

Abstract

The transboundary Mekong River is facing two on-going changes that are estimated to significantly impact its hydrology and the characteristics of its exceptional flood pulse. The rapid economic development of the riparian countries has led to massive plans for hydropower construction, and the projected climate change is expected to alter the monsoon patterns and increase temperature in the basin. The aim of this study is to assess the cumulative impact of these factors on the hydrology of the Mekong within next 20–30 yr. We downscaled output of five General Circulation Models (GCMs) that were found to perform well in the Mekong region. For the simulation of reservoir operation, we used an optimisation approach to estimate the operation of multiple reservoirs, including both existing and planned hydropower reservoirs. For hydrological assessment, we used a distributed hydrological model, VMod, with a grid resolution of 5 km × 5 km. In terms of climate change's impact to hydrology, we found a high variation in the discharge results depending on which of the GCMs is used as input. The simulated change in discharge at Kratie (Cambodia) between the baseline (1982–1992) and projected time period (2032–2042) ranges from –11% to +15% for the wet season and –10% to +13% for the dry season. Our analysis also shows that the changes in discharge due to planned reservoir operations are clearly larger than those simulated due to climate change: 25–160% higher dry season flows and 5–24% lower flood peaks in Kratie. The projected cumulative impacts follow rather closely the reservoir operation impacts, with an envelope around them induced by the different GCMs. Our results thus indicate that within the coming 20–30 yr, the operation of planned hydropower reservoirs is likely to have a larger impact on the Mekong hydrograph than the impacts of climate change, particularly during the dry season. On the other hand, climate change will increase the uncertainty of the estimated hydropower impacts. Consequently, both dam planners and dam operators should pay better attention to the cumulative impacts of climate change and reservoir operation to the aquatic ecosystems, including the multibillion-dollar Mekong fisheries.

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1 Introduction

The Mekong is the largest river basin in Southeast Asia, and is shared by the six riparian countries of China, Myanmar, Laos, Thailand, Cambodia and Vietnam. Its annual hydrological cycle is driven mainly by a monsoon climate, resulting in a very regular monomodal flood pulse from approximately July until September. The Mekong has unique ecological values (e.g. Junk et al., 2006), high aquatic ecosystem productivity (e.g. Poulsen et al., 2004; Lamberts, 2006), and is able to provide livelihoods for a large proportion of the people living in the basin (e.g. Keskinen, 2006; Mekong River Commission, 2010b). The high aquatic ecosystem productivity is mainly fuelled by the flood pulse (Lamberts and Koponen, 2008). This is particularly the case for the large floodplains in Cambodia (Kummu et al., 2006; Lamberts, 2006; Lamberts and Koponen, 2008).

A large proportion of the basin's population is dependent on the availability of rich natural resources, particularly fisheries (Hortle, 2007; Dugan et al., 2010; Mekong River Commission, 2010b). At the same time, the basin is facing rapid development related to water resources management, including various hydropower plans and large irrigation schemes (King et al., 2007; Mekong River Commission, 2009; Keskinen et al., 2012), which will alter the current flow regime. On top of these developments, projected climate change is also expected to alter the flow regime (Eastham et al., 2008; Hoanh et al., 2010; Mekong River Commission, 2010c; Västilä et al., 2010). Hydropower operation and climate change are among the most influential drivers of future hydrological change in the Mekong (e.g. Keskinen et al., 2010); other drivers include, for example, land cover change, new irrigation and water diversion schemes, and urbanisation.

Changes in the Mekong's flow regime, especially its flood component, are expected to have significant impacts on several key functions of the river, such as aquatic ecosystem productivity (Kummu and Sarkkula, 2008; Lamberts, 2008; Lamberts and Koponen, 2008; Mekong River Commission, 2010c), riverine transport (Kummu et al., 2006), and freshwater supply. The flow changes are also expected to have an impact on

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agriculture, including e.g. (dry season) irrigation as well as more traditional agricultural practices such as recession rice (Mekong River Commission, 2010c). It is therefore extremely important to understand the possible impact of both hydropower operation and climate change (separately and together) on the basin-wide hydrology of the Mekong.

5 The impacts of these two drivers on the Mekong's hydrology have been the focus of many studies (ADB, 2004; World Bank, 2004; Eastham et al., 2008; Hoanh et al., 2010; Västilä et al., 2010). However, with the exception of Hoanh et al. (2010) and Mekong River Commission (2010c), these assessments have only investigated one of these two drivers.

10 The impacts of hydropower operation on the basin's hydrology have mainly been studied by the Mekong River Commission (MRC) and the Asian Development Bank (ADB) (Adamson, 2001; ADB, 2004; World Bank, 2004; Hoanh et al., 2010; Mekong River Commission, 2010c). All of these studies agree on the direction of change (lower flood peaks and higher dry season flows), but the magnitude of change varies between
15 the studies due to different models and assumptions (Johnston and Kumm, 2012; Keskinen et al., 2012). For example, some of the studies (World Bank, 2004; Hoanh et al., 2010) have included considerable irrigation expansion in the basin, while others (Adamson, 2001; ADB, 2004) have not included this in their models.

20 Detailed and reliable climate change studies are scarce in the Mekong. The study of Kingston et al. (2011) is to our knowledge the only one that uses results of several General Circulation Models (GCMs) downscaled to the Mekong basin. Their findings indicate high uncertainty in the direction of climate change impacts, supporting the general findings for the Asian monsoon region (e.g. Ashfaq et al., 2009). Eastham et al. (2008) also included results from several GCMs, but did not downscale them to
25 the Mekong: this may partly explain the more significant increase in wet season runoff compared to the findings of Kingston et al. (2011). Other studies only use one GCM to project the climate change impacts on hydrology (Hoanh et al., 2010; Mekong River Commission, 2010c; Västilä et al., 2010); these studies both used the same GCM (ECHAM 4), and projected that climate change will lead to more variable conditions

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and slightly increased annual runoff. Simulations carried out by Aerts et al. (2006) and Ward et al. (2007) suggest that anthropogenic climate change in the coming century may have as large an impact on Mekong discharge as long-term natural climate change over the last 9000 yr.

Hoanh et al. (2010) and Mekong River Commission (2010c) are to our knowledge the only basin-wide studies in which both climate change and basin development activities (including hydropower) are assessed together. However, both of them used only the results of one GCM (ECHAM4) to project climate change. Yet, both regional (e.g. Ashfaq et al., 2009) and Mekong-specific (Kingston et al., 2011) studies have shown that there is no general consensus of the impacts of climate change on monsoon climates, as different GCMs show different impacts, particularly with regards to precipitation. Hence, we see that it is essential to use multiple GCMs to provide a range of possible future climatic conditions and consequent hydrological impacts.

The aim of our study is to assess in detail the individual and cumulative impacts of climate change and hydropower development on the hydrology of the Mekong River. To achieve our aim, we downscaled five GCMs that performed well in the region according to the analyses by Eastham et al. (2008) and Cai et al. (2009). In addition, a hydropower operation optimisation algorithm was developed to simulate the reservoir operations of both existing and planned hydropower dams. The downscaled GCM data for 2032–2042 AD and hydropower operation rules were incorporated in a state-of-the-art distributed hydrological model to simulate their separate and combined effects on river flow. The used timeframe was selected so that it would link to the on-going discussion about hydropower dams: a great majority of the planned dams are expected to be ready by 2030 (Mekong River Commission, 2009; Kummu et al., 2010). The emphasis of our analysis is on computing the possible changes in discharge at Kratie in Cambodia (Fig. 1), as the discharge there largely defines the nature of the flood pulse in the highly productive floodplains of Cambodia and Vietnam.

