consequences.

METHODS

Climate change impacts on the Lower Mekong flood pulse were simulated with the combination of models shown in Figure 2. All the models were run for two periods: the baseline (years vary depending on data availability) and the future (2010–2049). The regional climate model developed by the Hadley Centre for Climate Prediction and Research (PRECIS) was employed to simulate the changes in the meteorological elements in the Mekong Basin under the influence of increasing greenhouse gas concentration. Output from the climate simulations was used to obtain the changes in the discharge of the Mekong River (at Kratie) with the Variable Infiltration Capacity (VIC) hydrological model and the changes in the sea level of the South China

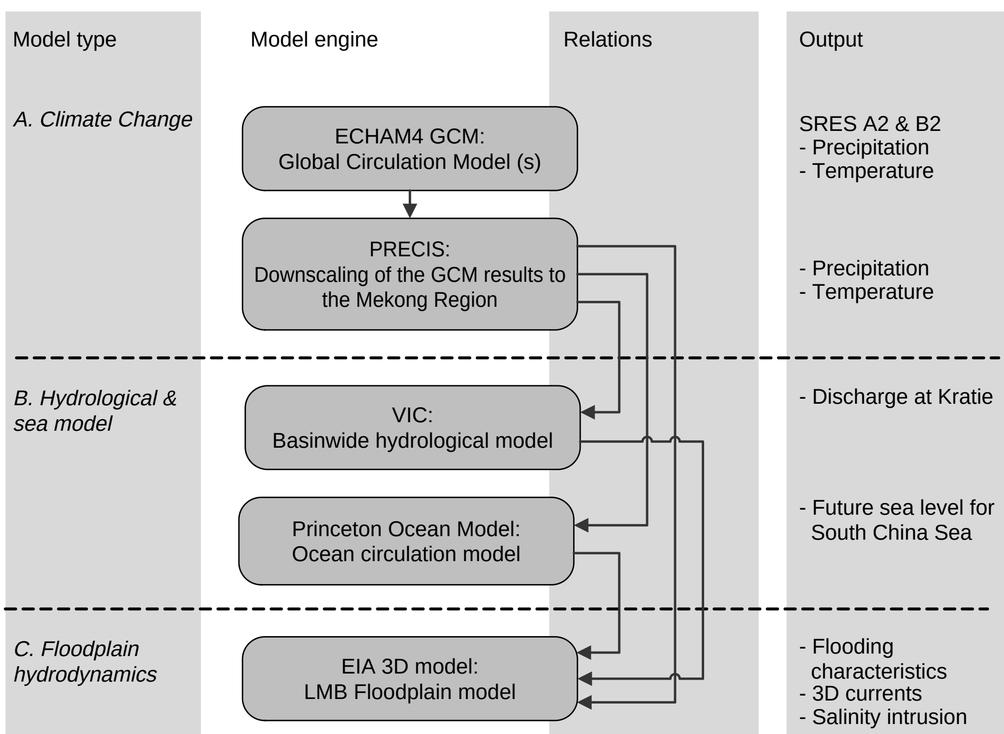

Figure 2 | Modelling approach.

Sea with the Princeton Ocean Model (POM) and the Dynamic Interactive Vulnerability Assessment tool (DIVA).

The discharge of the Mekong (at Kratie) and the sea level of the South China Sea were the boundary conditions of the EIA 3D (Environmental Impact Assessment three dimensional) hydrodynamic model, which was used to simulate the flood pulse in the Lower Mekong floodplains. The EIA 3D model was calibrated to reproduce the flood pulse in the baseline period (1997–2000), and future decades were simulated using the projected changes in the boundary condition time series. Climate change impacts were assessed by determining the differences in the key flood pulse characteristics between the simulated future scenarios and the simulated baseline.

Climate change analysis

Climate simulation

Climate was simulated by dynamically downscaling data from the ECHAM4 atmospheric–ocean general circulation model (GCM) runs (Roeckner *et al.* 1996) for the SRES A2 emissions scenario (Nakićenović & Swart 2000). Downscaling was accomplished with the PRECIS regional climate model (Jones *et al.* 2004). The resolution of the PRECIS model, 0.22 × 0.22° (~25 km × 25 km) allows the output to be used as input into semi-distributed hydrological models.

The PRECIS model tended to overestimate temperature by 1–2°C and underestimate annual rainfall by over 100 mm in the baseline (1980s) (Figure 3). A re-scaling technique was thus developed so that the model would simulate the baseline more accurately. The re-scaling factors for temperature and rainfall were determined as the absolute difference in average daily maximum temperature and annual rainfall, respectively, between the simulation and observation data at 130 weather observation stations in the region. The re-scaling factors at these grid cells were interpolated using kriging technique to obtain the re-scaling factors for every grid cell in the simulation domain (Figure 3). The re-scaled daily minimum temperatures were obtained by subtracting the difference between simulated daily maximum and minimum temperature from the re-scaled maximum temperature. The re-scaled maximum temperatures and rainfall differed by ±1°C and ±50 mm from the observed values in most observations stations (Figure 3), but the re-scaled minimum temperature was underestimated especially in the inland areas and overestimated in the coastal areas. The same re-scaling factors were used to re-scale the simulated values for the future.

Hydrological analysis

Changes in the discharge of the Mekong (at Kratie) were simulated using the VIC model, which is a semi-distributed grid-based hydrological model that simulates the dominant hydro-meteorological processes taking place at the interface between the land surface and the atmosphere (Liang *et al.* 1994). The VIC model was applied to the Mekong Basin upstream of Kratie, and it was coupled with a flow routing scheme including six routing stations. The VIC model was fed temperature and rainfall data obtained from the PRECIS runs. The baseline period was 1995–2004.

Two coefficients of the flow routing scheme were calibrated against observed monthly discharges in 1995–2004 at each routing station. The calibrated coefficients were the one controlling the base flow and runoff, which affects the amount of flow, and the one controlling the flow velocity, which affects the timing of flow. Figure 4 shows the simulated and observed monthly discharges for 1997–2000 at Kratie, and the squared correlation coefficient (R^2) between them was 0.63. The total wet season discharges were simulated reliably, but their timing was approximately 1 month too late in the model. The simulated annual discharge was on average 3% higher than the observed discharge in 1995–2002, but it had a 46% smaller standard deviation. The simulated discharges were thus close to the observed values in the average years but 8% smaller than the observed in the wettest year and 38% greater than the observed in the driest year. The calibrated VIC model was used for the simulations of the future.