We acknowledge that the considered climate change and hydropower developments impact multiple other factors as well, but in order to maintain focus we are in our

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analyses looking only at the hydrological impacts. Moreover, although the analysed drivers (i.e. hydropower reservoir operation and climate change) are often seen as the most important factors for future hydrological changes in the Mekong (e.g. Keskinen et al., 2010; Mekong River Commission, 2010c), those are not the only driving forces causing changes to the hydrology and water-related resources. Others include, for example, irrigation expansion, inter-basin water transfers, land-cover change and urbanisation. These important factors are, however, outside the scope of this paper and should thus be subject for future studies.

2 Study area: the Mekong basin

The Mekong River extends from the Tibetan Plateau in China to the Mekong Delta in Vietnam. The river basin is located between latitudes 8° N and 34° N, containing uplands with mountains over 5000 m and alpine climate in the northern part of the basin, and large tropical floodplains in the southern part of the basin.

The lower part of the basin belongs mostly to tropical savannah and monsoon climate zones, where the year is divided into dry and wet seasons. The wet season lasts approximately from early May to October, and the dry season from November to April. The wet season climate is dominated by the summer monsoon, arriving partly from the Southwest and partly from the Southeast. In addition to the monsoon, the climate is affected by tropical cyclones coming from the east. These cyclones contribute to precipitation mainly during August, September, and October (Mekong River Commission, 2005). The uppermost part of the basin is located in the Tibetan plateau, where the precipitation distribution is similar to that in the lower part of the basin, with most of the precipitation occurring during summer. Due to lower temperatures caused by high elevation, the precipitation during winter falls mainly as snow. In the upstream basin areas with highest altitudes, there are also several glaciers with a combined surface area of ca. 320 km² (Armstrong et al., 2005).

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required by the hydrological model, was computed separately by calculating the minimum elevation from the 1 km DEM data. The main course of the Mekong was forced into the flow direction raster by lowering the elevation model along the river's course.

3.1 Meteorological input data

Daily meteorological input data for the model were obtained from meteorological station observations. Due to data availability and data quality reasons, the model was configured to use precipitation, and daily minimum and maximum temperatures, for the soil surface water and energy balance computation. Meteorological data were collected for the period 1981–2005 from 151 precipitation and 61 temperature stations, the locations of which are shown in Fig. 1. Precipitation data were mainly extracted from the MRC hydrometeorological database (Mekong River Commission, 2011) and supplemented with GSOD (Global Surface Summary of Day) data (NCDC, 2010) for the Chinese part of the Mekong basin (see Fig. 1). Temperature data were taken from the same two datasets and were supplemented with NCEP Reanalysis 2 (NOAA, 2011) data in Laos and Cambodia (see Fig. 1). The MRC data were quality assured by the data provider and the GSOD data were quality checked by Räsänen et al. (2012).

3.2 Discharge data

From the existing Mekong discharge gauging stations we selected six for use in the calibration and validation of the hydrological model: Chiang Saen, Vientiane, Nakhom Phanom, Mukdahan, Pakse, and Stung Treng (shown in Fig. 1). The discharge data were acquired from the MRC database (Mekong River Commission, 2011). We consider the Stung Treng gauging station to be the most suitable for calibration, as it is the most downstream observation station with high quality discharge data. In Kratie, which is located further downstream, there are some problems in discharge data, probably induced by gradual changes in river cross-section. It was thus considered not adequate for the calibration and validation of the hydrological model.

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3.3 Reservoirs

The reservoir data for existing, under construction and planned dams were obtained from the MRC hydropower database (Mekong River Commission, 2009). There are altogether 136 reservoirs in the hydropower database, with most of them being still at planning stage. As the MRC database included only the reservoirs in the Lower Mekong basin (excluding China), we added six reservoirs in the Chinese part of the basin based on ADB (2004). Some reservoirs were omitted, namely: those with active storage of less than 2 Mm³; re-regulating dams; and the Don Sahong dam (which captures only part of the flow of the main river). This resulted in a database of 126 reservoirs that were taken into account in our study. Many of the included reservoirs have still a relatively small regulation capacity relative to river discharge, and thus would most likely only have a small effect on outflows at the basin scale. Since the reservoir operation rules are not available in the databases, we computed these for each reservoir using a linear optimisation method presented in the Methods section.

The Lower Mekong basin reservoir locations were taken from the MRC hydropower database (Mekong River Commission, 2009). Due to the relatively large grid size of the model, inaccuracies in the model river network, and sparse precipitation data, the reservoir inflow data may be biased, so that the average inflow to the reservoir may be larger or smaller than the inflows estimated elsewhere. Summary data of the reservoirs grouped by riparian country are shown in Table 1. When the sum of the active storage volume is compared to main river discharge at Stung Treng, the sum corresponds to 96 days of average discharge, 602 days of driest month discharge, or 34 days of wettest month discharge.

3.4 Climate change data

Five GCMs were selected for downscaling on the basis of their performance in the simulation of precipitation in the 20th century in the SE Asia region (Eastham et al., 2008; Cai et al., 2009). For the selected GCMs, the B1 (550 ppm stabilisation) and A1b

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emission scenarios (720 ppm stabilisation) were used (IPCC, 2007). Monthly average surface temperature (tas) and monthly total precipitation (pr) output covering the 20th and 21st century were used for the downscaling. The models have various spatial resolutions, roughly varying between 1° to about 4° cells (Table 2).

4 Methods

We modelled the hydrology of the Mekong basin using VMod, which is a distributed hydrological model based on a gridded representation of the modelled watershed. The model grid is constructed from square grid cells, the side length of which may be set from a few hundred metres up to several kilometres. VMod is a dynamic model, i.e. the computation is started from a given initial state and advanced through the defined computation period using time steps from 3–12 h of length. For each time step and grid cell, the model first computes meteorological variables from the given input data, and then proceeds to compute soil surface layer processes and vertical soil column water balance. After all grid cell processes have been computed, the time step is completed by calculating 2-dimensional soil water flow between the grid cells and water flow into the river network model. A detailed description of the model computation methods and model equations can be found in the VMod model manual (Koponen et al., 2010).

4.1 Hydrological model setup

The VMod model grid was constructed from the 5 km raster dataset, which is described in the data section of this paper. River widths for each grid cell were obtained by estimating discharge from average leaching and computed flow network. Manning's friction coefficients were estimated using estimated discharge and values from the literature (Chow, 1959). The 5 km × 5 km cell size was used to keep the model computation time reasonable. The model was run using a daily time step for the soil surface layer and a 12 h time step for the soil and river modules.

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The initial model parameterisation was obtained from a previous model setup applied in the area using different input data (Sarkkula et al., 2010). To refine the model, the available data period was divided into a calibration period (1982–1991) and a validation period (1993–1999). Year 1992 was not used due to possible inaccuracies in the GSOD data in the Chinese part of the Mekong. Computation periods started on 1 April, and finished on 31 March.