Data of the Mekong's daily discharge were obtained from the MRCS (Mekong River Commission Secretariat) for 1961–2002. The annual average discharges were analysed to determine how representative the selected baseline period and the baseline years for the EIA 3D model (1997–2000) were of the long-term average. Years 2000, 2001 and 2002 had all very high discharge, so the

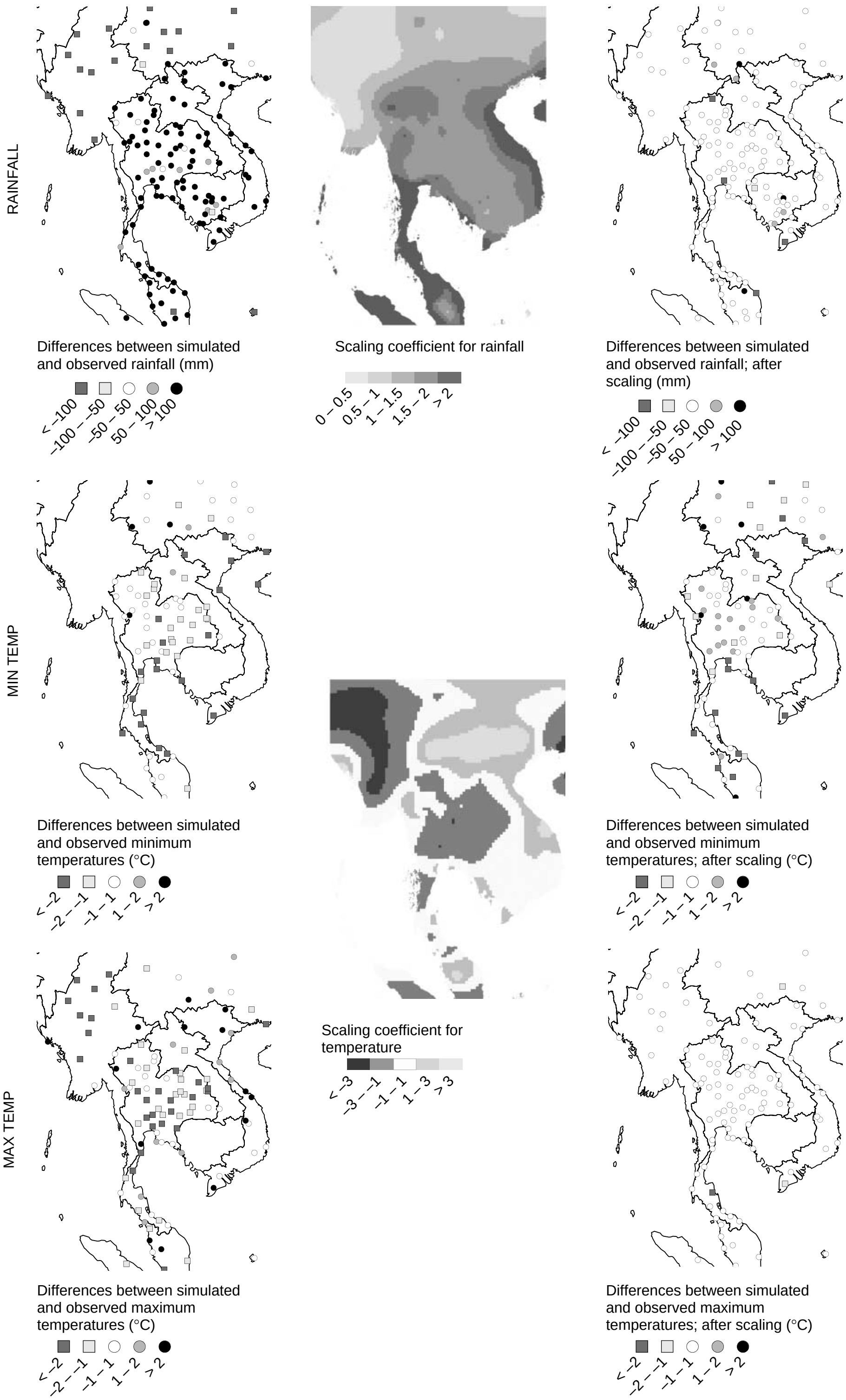

Figure 3 | Differences between simulated and observed average values before and after re-scaling for rainfall, and minimum and maximum temperatures. The re-scaling factors for temperature and annual rainfall are presented as well.

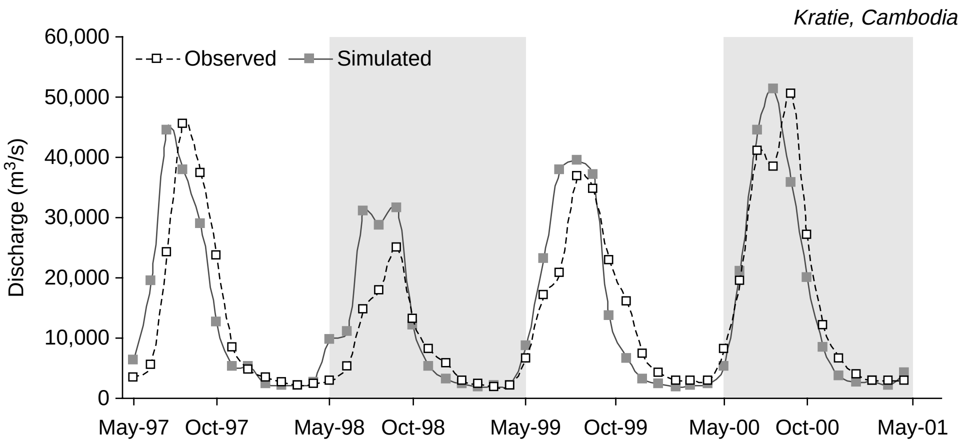

Figure 4 | The observed and simulated (by the VIC model) monthly discharges of the Mekong mainstream at Kratie in hydrological years 1997–2000.

selection of the 40-year baseline period (1961–2000 or 1963–2002) affected the baseline values. The natural variability of the Mekong's discharge was notable: 10-year moving average discharge varied from 11,700 to 13,200 m^3/s, 10-year moving lowest discharge from 8,600 to 10,400 m^3/s, and 10-year moving highest discharge from 13,900 to 18,100 m^3/s during 1961–2000.

The 1997 discharge was 10% higher than the 1961–2000 average but 2% lower than the 1993–2002 average. Thus 1997 was considered representative of the baseline average hydrological year. 1998 was the driest year in 1961–2002, and its discharge was 9% smaller than the average of 10-year moving lowest discharge and 7% smaller than the average of the four lowest discharges in 1961–2000. 2000 had the highest discharge in 1961–2002, which was 19% greater than the average of 10-year moving highest discharge, 11% greater than the average of the four highest discharges in 1961–2000 and 7% greater than the average of the four highest discharges in 1961–2002. 1998 was slightly drier and 2000 somewhat wetter than the 10-year average values in the baseline, but they were considered representative enough of the baseline period.

Sea level analysis

Future sea levels in the South China Sea were estimated by combining the effects of sea level rise and changing sea surface fluctuations. The average rate of sea level rise due to climate change was assessed using the DIVA tool (Hinkel & Klein 2006), and the local sea surface fluctuations caused by changing wind conditions were simulated using the POM (Mellor 2004). The POM used the wind speed and wind direction simulated by the PRECIS model as input, and it was run at a resolution of $0.2° \times 0.2°$. The POM simulated the seasonal changes in sea level satisfactorily but was not able to reproduce the short-term sea level fluctuations caused by meteorological phenomena. The POM output was combined with DIVA output to obtain the future sea levels.