Temperature and precipitation were interpolated for each model grid cell from the three nearest observation locations using inverse distance weighting and elevation corrections. This interpolation was used since the observation data are sparse (excluding Thailand). Using the three nearest locations also means that the interpolation evens out local maximum and minimum values so that a single large or small precipitation value has less impact on the runoff. Elevation correction factors were used to modify the observed weather data using the difference of elevation between the model grid cell elevation and the elevation of the observation stations. For precipitation, a multiplicative correction was used with multiplier $1 + 0.0002h$, where h is the elevation difference in metres. For temperature, an additive correction with addition of $-0.006h$ was used. The precipitation correction factor was determined in a separate study in two small catchments in Thailand (Sarkkula et al., 2010). The temperature correction value used is somewhat smaller than the standard $0.0065\text{ }^{\circ}\text{C m}^{-1}$ temperature lapse rate. A recent study (Minder et al., 2010) supports using an even smaller correction factor for temperature.

Evaporation was computed using the Hargreaves-Samani evaporation formulation (Hargreaves and Samani, 1982). This method estimates potential evaporation based on measured daily minimum and maximum temperatures, latitude, and date. Evapotranspiration in the model also depends on leaf area index (LAI), which was computed using a method in which the LAI increases for warm conditions when water is available and decreases in cold and/or dry conditions. LAI minimum and maximum values depend on land-use type.

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4.2 Hydrological model calibration and validation

After setting up the model grid and the data, the model was calibrated against measured discharge for the calibration period. The whole basin was calibrated as one unit so that grid cell parameters are dependent on land cover and soil type, but not the location of the grid cell within the basin. The Stung Treng gauging station was used as the main calibration point being the most downstream station with high quality discharge data (see Sect. 3.2). The Chiang Saen gauging station was used to calibrate parameters that affect only the upper basin, such as snow and glacier related parameters, whereas the other discharge gauging stations were mainly used for verification. The fit between modelled and measured discharges was evaluated using the Nash-Sutcliffe efficiency coefficient E (Nash and Sutcliffe, 1970; Krause et al., 2005). The validity of the model calibration was then checked by computing the validation period using the previously calibrated parameters, and comparing the fit from the validation period to calibration period results (Table 3).

For the calibration period, the model agreement is better at the downstream stations than at the upstream stations (Table 3). In the upper part of the catchment the model somewhat underestimates dry season flows, and computed discharge peaks do not always match measured discharge peaks (Fig. 2). At Nakhon Phanom, the location with the lowest coefficient E , the modelled discharge is 12 % larger than the observed discharge. The best agreement between the modelled and observed data is for Pakse and Stung Treng (Table 3).

For the validation period, the agreement between modelled and observed discharges is slightly worse for the two most upstream stations (compared to the calibration period), but somewhat better for the other stations (Table 3). In the upper basin, the lower E values can be partly explained by the operation of the Manwan dam (closed 1993) in the Chinese part of the catchment, which is not taken into account in the model. Generally, the agreement between observed and modelled data is good for both the calibration and validation periods.

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4.3 Climate model downscaling

In order to assess the potential impact of climate change on hydrological processes at the basin scale, it is essential to downscale GCM data, as the spatial resolution of GCMs is too coarse for basin-scale hydrological modelling. The downscaling process was carried out using a statistical downscaling method. The downscaled parameters are precipitation, average daily temperature, minimum daily temperature, and maximum daily temperature.

To create the future daily time-series, changes observed in the monthly GCM data between a baseline and future period were applied to the daily observed time series; this is known as the delta or change factor method (see, e.g. Diaz-Nieto and Wilby, 2005; Choi et al., 2009). Delta factors were calculated compared to the reference period of 1981–2005. The change was calculated over 25 yr periods in order to distinguish the long-term trend from the GCM output, and not the (natural) annual variation. A moving window of 25 yr was used and compared to the baseline situation for each month (i.e. January, February, March, etc.). The delta factors for temperature were calculated as a fraction of the standard deviation instead of an absolute increase (see Eq. 1) in order to account for differences between observed and modelled variability. For precipitation, the relative increase in average precipitation was calculated with the moving window (see Eq. 2) as precipitation does not follow a Gaussian distribution, meaning that the standard deviation is not a correct indicator of its variation.

$$\Delta_{\text{TMP}} = \frac{\bar{T}_{\text{series},i} - \bar{T}_{\text{ref},i}}{\sigma_{\text{ref},i}} \quad (1)$$

$$\Delta_{\text{PRE}} = \frac{\bar{P}_{\text{series},i}}{\bar{P}_{\text{ref},i}} \quad (2)$$

In Eq. (1) and (2), $\bar{T}_{\text{series},i}$ and $\bar{P}_{\text{series},i}$ are the (25 yr) average for month i of a particular month in the GCM time series; $\bar{T}_{\text{ref},i}$ and $\bar{P}_{\text{ref},i}$ are the (25 yr) averages for

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the reservoir is filled up to full capacity each year. A more detailed description of the method can be found in Sect. S1 in the Supplement.

We performed the reservoir optimisation procedure first for the baseline conditions. To ensure correct operation of the reservoirs also under the climate change scenarios, the reservoir use was optimised separately for each climate change scenario set-up (i.e. model run).

5 Results

The effects of climate change, reservoirs, and the combination of these on Mekong discharge were assessed using the downscaled GCM results as input to the hydrological model, and comparing the computation results to the baseline result. The performed hydrological model runs with associated GCM, emission scenario, and reservoir configuration are listed in Table 4.

5.1 Effect of climate change on temperature and precipitation

The temperature and precipitation of different model runs for the years 2032–2042 were compared to the baseline data for the years 1982–1992 (Fig. 3; Table 5). Daily average temperature for the whole catchment, computed as the mean of minimum and maximum temperature, increased by 0.8°C–1.4°C in the model runs using the A1b emission scenario, and 0.6°C–1.3°C in the runs using the B1 scenario. The spatial distribution of annual average temperature increase is similar for all runs using the A1b emission scenario: the increases are greater in the southern and northern parts of the basin when compared to the middle part, and the largest temperature increases are found in the south-eastern part and in the narrow mid-north part of the catchment (Fig. 3). For the runs using the B1 emission scenario, the temperature changes show a similar pattern compared to the runs using the A1b scenario, but the magnitude of change is smaller in the former.

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most of the runs using the B1 scenario, staying at the baseline level only during May and June (Fig. 4; Table 6). The largest decrease takes place in August.

5.3 Effect of reservoirs on main river discharge

To investigate the effect of reservoirs on the Mekong's discharge (without climate change), the model was run using baseline input data and reservoirs (BL + rv run). The resulting discharges at Chiang Saen, Vientiane, Pakse, and Stung Treng are shown in Fig. 5. When compared to the baseline run (BL), the reservoirs cause a clear increase in monthly average dry season (December–May) discharges (by 25–160 % in Kratie and 41–108 % in Chiang Saen), and a decrease in wet season (June–October) discharges (by 5–24 % in Kratie and 3–53 % in Chiang Saen). The largest relative decrease is at the beginning of the wet season in July (24 % in Kratie and 53 % in Chiang Saen) when the reservoirs are filling up after the dry season. During the wettest month, September, the discharge decreases by 8 % in Kratie and 13 % in Chiang Saen. The relative increase of discharge during the dry season is largest in the most downstream section of the catchment at Kratie, whereas the relative decrease during the wettest month is largest at the upstream part of the catchment at Chiang Saen (Fig. 5).