Flood pulse simulation

The Lower Mekong flood pulse was simulated using the EIA 3D hydrodynamic model (Koponen *et al.* 2005; Kummu *et al.* 2006; MRCS/WUP-FIN 2008*a*), a three-dimensional baroclinic multilayer model which numerically solves the simplified Navier–Stokes equations using the implicit finite difference method (Koponen *et al.* 2005). The EIA 3D model has also been used for climate change simulations in the floodplains of the Nam Songkhram River, a tributary of the Mekong in Thailand (Veijalainen *et al.* 2007).

The EIA 3D model has been set up for the Lower Mekong floodplains during the WUP-FIN project (MRCS/WUP-FIN 2008*b*). The model covers an area of 430 km × 570 km, extending from Kratie down to the South China Sea (Figure 1). The grid resolution of the model is 1 km × 1 km, and the flow is simulated in 10 vertical layers. The EIA 3D model incorporates data on topography, bathymetry and land use. The model takes into account the natural stream network of the Mekong and the large man-made channels. The smaller irrigation and drainage channels are excluded from the model due to the coarse resolution of the model grid, which might cause the simulated water levels in the Delta to be somewhat too high. However, this did not affect the results concerning climate change impacts on flood pulse because the simulated flood pulse characteristics for the future were compared against the simulated characteristics for the baseline period, and not against the observed characteristics. The model determines flow resistance based on two friction parameters: bottom friction, which is uniform across the whole modelling area, and vegetation drag, which differs according to the land use class.

The boundary conditions of the model include daily discharges of the Tonle Sap tributaries and the Mekong, and hourly sea levels at the South China Sea. The EIA 3D model does not consider hydrological processes in the modelling area, but direct rainfall on the water surface of Tonle Sap Lake was included in the model by adding it to the observed tributary discharges. The EIA 3D model was separately run for each simulated hydrological year, defined as the period from 1st May of the year indicated to 30th April of the following year. The simulations were run with time steps of 45–2,000 s depending on the simulated process, and the initial water level was set at 1 m above mean sea level (amsl) in the whole modelling area.

Baseline runs

The baseline period was chosen as 1997–2000 because of the shortage of long-term observational data and because it was representative enough of the year-to-year hydrological variations: the period included an average hydrological year (1997), a very dry hydrological year (1998) and a very wet hydrological year (2000). The baseline simulations were carried out using observational data received from the Mekong River Commission.

The friction parameters of the model were calibrated against observations of daily water level at the Kompong Luong station in Tonle Sap Lake (KgLuong in Figure 1). The calibration aimed at reproducing the flood pulse as accurately as possible without significantly over-predicting the dry season water levels. This was achieved with the bottom friction set at 0.015 and the vegetation drag set at 0 to 0.2 depending on the type of land use. The overall root mean square error (RMSE) was 0.53 m for daily water levels during the peak of the flood pulse (August–January). The model was able to simulate the rise of the flood and the highest water levels satisfactorily (Figure 5). However, the drying of the floodplains was too slow in the model, and water levels remained too high at the end of each hydrological year. Water levels were also consistently over-predicted in 1998, a very dry hydrological year. The overall RMSE was 0.69 m for daily water levels in the drier months (February–July). The model was validated against water levels of Phnom Penh port and Tan Chau in hydrological years 1997–2000 (Figure 5).

Scenario runs

The scenarios were run using the calibrated EIA 3D model. The scenarios were simulated for the wettest, driest and average years of each decade in 2010–2049. The type of hydrological year was determined on the basis of annual discharge of the Mekong at Kratie simulated by the VIC model. This approach allowed comparison of the average, dry and wet years between the baseline and future decades. Apart from the modifications mentioned below, the boundary condition time series of the EIA 3D model were kept the same as in the corresponding type of hydrological year in the baseline. The following scenarios were simulated:

(1) sea level rise (SEA), run using modified sea levels of the South China Sea,
(2) changed basin water balance (BASIN), run with modified discharges of the Mekong,
(3) cumulative impacts of sea level rise and changed basin water balance (SEA + BASIN), run with modified sea levels of the South China Sea and modified discharges of the Mekong.

The ‘delta change’ method (e.g. Andersson *et al.* 2006) was adopted to construct the required boundary condition time series for the scenario runs. In this method, the changes between the simulated baseline and the simulated future are imposed on the observed time series. For instance, the simulated daily discharges of the Mekong for each future year were compared to the simulated daily discharges of the baseline period. The relative changes between these were obtained separately for each future year, and the time-series of the observed Mekong discharges were changed by those relative amounts for each of the scenario runs. The same methodology was conducted for the sea level time series. Since the timing and amount of the simulated baseline discharges did not fully agree with the observed baseline discharge (see above: *Hydrological analysis*), it was more reliable to use the 'delta change' method, and thus the simulated relative change in the input data, instead of directly using the absolute simulated values.

Flood pulse characteristics

Flood pulse characteristics have been previously presented for the Tonle Sap system (e.g. Kummu & Sarkkula 2008;

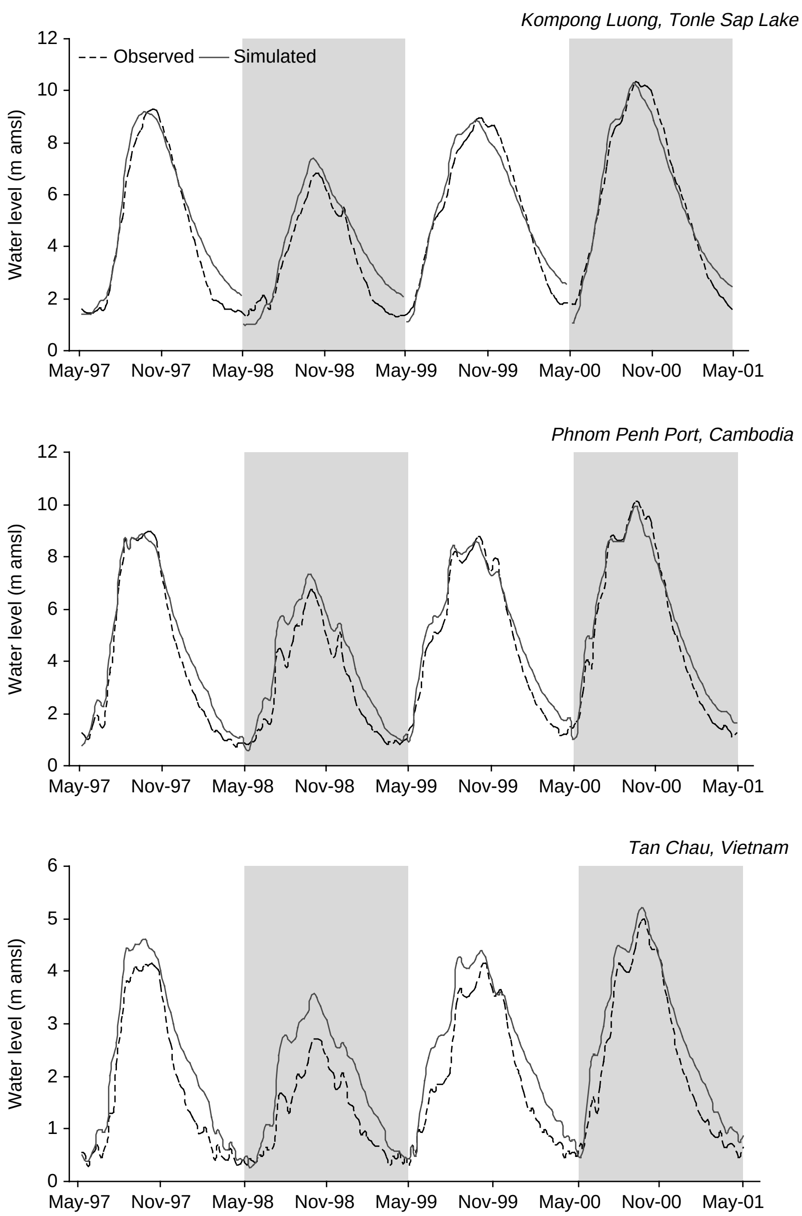

Figure 5 | The observed and simulated (by the EIA 3D model) water levels (as above mean sea level) in Kompong Luong (Tonle Sap Lake), Phnom Penh port and Tan Chau in hydrological years 1997–2000.

Lamberts 2008), and the following characteristics were considered in this study: average water level, average low water level, average high water level, maximum water depth, maximum flooded area, peak date, start date, end date and flood duration. Flood pulse characteristics were calculated for each model run as average values for three sub-areas: 1) the Tonle Sap system north of Prek Kdam (Kompong Luong); 2) the Cambodian floodplains between Prek Kdam and Tan Chau (Phnom Penh); and 3) the Mekong Delta south of Tan Chau (Tan Chau) (sub-areas shown in Figure 1).

The average, average low (February–July) and average high (August–January) water levels were obtained at one grid cell in each sub-area (at Kompong Luong, Phnom Penh and Tan Chau), considered to be representative of the sub-area in question. Peak date signifies the occurrence of maximum water depth, and these two characteristics were computed as average values over the EIA 3D model grid. Maximum flooded area was defined as the total area that has been inundated during each model run. Start date, end date and flood duration were obtained for the Tonle Sap floodplains following the methodology of Kummu & Sarkkula (2008). No corresponding method exists for determining the start and end dates for the other sub-areas. For them, flood duration was calculated as the average number of days that areas situated between 0 and 2 m amsl are inundated.

Likelihood assessment

Climate change impacts on flood pulse characteristics were assessed by comparing the simulated scenario (average over the four 10-year periods, 2010s–2049s) with the simulated representative baseline year. Determining whether the simulated changes are statistically significant would have required long time series, preferably 30 or 40 years, of the baseline flood pulse characteristics, but such data could not be obtained since there is not enough monitoring data to simulate the past decades with the EIA 3D model. However, as the hydrological analysis showed that the Mekong discharges in the selected baseline years (1997–2000) were representative enough of the decade's average, wettest and driest hydrological years for 1961–2000 (see *Hydrological analysis* above), it was assumed that the simulated flood pulse characteristics in the baseline years were representative of the long-term average, and the decade's wettest and driest hydrological years. An assessment of impact likelihood was thus carried out by comparing the simulation results of the scenarios to those of the baseline. If at least eight of the nine scenario runs produced similar direction of change averaged over the three sub-areas, the change was considered 'very likely'. If at least seven of the nine scenarios agreed, the change was considered 'likely'.

RESULTS

Climate change analysis

The PRECIS model projected that the daily average minimum and maximum temperatures increase on average by 1–2°C in the Mekong Basin by the 2040s compared to the baseline (1980s). The greatest changes were simulated for the northern areas of the Mekong Basin (Figure 6). The duration of the warm period extended longer in the scenario simulations than in the baseline.

Annual rainfall was projected to grow by 4% on average, but the simulated changes were very uneven across the basin (Figure 6). Rainfall increased in the northern areas of the basin but decreased in the Lower Mekong floodplains. The higher amount of rainfall was explained by increasing rainfall intensity as the length of the rainy season was projected not to change noticeably. According to the POM and DIVA simulation, sea level rises at a rate of 7–8 cm in a decade, the sea level being 31 cm higher in 2045 than in 1997.

The VIC simulations for the future (2010–2049) were compared to both observed discharges in 1961–2000 and the simulated discharges of the baseline (1995–2004). Comparing simulated and observed discharges required removing the bias from the simulated discharges. The bias in the decade's wettest and driest years was removed by scaling the four highest discharges in 2010–2049 down by 8% and the four lowest discharges up by 38% (see *Hydrological analysis*). The average annual bias (+3%) was then removed by decreasing all the simulated discharges by 3%. The so-obtained future annual discharges were on average 15% higher, the decade's maximum discharges on average 18% higher, and the decade's