5.4 Effect of climate change and reservoirs on main river discharge

To examine the cumulative impact of climate change and reservoirs, the climate change model runs discussed in Sect. 5.2 were computed with reservoirs in the hydrological model. For the model runs using the A1b emission scenario and reservoirs in Kratie, the dry season and early wet season discharges are defined mostly by reservoir operation (Fig. 6). Similarly to the baseline with reservoirs (BL + rv) model run (Fig. 5), there is an increase in January–May discharge, and a decrease in June–August discharge. During September, the discharge varies highly between model runs. From October to December, both the reservoir operation and climate change increase discharges, resulting in higher than baseline discharge values. The model runs using the B1 scenario

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and reservoirs display similar behaviour to the model runs using the A1b emission scenario and reservoirs, but with lower wet season discharges and less variation between the different GCMs (Fig. 6).

In Chiang Saen, during the dry season and early wet season the model runs using A1b scenario and reservoirs follow the BL + rv results closely, except for the cnA + rv run, which has lower than average discharges (Fig. 6). During August and September, there is a large variation between GCMs, with an average that is similar to BL + rv run results. October and November discharges for the model runs using A1b scenario and reservoirs are higher than those for the BL + rv model run. The model runs using the B1 emission scenario show similar discharge patterns to the A1b runs, but in the B1 runs the wet season discharge is lower, and there is less variation between the GCMs (Fig. 6).

5.5 Interannual variation of the cumulative impacts of climate change and reservoir operation

The effect of climate change and reservoirs on discharges has been investigated above using monthly average changes. In addition, it is important to assess the impacts of projected climate change on extremes, for example very dry or very wet years. Due to the change factor downscaling approach used in this study, specific effects of climate change on extremes (differing from the average change) cannot be assessed. However, it is possible to estimate the effect of average climate change on dry and wet years.

The computed monthly discharges for the driest and wettest years of the simulation period for the model runs using the A1b emission scenario, with and without reservoirs, are shown in Fig. 7. In the simulations without reservoirs there is a small absolute increase in April–June discharges and a larger increase of discharges for the period of August–October for both the dry and wet year. The addition of reservoirs to the system for the dry year leads to a decrease in discharges in July–August and evens out the flood peak during September. For the wet year, the reservoirs reduce the discharge

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during June and July, but are already full during the largest flow in September and therefore do not decrease the peak discharge.

5.6 Impact of climate change and reservoir operation on flood pulse parameters

The Mekong river flood pulse at Kratie was characterised using three parameters computed from the river discharge time-series: annual peak discharge, day of peak discharge, and flood volume. The annual peak discharge was computed as the average discharge of five days around the highest discharge of the year. The peak discharge day is the day of the year on which the peak discharge occurs. The flood volume was computed as the cumulative flow during the flood season, i.e. from the start of June to the end of December.

The flood pulse parameters for all model runs are shown in Table 7. In the climate change simulations without reservoirs, the flood peak discharge increases 2% to 20% in the runs using the A1b emission scenario and 0% to 13% for the ones using the B1 emissions compared to baseline. The flood volume changes by -17% to +7% in the runs using the A1b scenario and -13% to +1% in the runs using the B1 scenario. In the runs with both climate change and reservoirs, the average peak discharge changes by -15% to +7% in the A1b + rv runs, and 0% to -15% in the B1 + rv runs, compared to baseline. The flood volume decreases by 2% to 25% in the A1b + rv runs and by 7% to 22% in the B1 + rv runs. The large volume reduction is caused partly by the reservoirs storing water during the wet season and releasing it during the dry season, and partly by climate change.

The statistical significance of the change in the flood parameters was tested using a paired two-sided t-test between average parameter values computed from the scenario and baseline data (indicated in Table 7). The test showed the changes in flood volume to be significant in almost all model runs. The change of peak discharge is statistically significant for some GCMs, and not for others. We found no statistically significant changes in the flood peak discharge timing, except for model run mpB.

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We hope that our assessment of the cumulative impacts of climate change and reservoir operations on the Mekong's basin-wide flow regime will deepen the understanding of the possible flow changes occurring in the Mekong, and thus also help the planning of future hydropower dams. Next, our findings are discussed and compared with those of other existing assessments (Sects. 6.1–6.3), followed by more general discussion about the remaining challenges and, consequently, future research themes.

6.1 Comparison: impact of climate change on hydrology

On a global scale, climate change is projected to lead to an increase in both evaporation and precipitation (IPCC, 2007). Changes in runoff at the local scale depend then on the relative change of precipitation compared to the change in evaporation. According to the downscaled results of the GCMs used in this study, annual precipitation in the Mekong region is generally projected to increase in the future, leading to increases in river discharges. However, the five GCMs used in this study show large differences in how the Mekong's hydrology will change (Fig. 6, Table 7), indicating high uncertainty in even the direction of hydrological change due to climate change. This will naturally present a challenge for the assessments focusing on the impacts of hydropower development (which is the focus of majority of the assessments in the region), increasing their long-term uncertainty.

In terms of the impacts of climate change on discharge, our findings and those of Kingston et al. (2011) both show that there are significant uncertainties in the direction and magnitude of the change; the variation in simulated discharge between individual GCMs is relatively large in both studies. Moreover, both studies suggest that the largest flow changes in the lower Mekong basin, in terms of volumes, occur during August and September.

There are large differences between our results and those of Eastham et al. (2008) in terms of the results for the range of different climate change scenarios. Our results

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indicate more moderate impacts on hydrology due to climate change than the latter (Fig. S2 in the Supplement). Our results from 5 GCMs (A1b scenario) indicate changes in the discharge at Kratie ranging from -12% to $+16\%$ with a median of $+7\%$, whereas Eastham et al. (2008) projected a change ranging from -2% to 82% with a median of 22% using 11 GCMs (A2 scenario) for year 2030. These differences are likely to originate from the selection of different sets of GCMs and different scenario assumptions. Furthermore, Eastham et al. (2008) did not downscale the GCM results to the Mekong. However, both studies agree that the largest increases of flow occur during the first (May–June) and last months (September–October) of the monsoon season.

Other basin-wide studies related to climate change impacts on the hydrology of the Mekong (Hoanh et al., 2010; Västilä et al., 2010) used only one GCM (ECHAM4) as input to the hydrological model, and therefore we compare solely our ECHAM5 results to their findings. It should be noted that for these studies, the time horizons of the projections are different, and for climate change also relatively short-term: Hoanh et al. (2010) projected to 2010–2050; Västilä et al. (2010) to 2030–2049; and our study to 2032–2042. Nevertheless, the estimates from our study and Hoanh et al. (2010) show good agreement in terms of the overall direction of flow changes, but the magnitude of change differs (Fig. S3 in the Supplement). The results of Hoanh et al. (2010) at Kratie suggest a 5–11 % increase in June–November flows and a 19–23 % increase in December–May flows, whereas our results suggest a 2–6 % increase and a 4–13 % increase in flows for the same months. The total annual flow increase at Kratie based on the findings of Hoanh et al. (2010) is 7–13 %, whereas our results suggest a 2–7 % increase. The estimates of Västilä et al. (2010) show better agreement with our results on the direction and magnitude of the change (Fig. S3c in the Supplement). Västilä et al. (2010) suggest a 7 % increase in June–November flows, an 8 % decrease in December–May flows, and a 10 % increase in annual flows at Kratie. All three studies thus seem to agree on the direction of June–November and annual flow changes although magnitudes differ. More detailed comparison of the climate change impact assessments can be found in Sect. S2.1 in the Supplement.

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6.2 Comparison: impact of reservoir operation on hydrology

The overall effect of reservoirs on monthly average flows is similar at all presented locations, with only the magnitude differing between them. The dry season flow in the baseline with reservoirs (BL + rv) model run increases by 100–200%, but peak flow during the wet season decreases by 20–35% with respect to the baseline (BL). The relative increase of dry season flow is larger at the downstream locations, while the decrease in wet season flow is larger in the upstream locations, due to larger reservoir storage compared to average flow in the upstream part. The outflow depends strongly on how the reservoirs are used, i.e. on the operation rules. The presented scenario results are believed to be near the maximum reasonable reservoir utilisation.

Our results indicate similar changes in Upper Mekong basin (UMB) hydrology compared to other existing studies (Adamson, 2001; Hoanh et al., 2010; Räsänen et al., 2012). However, the magnitudes of the changes do vary rather significantly between the studies (Fig. S4a in the Supplement). On a seasonal scale, our findings agree well with three other studies (Fig. S4b in the Supplement). The differences in the Chiang Saen results most likely originate from two factors; the studies use different baseline data periods and different methods for the estimation of reservoir operations. Despite these underlying differences in the methodologies, all four studies agree well on how the dam operations will change the downstream flows on the monthly and seasonal scale.

In Kratie, our findings for the directions of flow changes are also in line with those of other basin-wide studies (ADB, 2004; Hoanh et al., 2010). The magnitude of change between the studies differs, however, more than in the UMB case (see Figs. S4 and S5 in the Supplement). Our results are well in line with the results of ADB (2004) on both the monthly and seasonal scale. The comparison on seasonal scale shows that although the direction of change is similar in all three studies, Hoanh et al. (2010) suggest significantly smaller changes for the December–May months than ADB (2004) or our study. A reason for this difference is most likely that Hoanh et al. (2010) include

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as pointed out e.g. by Lamberts (2008), even relatively small hydrological alterations in the flood pulse system may have significant impacts on ecosystem productivity. Our results could be further used to quantify these flood pulse changes in the most important floodplains in the basin, and thus to estimate possible implications for aquatic productivity.

Furthermore, reservoir construction is only one of the many development aspects in the Mekong causing changes to the river system. Others include, for example, irrigation expansion, inter-basin water transfers, land use changes, and urbanisation. For example the impact of expanded irrigation, if realised as planned, might have significant impacts on the flow (Hoanh et al., 2010; Mekong River Commission, 2010c). Consequently, the cumulative impacts of different development plans and climate change – including estimates derived from several GCMs – should therefore be subject to further studies, building on and extending already existing studies (see e.g. Hoanh et al., 2010; Mekong River Commission, 2010c).

Reservoirs have also various other impacts on river ecosystems than altered hydrology. For example, in the Mekong River, reservoirs have been estimated to block migration routes of various migrating fishes (Dugan et al., 2010; Ziv et al., 2012) as well as to trap significant amounts of sediments (Kummu and Varis, 2007; Kummu et al., 2010) that are important nutrient sources for the aquatic ecosystem. All of these aspects together are likely to have very significant impacts on the Mekong ecosystem, and more detailed studies are therefore needed to investigate what are the combined effects of expected flood pulse change, sediment trapping, and blocking migration routes on aquatic productivity and to the fisheries in particular.

As our study and the review of earlier climate change studies have shown, there are uncertainties in the magnitude and even in the direction of flow change assessments. However, there are also other factors that should be considered together with the climate change studies based on GCMs. For example Delgado et al. (2010, 2011) report an increased likelihood of extreme floods and increase in hydrological variance in the flows of Mekong towards the end of 20th century. But whether the changes in variance

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are climate change related is still not known. The Mekong's hydrology is also influenced by several climate variables such as El Niño-Southern Oscillation (ENSO) (Yongqin and Chappell, 2009; Ward et al., 2010). These factors have been less covered by climate studies and they are therefore important future research areas. Furthermore, paleo-climatological studies would increase the understanding of the Mekong's hydrological character in the longer historical context.

Our study included hydropower reservoirs that are existing, under construction and planned, with majority of the studied reservoirs being still at the planning stage (Mekong River Commission, 2009, 2010c). Hence, the estimated impact of the reservoir operation represents a kind of ultimate case, and the actual number of reservoirs – and their consequent hydrological impact – may end up being much smaller. At the same time, the location of a dam and the related reservoir may have a remarkable effect on the impacts it is causing, particularly in terms of fish migration. For meaningful and well-informed hydropower planning, it would thus be beneficial to look at the impacts of hydropower reservoirs also in a more step-wise manner so that the impacts of different “dam blocks” (e.g. each tributary separately, and mainstream divided into parts) would become visible. While some studies have already included this kind of step-wise assessment – most notably Mekong River Commission (2010c), the “dam blocks” have to our knowledge been divided largely based on their construction timeframes, and not according to their geographic location.

Finally, our analysis has shown that the VMod model is able to simulate Mekong discharges of the Lower Mekong basin with relatively good accuracy. At Stung Treng, the simulated monthly averages show good agreement with the measured data, and for daily discharges the Nash-Sutcliffe efficiency coefficient is greater than 0.9 for both the calibration and validation periods. Yet, there is always room for further development. Improvements in the model accuracy would be possible by increasing the model grid resolution, by using more dense precipitation data, or by modifying the evapotranspiration computation method if the required data for a more accurate computation method could be obtained.

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7 Conclusions

In this paper we assessed the impact of climate change and reservoir operation on hydrology of the Mekong River within next 20–30 yr. Although the Mekong River basin is facing rapid hydropower development, little is known about how the combination of projected climate change and planned hydropower reservoir operation would alter the discharge of the main river. We aimed to fill part of this knowledge gap with state-of-the-art hydrological modelling, using multiple downscaled GCMs and novel reservoir operation optimisation algorithms, and then looking at the impacts of climate change and reservoir operations both separately and together.

We found that within the timescale used in our study (2032–2042), climate change is likely to increase basin precipitation and average temperature. The range between GCMs is, however, relatively large in both. We also found that under the two used emission scenarios, A1b and B1, there is a large variation in results between the model runs using different GCMs. In some cases even the direction of climate change impacts to Mekong discharges remains uncertain. We see that this highlights the importance of using multiple GCMs – instead of just one GCM as has so far been mainly the case – when estimating the possible climate change impacts to the Mekong discharge.

Our study also shows that, at least within the studied timeframe, the impacts of the reservoir operations are clearly larger than the effects of climate change, resulting in higher dry season flows and lower flood peaks in Kratie and particularly affecting the dry season flow. The cumulative impacts of climate change and reservoir operations are similar to the impacts of the reservoir operations alone, but contain an envelope of change around the altered flow regime by reservoir operation alone. Hence, climate change increases the uncertainty of the estimated hydropower impacts, emphasising the importance of looking at these impacts in a cumulative manner.

The impact of reservoir operation on hydrology depends largely on the applied operation rules and, naturally, on the actual number and location of the dams. Consequently, collaboration with dam planners and dam operators to minimise the reservoirs' impacts

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on aquatic ecosystems should be high on the political agenda of the countries sharing the Mekong basin. Furthermore, as the projected climate change impact on flow varies remarkably between the different GCMs, planners and decision-makers need to take this uncertainty into account in both water management and climate change adaptation activities.