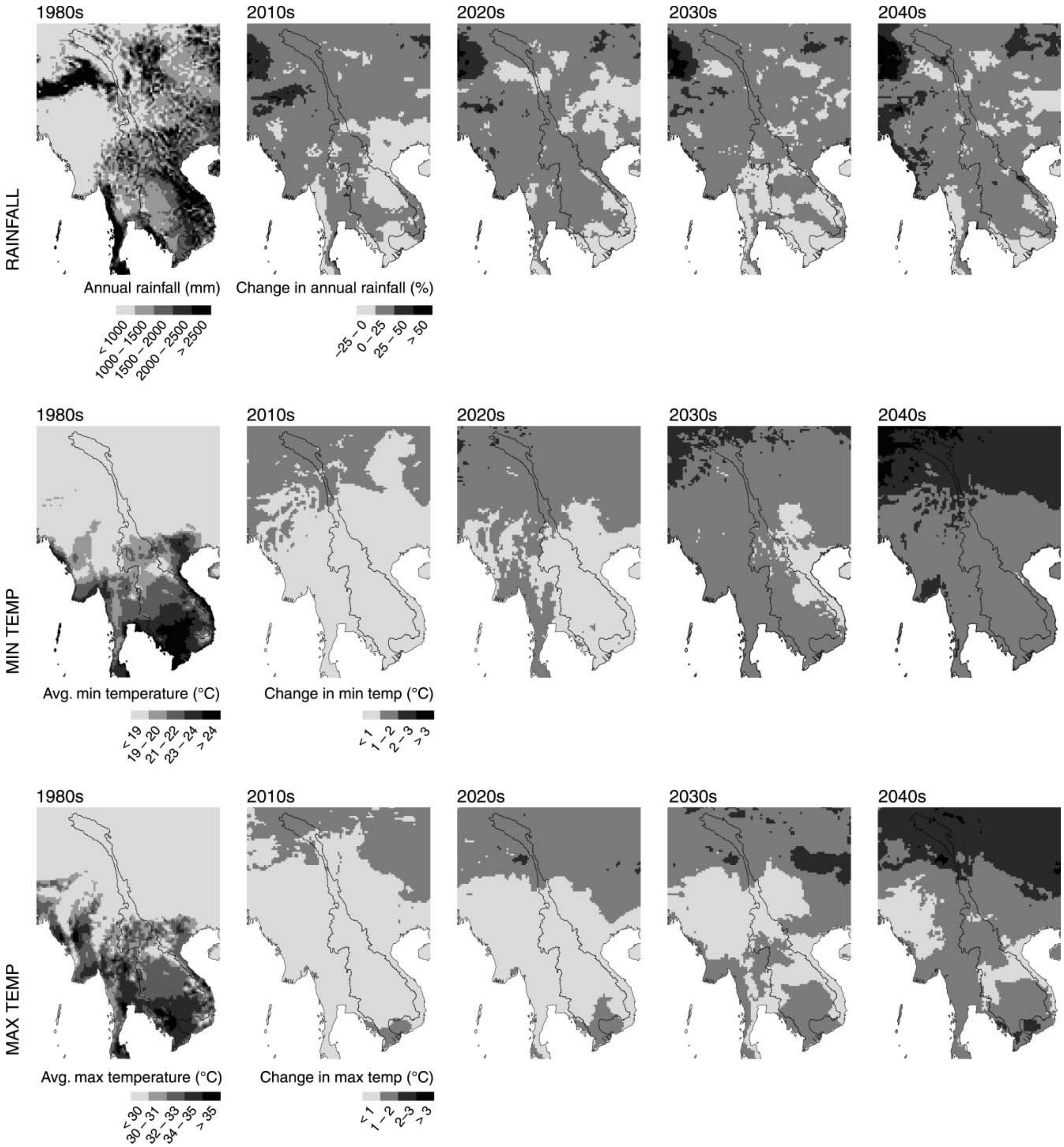

Figure 6 | Simulated future change compared to the baseline decade (1980s) under the SRES A2 scenario. From top: Annual average rainfall, average daily minimum temperature and average daily maximum temperature.

minimum discharges on average 3% lower than those in 1961–2000.

Compared to the simulated discharges in the baseline (1995–2004), the average annual discharge of the Mekong increased by 4% in 2010–2049 (Figure 7). The wet season discharges (May–October) increased by 5%, and the dry season (November–April) discharges decreased by 2%. In 2010–2049, the decade's greatest discharge was on

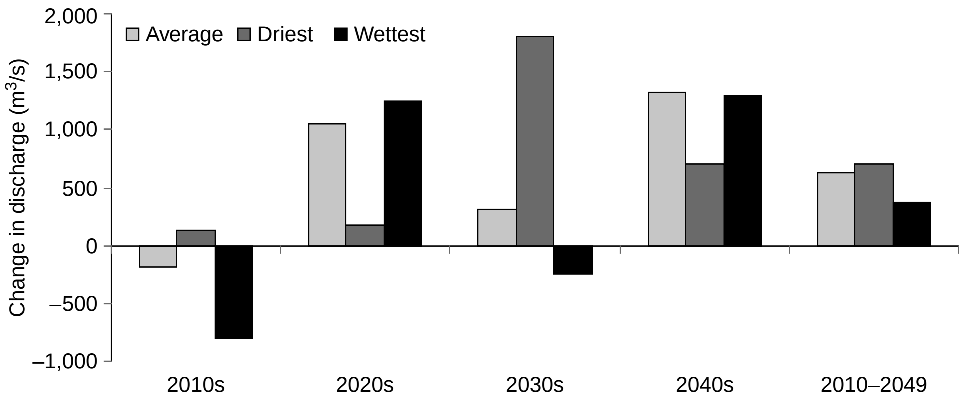

Figure 7 | The changes in annual discharge of the Mekong (at Kratie) relative to the baseline for the average, driest and wettest hydrological years simulated by the VIC model.

average 4% higher and the decade's lowest discharge on average 6% higher than in 1995–2004. There were thus notable differences in the simulated discharge changes with different reference periods, which is mostly explained by the fact that the period 1995–2004 was significantly wetter than the period 1961–2000.

Climate change impacts on flood pulse characteristics

In this sub-section, results from the analysis of flood pulse characteristics are presented. The results are given as difference between the simulated scenario (average over the four 10-year periods, 2010s–2049s) and the simulated baseline (1997–2000). A more detailed analysis for the Tonle Sap area is provided by Västilä (2009).

Average water levels

In all the three sub-areas, annual average water level was projected to increase in every scenario (Figure 8). Higher annual average water level also results in a greater annual cumulative flooded area. The average low and high water levels were simulated to rise in seven to eight scenarios out of nine (Figure 8). As both BASIN and SEA scenarios mostly caused the average water levels to rise, the cumulative impact scenario (SEA + BASIN) generally produced the most significant changes in water levels compared to the baseline.

The greatest relative changes occurred in the average low water level (−3–17%), with the Mekong Delta generally experiencing more notable changes than the other sub-areas. The annual average and average high water levels underwent changes of 0–7% and −4–5%, respectively, with the Delta mostly exhibiting somewhat greater changes than the other two sub-areas. Changed basin water balance caused more similar relative impacts between the sub-areas than sea level rise.

Sea level rise increased the annual average water levels by raising the average low water levels. The projected sea level rise hardly affected the average high water levels even in the Mekong Delta. The effects of sea level rise were more notable in the dry and average hydrological years compared to the wet years since sea level is of greater importance as a forcing factor in the less wet years. The Tonle Sap area remained almost unaffected by the simulated sea level rise.

Annual maximum water depths and flooded areas

Annual maximum water depth and flooded area increased in the simulated average and driest hydrological years of the future, whereas the wettest hydrological years experienced decreases or only small increases in these characteristics (Figure 9). The projected annual maximum water depth and flooded area differed by −3–12% and −3–14%, respectively, from the baseline values.

The most significant changes took place in the average hydrological years. The absolute changes in maximum depth were the greatest in the Tonle Sap area, but the relative changes were higher in the other sub-areas. Maximum flooded area underwent the greatest absolute and relative changes in the Cambodian floodplains (−3–14%) and the smallest relative changes in the Mekong Delta (0–3%). Changes in simulated maximum depth did not always correspond to changes in the simulated maximum flooded area, particularly in the Mekong Delta, because the relationship between water depth and flooded area varies according to the location.

The simulated changes in the Tonle Sap and Cambodian floodplains were caused by changed basin water balance, whereas the Mekong Delta was affected by both changed basin water balance and sea level rise. One reason for the fact that sea level rise increased the maximum extent of flooding in the Delta but hardly affected the average high water level (see previous sub-section) is that the water levels