Supplementary material related to this article is available online at:
<http://www.hydrol-earth-syst-sci-discuss.net/9/6569/2012/hessd-9-6569-2012-supplement.pdf>.

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Table 1. Existing, under construction and planned reservoirs in different Mekong countries, N = number of reservoirs, AS = volume of active storage.

Country	Tributaries		Mainstream		Total	
	N	AS (10^6 m^3)	N	AS (10^6 m^3)	N	AS (10^6 m^3)
China	0	0	6	21 387	6	21 387
Lao PDR	81	55 435	8	3040	89	58 475
Thailand	7	3566	0	0	7	3566
Vietnam	11	3145	0	0	11	3145
Cambodia	11	16 824	2	4390	13	21 214
Total	110	78 970	16	28 817	126	107 787

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Table 2. Downscaled GCMs (General Circulation Models), used emission scenarios, and spatial resolution of each GCM.

GCM	Emission scenarios	Spatial resolution
CCCMA_CGCM3.1	A1b, B1	48 × 96 cells, 3.75° × 3.75°
CNRM_CM3	A1b, B1	64 × 128 cells, ~2.8° × 2.8°
GISS_AOM	A1b, B1	60 × 90 cells, 3° × 4°
MPI_ECHAM5	A1b, B1	96 × 192 cells, ~1.9° × 1.9°
NCAR_CCSM3	A1b, B1	128 × 256 cells, ~1.4° × 1.4°

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Table 3. Nash-Sutcliffe efficiency coefficient (E) and ratio of cumulative discharge volumes (computed/measured) for the calibration (1982–1991) and validation (1993–1999) periods. The number of days for the calibration period is 3652, and for the validation period 2557.

Location	Calibration		Validation	
	E	comp/ meas	E	comp/ meas
Chiang Saen	0.827	0.94	0.779	1.05
Vientiane	0.872	1.06	0.808	1.13
Nakhom Phanom	0.819	1.12	0.933	0.93
Mukdahan	0.878	1.05	0.926	1.01
Pakse	0.925	0.98	0.928	0.96
Stung Treng	0.922	1.01	0.941	0.95



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Table 4. Hydrological model runs and their settings used in this study. BL stands for baseline simulation, +rv stands for reservoirs (i.e. reservoir operation included in the simulations).

Group	Model run	GCM	Emission scenario	Reservoirs included
Baseline	BL	None	none	no
	BL + rv	None	none	yes
A1b	ccA (+ rv)	CCCMA_CGCM3.1	A1b	no (yes)
	cnA (+ rv)	CNRM_CM3	A1b	no (yes)
	giA (+ rv)	GISS_AOM	A1b	no (yes)
	mpA (+ rv)	MPI_ECHAM5	A1b	no (yes)
	ncA (+ rv)	NCAR_CCSM3	A1b	no (yes)
B1	ccB (+ rv)	CCCMA_CGCM3.1	B1	no (yes)
	cnB (+ rv)	CNRM_CM3	B1	no (yes)
	giB (+ rv)	GISS_AOM	B1	no (yes)
	mpB (+ rv)	MPI_ECHAM5	B1	no (yes)
	ncB (+ rv)	NCAR_CCSM3	B1	no (yes)

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Table 5. Differing estimates of the effects of climate change: changes in average annual precipitation, maximum temperature, and minimum temperature; and annual discharges in Kratie and Chiang Saen; scenario years 2032–2042 compared to baseline 1982–1992.

Model run	Prec. (%)	T_{\max} (°C)	T_{\min} (°C)	Discharge Kratie (%)	Discharge C. Saen (%)
A1b scenario					
ccA	7.8	1.09	0.72	13.4	4.9
cnA	-2.5	1.20	0.80	-10.6	-15.5
giA	5.2	1.65	1.10	-0.9	-5.1
mpA	5.6	0.93	0.62	7.1	6.7
ncA	8.6	1.41	0.96	10.9	11.0
B1 scenario					
ccB	5.8	0.86	0.59	8.1	1.2
cnB	1.2	0.85	0.57	0.1	-11.8
giB	1.4	1.58	1.04	-6.9	-6.3
mpB	3.7	0.68	0.44	2.0	-4.4
ncB	4.7	1.05	0.72	4.2	-5.7

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Table 6. Minimum and maximum change in monthly discharges for model runs using A1b and B1 emission scenarios from years 2032–2042 compared to baseline 1982–1992.

Month	Kratie (%)				Chiang Saen (%)			
	A1b		B1		A1b		B1	
	Min	Max	Min	Max	Min	Max	Min	Max
Jan	-10.3	7.6	-6.9	4.2	-13.5	8.9	-7.2	4.1
Feb	-9.9	4.9	-7.1	2.7	-11.3	5.1	-6.8	-2.5
Mar	-11.3	8.2	-7.7	2.3	-8.7	18.0	-7.1	-0.3
Apr	-9.8	16.1	-5.6	3.3	-3.5	21.3	-5.5	4.2
May	-22.6	32.7	-11.7	18.3	-2.4	8.0	-5.5	7.1
Jun	-28.6	21.9	-15.1	15.7	-4.8	16.5	-9.4	14.3
Jul	-14.7	13.7	-14.0	15.7	-13.5	4.2	-14.9	3.6
Aug	-11.1	6.0	-15.5	8.5	-20.5	5.5	-17.3	-0.9
Sep	-9.4	18.7	-6.4	14.8	-20.7	19.4	-15.7	9.5
Oct	-12.4	25.3	-3.1	20.9	-17.3	27.5	-13.3	1.1
Nov	-10.5	23.3	-4.2	7.8	-15.9	38.4	-13.2	-2.6
Dec	-6.7	19.2	-4.1	4.7	-14.3	16.1	-9.9	-4.2

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Table 7. Flood parameters in Kratie for model runs computed as an average of 10 yr discharge data (2032–2041). Statistically significant changes compared to baseline (at a confidence level of 95 %) are marked with asterisk (*). The flood volume is computed as the cumulative flow from start of June to end of December.

Model run	Peak-day	Peak $10^3 \text{ m}^3 \text{ s}^{-1}$	Volume km^3	Model run	Peak-day	Peak $10^3 \text{ m}^3 \text{ s}^{-1}$	Volume km^3
BL	245	47.5	379	BL	245	47.5	379
				BL + rv	248	42.7*	322*
ccA	251	56.8*	404*	ccA + rv	245	50.8	372
cnA	239	48.7	316*	cnA + rv	247	40.6*	285*
giA	244	48.6	350*	giA + rv	251	42.7*	317*
mpA	263	53.4*	376	mpA + rv	258	47.2	345*
ncA	250	55.2*	393*	ncA + rv	248	49.4	361*
ccB	241	52.7*	384	ccB + rv	245	46.6	351*
cnB	239	53.8*	355*	cnB + rv	246	46.1	322*
giB	248	47.4	329*	giB + rv	251	40.5*	296*
mpB	256*	53.1*	359*	mpB + rv	258	47.4	328*
ncB	250	53.0*	367*	ncB + rv	250	46.1	336*

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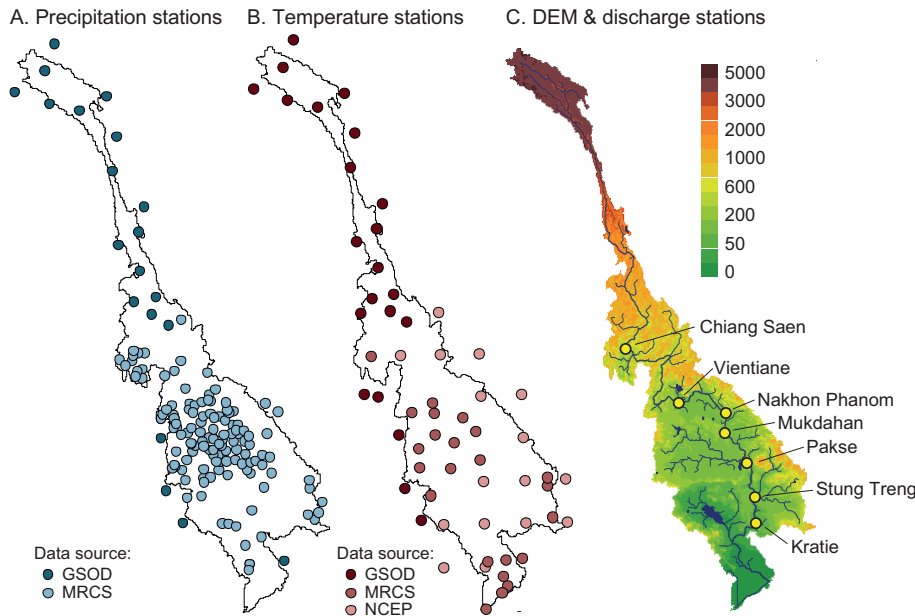


Fig. 1. Location of the hydrometeorological stations used in the study. **(A)** Precipitation stations; **(B)** temperature stations; **(C)** main river discharge gauging stations over the DEM (digital elevation model). GSOD stands for Global Surface Summary of Day data (NCDC, 2010); MRCS stands for Mekong River Commission hydrometeorological database (Mekong River Commission, 2011); and NCEP for NCEP reanalysis data (NCEP, 2011).

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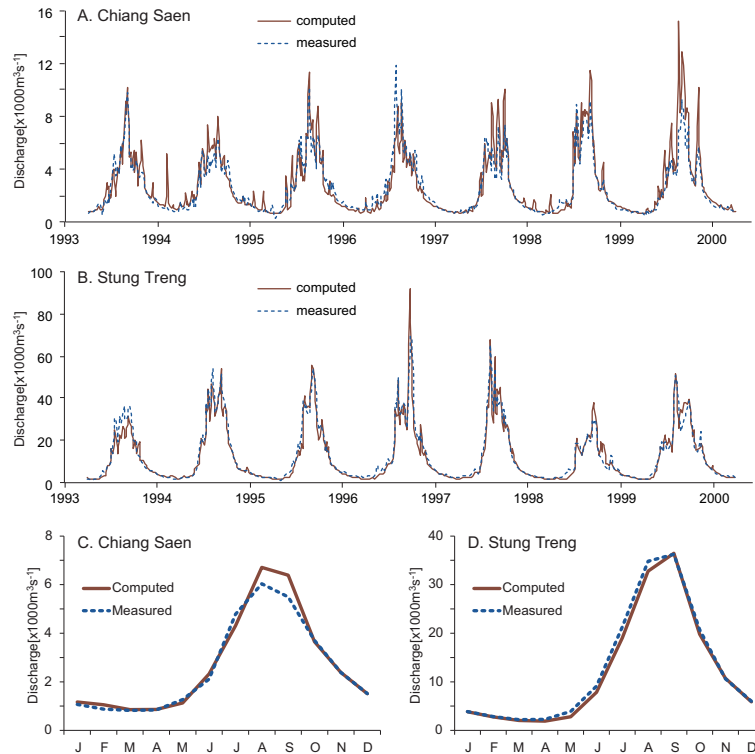


Fig. 2. Validation results of the VMod hydrological model. **(A)** Daily discharge at Chiang Saen; **(B)** daily discharge at Stung Treng; **(C)** monthly average discharge at Chiang Saen; and **(D)** monthly average discharge at Stung Treng. The validation period is 1993–1999. See Table 3 for efficiency coefficient results and Fig. 1c for the location of the measurement stations.

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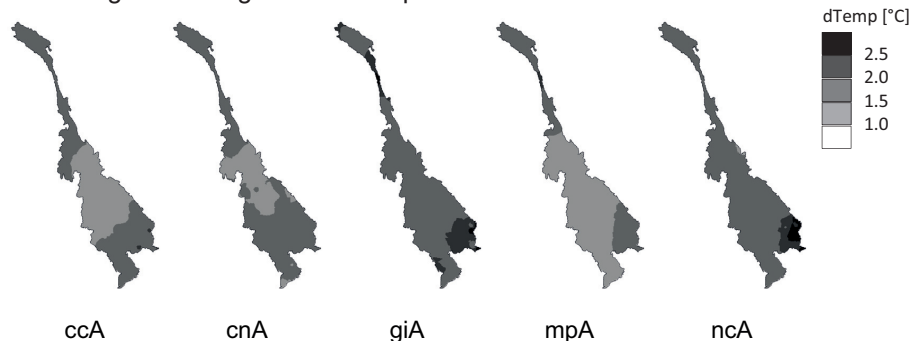
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A. Change of average annual temperature under A1b scenario



B. Change of average annual precipitation under A1b scenario

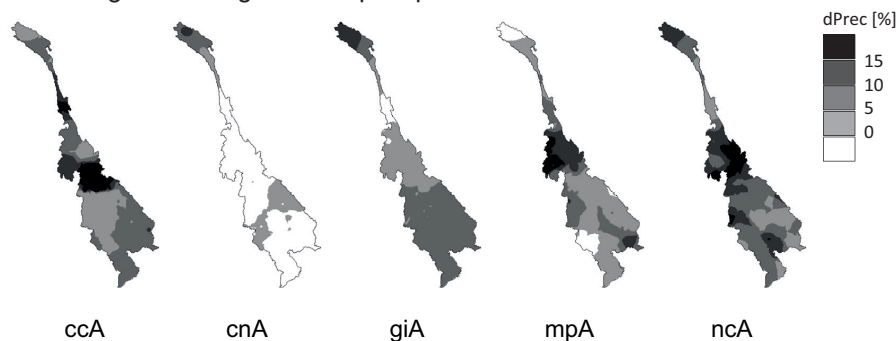


Fig. 3. Climate change in the Mekong, years 2032–2042 compared to baseline years 1982–1992 for different model runs. **(A)** Change of the average annual daily maximum temperature (°C) under the A1b scenario and used GCMs. **(B)** Change in average annual precipitation (%) under the A1b scenario and used GCMs. Abbreviations are stated in Table 4.