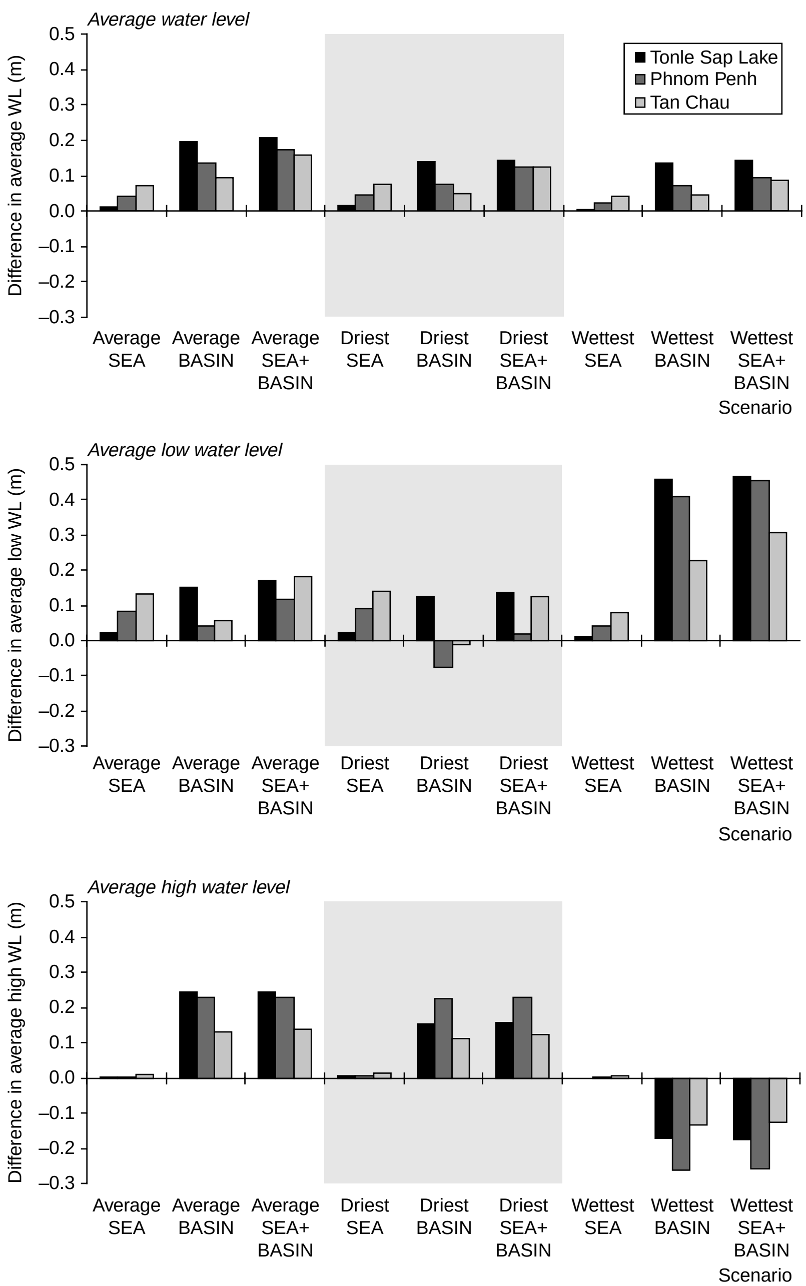

Figure 8 | The simulated differences in average water level, average low water level and average high water level in 2010–2049 (average over the four 10-year periods) compared to the baseline.

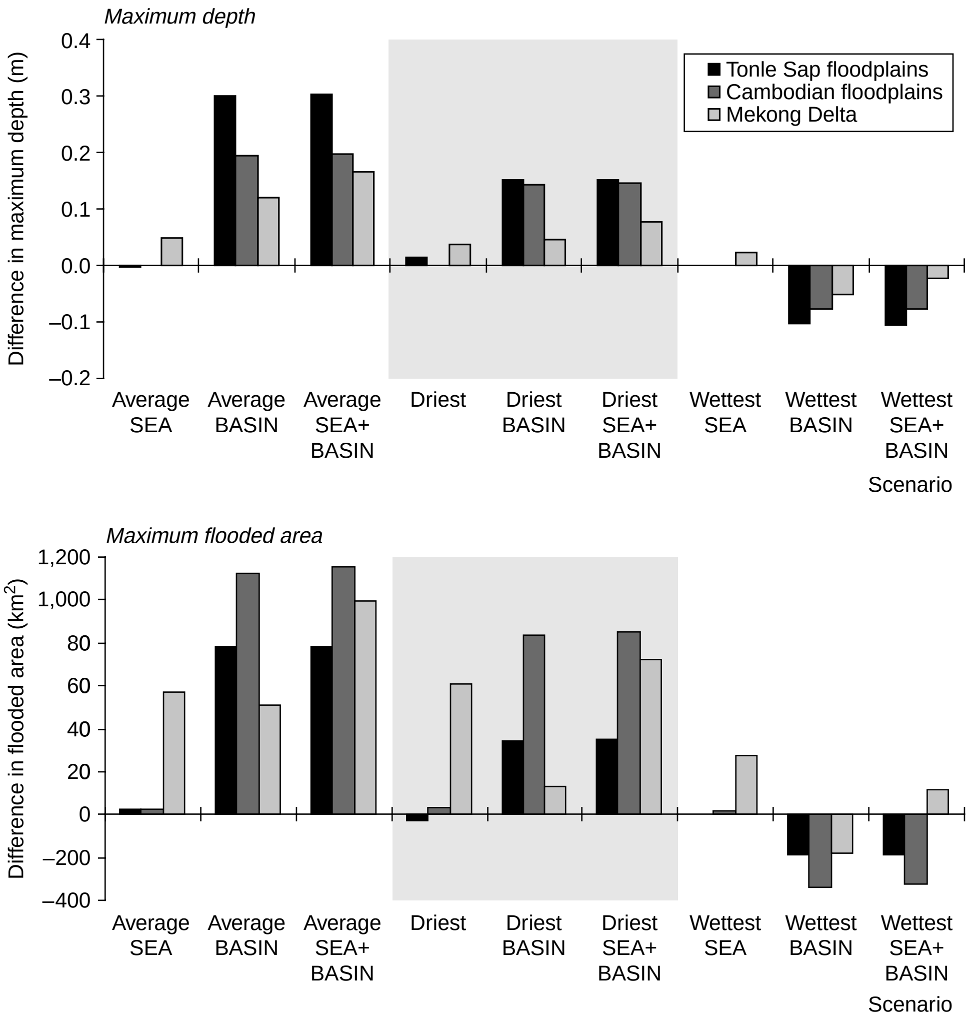

Figure 9 | The simulated differences in annual maximum water depth and flooded area in 2010–2049 (average over the four 10-year periods) compared to the baseline.

were determined for Tan Chau, situated in the upstream end of the Mekong Delta, whereas the maximum extent of flooding was calculated for the whole Delta. The effects of sea level rise are more pronounced closer to the sea.

Flood duration and timing

Flood duration increased in all the simulated scenarios (Figure 10). Changes in flood duration could not be determined for the wettest hydrological years in the Tonle Sap area because the water level did not fall below the pre-determined flood level in the baseline simulation. The relative increases in flood duration were 0–9%, and the greatest changes took place in the driest hydrological years. The BASIN and cumulative impact (SEA + BASIN) scenarios caused the greatest absolute and relative changes in the Tonle Sap area (6–9%). The impacts of changed basin water balance were small in the Delta.

The changes in peak date were not consistent between different scenarios (Figure 10). In the SEA scenario, the flood pulse peaked up to 26 d later in the Mekong Delta, which can be explained by the strong backwater effect caused by sea level rise. Sea level rise did not cause changes in peak date in the Tonle Sap area. In all the sub-areas, changed basin water balance shifted the peak date forward in the average hydrological years and backward in the driest and wettest hydrological years compared to the baseline.

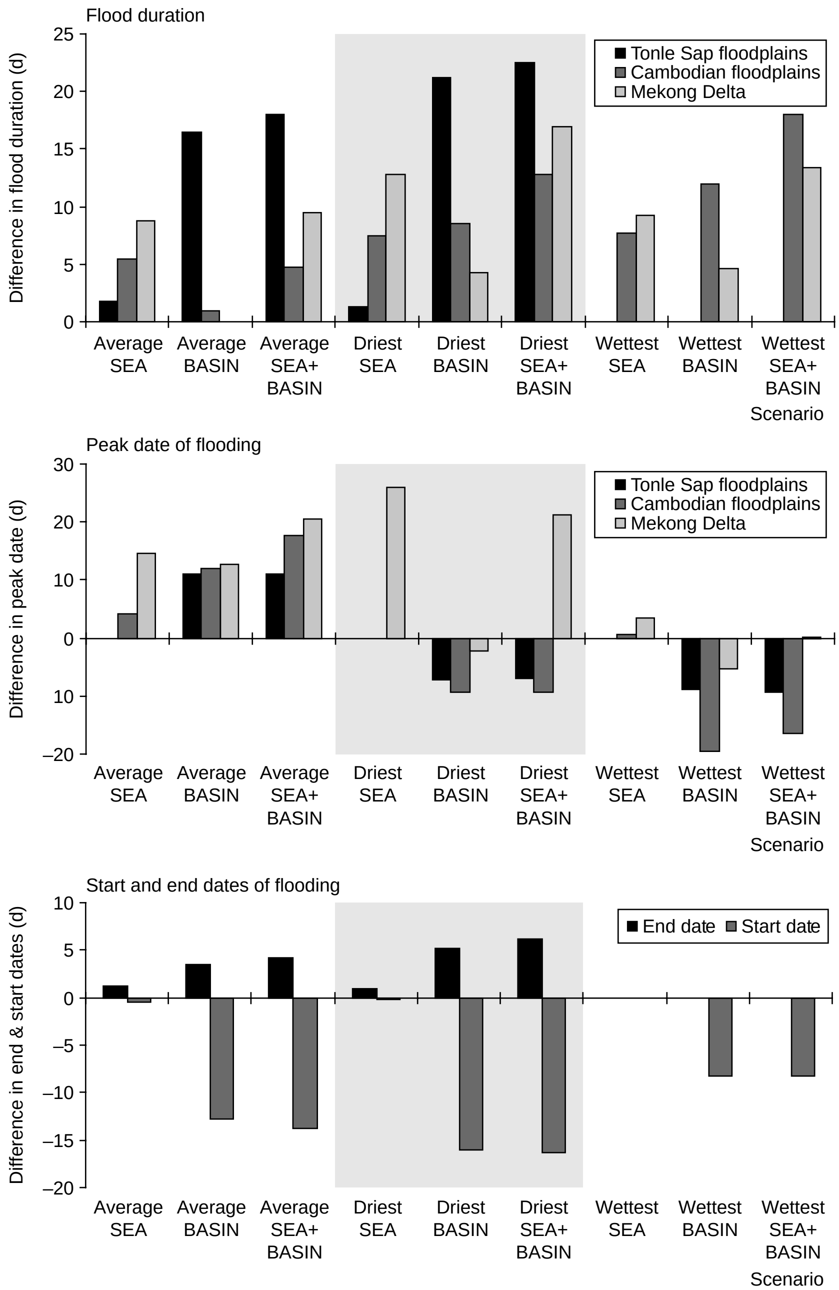

Figure 10 | The simulated differences for selected flood pulse characteristics. Average change in 2010–2049 (average over the four 10-year periods) in comparison to the baseline for the following characteristics (from the topmost figure): flood duration, peak date of flooding, and start date and end date of flooding. The start and end dates were calculated only for the Tonle Sap floodplains.

The greater flood duration was accompanied with an earlier start date and a later end date of flooding in the Tonle Sap area (Figure 10). These changes occurred in all the scenarios even though the effects of the sea level rise scenario were very small. The start date experienced greater changes than the end date, but this might be due to the problems with the EIA 3D model in simulating the drying phase of the flood.

Likelihood assessment

The likelihoods of the directions of change are presented in Table 1. The changes simulated for average low water level,

Table 1 | The simulated changes in the flood pulse characteristics and their likelihoods based on the SRES A2 emissions scenario and the ECHAM4 and PRECIS climate models

Characteristic	Change	Description
Average water level (Feb–Jul)	↑	Very likely increases
Average water level (Aug–Jan)	↑	Likely increases
Annual cumulative flooded area	↑	Very likely increases
Maximum water level	↑	Likely increases
Maximum flooded area	↑	Likely increases
Flood start date	←	Very likely occurs earlier
Flood peak date	→ / ←	Occurs possibly later in the average years
Flood end date	→	Likely occurs later
Flood duration	↑	Very likely increases

flood start date and flood duration are very likely while the changes simulated for most other characteristics are likely. In the likelihood assessment, the average years were given the same weight as the driest and wettest years, even though a random hydrological year has a higher likelihood to be more similar to the average year than the driest or wettest year. If this is taken into account, the likelihood of estimated direction of change increases for all the flood pulse characteristics. It is emphasised here that the likelihood assessment was based on representative baseline years and not on long time series, and that the likelihoods represent the results of only one climate model.

DISCUSSION

The ECHAM4 and PRECIS climate models and the SRES A2 emissions scenario indicated that temperature increases on average by 1–2°C and rainfall by 4% in the Mekong Basin by the 2040s compared to the 1980s. The simulated annual and wet season discharges increased by 4% and 5%, respectively, over 2010–2049 compared to 1995–2004. Overall, these findings are in accordance with other studies on climate change in the Mekong River Basin (Nijssen *et al.* 2001; Hoanh *et al.* 2004; Eastham *et al.* 2008; Kiem *et al.* 2008). The results also fall close to the average changes projected by IPCC for Southeast Asia with the ensemble of 21 GCMs (IPCC 2007). The ensemble projects a temperature increase of approximately 1–2.2°C for the SRES A1B scenario and 1.2–2.4°C for the SRES A2 scenario by the 2040s. Most models of the ensemble simulate increasing rainfall, on average by 7%, by 2100.

The simulated increases in water levels and flood duration are in line with the findings of Eastham *et al.* (2008) who looked at the impacts of climate change-induced alterations in basin water balance in the Tonle Sap area. Other studies support our finding that sea level rise notably aggravates flooding in the Mekong Delta (Wassmann *et al.* 2004; Le *et al.* 2007).

The EIA 3D model was not able to reliably simulate the 2–3 driest months of the year, but the VIC model projected that the dry season discharge of the Mekong (at Kratie) decreases. However, the higher amount of water stored in the Tonle Sap system and the Lower Mekong floodplains during the wet season might cause the 2–3 driest months of the year to become wetter in the Lower Mekong floodplains compared to the baseline.