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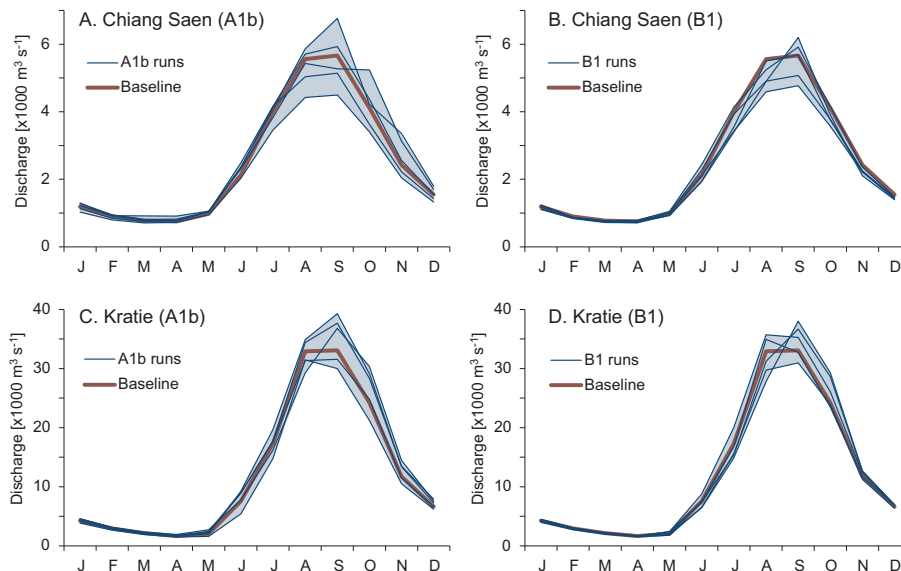


Fig. 4. Monthly average discharges of the model runs under emission scenarios (2032–2042) compared to the baseline (1982–1992). **(A)** Chiang Saen under A1b emission scenario; **(B)** Chiang Saen under B1 emission scenario; **(C)** Kratie under A1b emission scenario; and **(D)** Kratie under B1 emission scenario.

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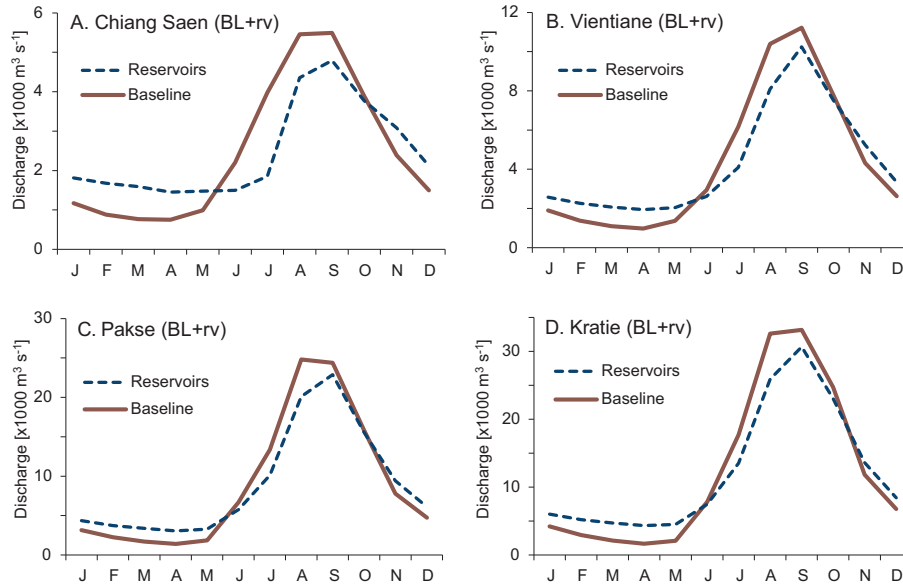


Fig. 5. Impact of reservoir operation on main river discharge. Monthly average baseline discharges (1982–1992) are compared with the discharge altered by reservoir operation at **(A)** Chiang Saen; **(B)** Vientiane; **(C)** Pakse; and **(D)** Kratie. See Fig. 1c for the location of the stations.

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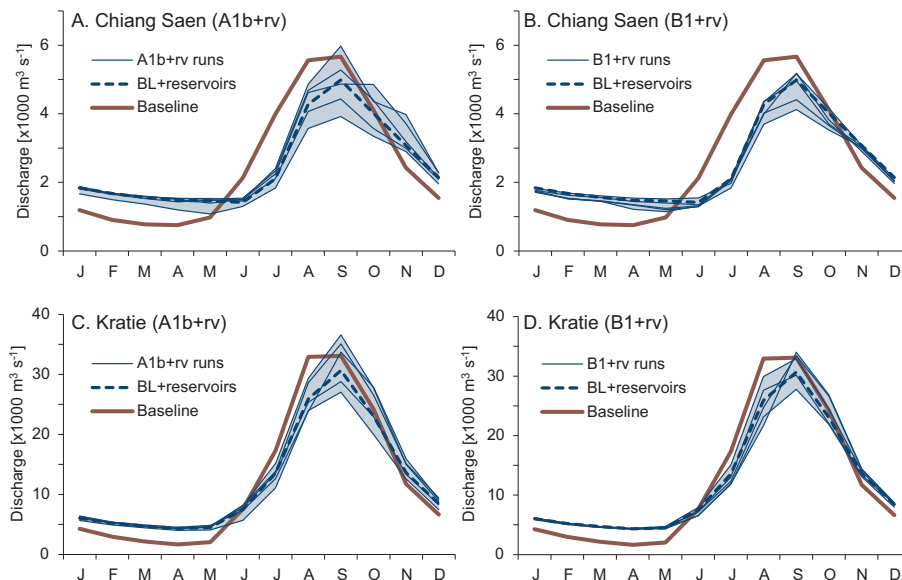


Fig. 6. Cumulative impacts of climate change and reservoir operation on Mekong main river. Monthly average discharges (2032–2042) for the model runs at **(A)** Chiang Saen using A1b emission scenario and reservoirs; **(B)** Chiang Saen using B1 emission scenario and reservoirs; **(C)** Kratie using A1b emission scenario and reservoirs; and **(D)** Kratie using B1 emission scenario and reservoirs.

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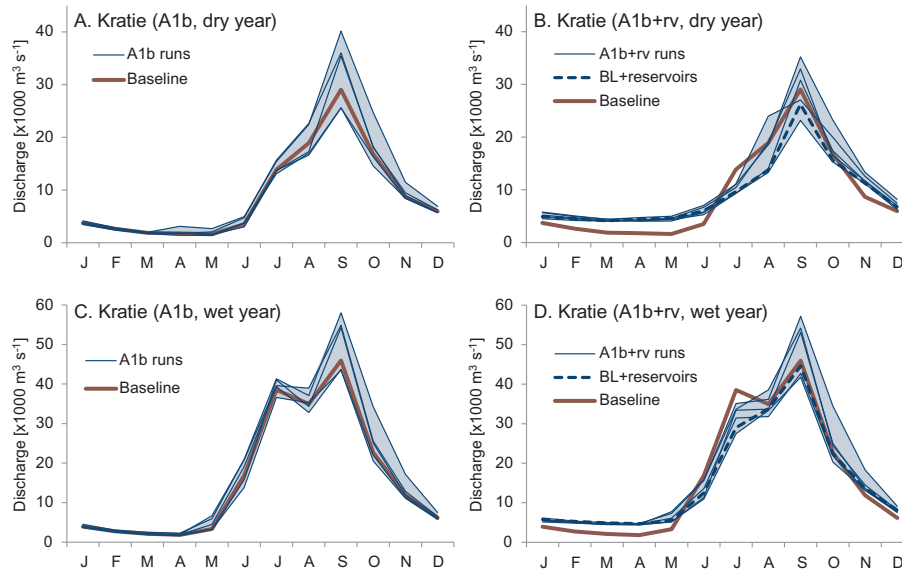


Fig. 7. Monthly average discharges at Kratie for **(A)** dry year using A1b emission scenario; **(B)** dry year using A1b emission scenario and reservoirs; **(C)** wet year using A1b emission scenario; and **(D)** wet year using A1b emission scenario and reservoirs.

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