The simulated increases in the average high (August–January) and maximum water levels and flood duration may cause more severe damage to roads, buildings and other infrastructure situated on the floodplain, destroy rice crops, worsen the hygienic conditions and claim more human victims. People living close to Tonle Sap Lake are particularly vulnerable to the projected changes as they are deeply dependent on water and related resources, and their possibilities to find alternative sources of livelihood are poor (Keskinen 2006; Nuorteva *et al.* 2010). On the other hand, the higher and longer flooding might benefit the ecosystems due to the enhanced cycling of nutrients and organic matter between the floodplain and the permanent water bodies (Lamberts 2008). The higher average low water level (February–July) could improve water availability and possibilities for navigation during the drier half of the year. However, it could decrease the fertile land area and damage the flooded gallery forests and other floodplain vegetation that form the basis for ecosystem production particularly in the Tonle Sap area (Lamberts 2008).

One issue worth considering is the fact that climate change is likely to alter the frequency and severity of extreme events. Changes in extreme events could cause more significant consequences in terms of short-term impacts to the ecosystems and human livelihoods than do changes in average values. The simulated changes in flood pulse characteristics were more notable in the driest and average hydrological years than in the wettest years. This finding is, however, somewhat affected by the selected baseline years.

Changing climate versus development activities

The impacts of climate change appear to be of the same order of magnitude but mostly opposite in the direction when compared to the impacts of planned water infrastructure projects in the Mekong Basin. The construction of hydropower dams and reservoirs, increasing water withdrawals for irrigation and other projected development activities have been estimated to decrease the wet season water levels and increase the dry season water levels. The water infrastructure projects decrease the maximum water levels by 0.03 – 0.6 m and increase the minimum water levels by 0.1 – 0.6 m, depending on the location, and shorten the flood duration by less than one month in the Lower Mekong floodplains (Asian Development Bank 2004; World Bank 2004; Kummu & Sarkkula 2008). The effects of the development projects, however, may be more significant than those predicted just few years ago due to the recent boom in water infrastructure development plans (King *et al.* 2007). Although the impacts of climate change and development activities appear to be mostly opposite, the dry season water level is likely to increase in both cases.

It is, however, important to note that climate change and water development projects cannot be considered to simply cancel out each other due to the differences in the timescale their impacts are felt (see also Keskinen *et al.* 2010). The current water development projects are planned to commence within a few years, and their impacts on the local and even regional water balance and hydrodynamics start to be felt immediately after their commissioning. The impacts of climate change, on the other hand, are likely to be gradual, becoming more severe only by the mid 21st century (IPCC 2007). Consequently, the cumulative impacts of climate change and water development projects–including their differing timescales–would require more detailed studies.

Modelling and its results

Models simulating natural systems are never completely accurate, and the great number of models and assumptions used in this study may have led to cumulative errors in the final results. This study was based on the SRES A2 emissions scenario, which seems a rather suitable choice considering the recent development in greenhouse gas emissions (Canadell *et al.* 2007). General circulation models, albeit having been criticized for failing to reproduce the natural large-scale decadal fluctuations in temperature and rainfall (Koutsoyiannis *et al.* 2008), are the best tools available to assess the future climatology. Climate projections are very model dependent (e.g. Mirza *et al.* 2003; Murray-Hudson *et al.* 2006; Eastham *et al.* 2008). This study used the results from only one GCM (the ECHAM4) and one regional climate model (PRECIS). Although the changes simulated by these models were close to the average changes simulated by the ensemble of 21 climate models (IPCC 2007), the results of the study are conditional to the climate models used and do not show the potential range into which future conditions are likely to fall. Therefore, it remains as a future task to utilize the downscaled results from various GCMs to the Mekong in order to obtain the likely range of climate change impacts on basin water balance and flood pulse characteristics.

The rate of sea level rise obtained in this study is low compared to the highest values found in the literature that amount up to 1.6 m in a century for a 2°C rise in global mean temperature (Rahmstorf 2007; Rohling *et al.* 2008). This study did not take into account changes in the characteristics of storm surges, tides and waves that climate change might bring about. Such changes could have dramatic impacts particularly in the Mekong Delta, and their modelling would provide valuable information for example for land use planning.

To distinguish the impacts caused by climate change from other impacts, the models were not modified between the runs except for the boundary condition data related to climate change. Thus, natural and man-made changes possibly occurring in the future decades, such as changes in geomorphology and land use, were not taken into account. The EIA 3D model did not simulate the hydrological processes, and its performance could probably be improved by incorporating actual rainfall into the model. On the other hand, the lack of evaporation in the modelling area had only a minor impact on the simulated water levels (up to 0.5%). Evaporation likely increases as the average temperature rises, but the effect of evaporation on the water levels was approximately one order of magnitude smaller than that of the changes in the Mekong's discharge. Due to the lack of reliable hydrological model for the Tonle Sap basin area, it was not possible to include the potential changes in the discharges of the Tonle Sap tributaries into the hydrodynamic simulation. However, the resulting error is estimated not to be significant because the Tonle Sap tributaries have relatively small discharges compared to the Mekong River. In the hydrodynamic modelling, the length of the baseline period was limited by the shortage of monitoring data, and the selection of the baseline years slightly affected the results.

CONCLUSIONS

Climate change has the potential to alter the water balance of river basins and to raise the sea level. Such alterations are expected to affect the hydrological characteristics of low-latitude flood pulse systems (see e.g. Wassmann *et al.* 2004; Murray-Hudson *et al.* 2006). This article has assessed the hydrological impacts of climate change in the Mekong River Basin in Southeast Asia, focusing on the characteristics of the flood pulse in the Lower Mekong floodplains. Despite the shortcomings in the models and data used in the study, this paper gives a valuable estimate of the combined impacts of sea level rise and changed basin water balance in the Lower Mekong floodplains.

Climate change was projected to increase the average temperature and annual rainfall in the Mekong Basin by the 2040s. The hydrological simulations suggested higher annual average and wet season discharges and lower dry season discharges for the Mekong River (at Kratie) in the future. The rate of sea level rise in the South China Sea was simulated to be 7–8 cm in a decade. These changes caused increases in the modelled annual average, average low (February–July) and average high (August–January) water levels in the Lower Mekong floodplains, particularly in the average and dry hydrological years. The scenario simulations also exhibited greater flood duration associated with an earlier start and a later end date of flooding. These projections are conditional to the ECHAM4 and PRECIS climate models, but the results of these models fell close to the average projections of the IPCC's GCM ensemble.

Both sea level rise and changed basin water balance had significant impacts on flood pulse in the Lower Mekong floodplains. The impacts of sea level rise extended relatively far from the sea due to the low topographical gradient of the area. In the Tonle Sap and Cambodian floodplains, changed basin water balance caused greater impacts than the projected sea level rise. The simulated changes in the flood pulse characteristics may bring both adverse and favourable consequences, including increased damage to crops, infrastructure and floodplain vegetation; decreased fertile land area; improved water availability and possibilities for navigation in the dry season; and both positive and negative changes in the ecosystem production.

Under current knowledge, the hydrological impacts caused by climate change and water infrastructure development in the Lower Mekong Basin are mostly opposite, but of similar order of magnitude. However, these impacts will take place at different timescales, and current water infrastructure plans cannot thus be justified on the grounds of climate change. Cumulative impact assessment of these two change factors would yield valuable information about the combined effects of infrastructure development and climate change.

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