Hydrol. Earth Syst. Sci., 16, 4603–4619, 2012
www.hydrol-earth-syst-sci.net/16/4603/2012/
doi:10.5194/hess-16-4603-2012

Hydrology and
Earth System
Sciences

Future changes in Mekong River hydrology: impact of climate change and reservoir operation on discharge

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Received: 25 April 2012 – Published in Hydrol. Earth Syst. Sci. Discuss.: 25 May 2012
Revised: 31 August 2012 – Accepted: 7 November 2012 – Published: 5 December 2012

Abstract. The transboundary Mekong River is facing two ongoing changes that are expected 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 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 the 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 the 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 on 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 reservoir operation impacts: our results indicate that even the direction of the flow-related changes induced by climate change is partly unclear. Consequently, both dam planners and dam operators should pay closer attention to the cumulative impacts of climate change and reservoir operation on aquatic ecosystems, including the multibillion-dollar Mekong fisheries.

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, 2010a). 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).

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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, 2010a). 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, 2008; Keskinen et al., 2012), which will alter the current flow regime. On top of these developments, projected climate change is expected to alter the flow regime (Eastham et al., 2008; Hoanh et al., 2010; Mekong River Commission, 2010c; Västilä et al., 2010; Kingston et al., 2011). Reservoir 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 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 agriculture, including 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 reservoir operation and climate change (separately and together) on the basin-wide hydrology of the Mekong. 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.

The impacts of reservoir operation on the basin's hydrology have been studied by different actors, including 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; Räsänen et al., 2012a). 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 the studies due to different models and assumptions (Johnston and Kummu, 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.

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 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 used the same GCM (ECHAM 4), and projected that climate change will lead to more variable conditions 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. While both of them used only the results of one GCM (ECHAM 4) to project climate change, regional (e.g. Ashfaq et al., 2009) and Mekong-specific (Kingston et al., 2011) studies have shown that there is no general consensus on the impacts of climate change on monsoon climates. Different GCMs show different impacts, particularly with regards to precipitation. Hence, 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 (using multiple GCMs) and reservoir operation 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 reservoir 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 reservoir operation rules were incorporated in a state-of-the-art distributed hydrological model to simulate their separate and combined impacts on river flow. Our approach of assessing the cumulative impacts of climate change (with multiple GCMs) and reservoir operation on hydrology is the first of its kind in the Mekong. Moreover, to the best of our knowledge, our study is also globally unique in a large river basin scale, as existing studies concentrate mainly on the impact of climate change on reservoir operation rules (e.g. Christensen and Lettenmaier, 2007; Hamlet et al., 2010).

The used timeframe was selected so that it contributes to the ongoing 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

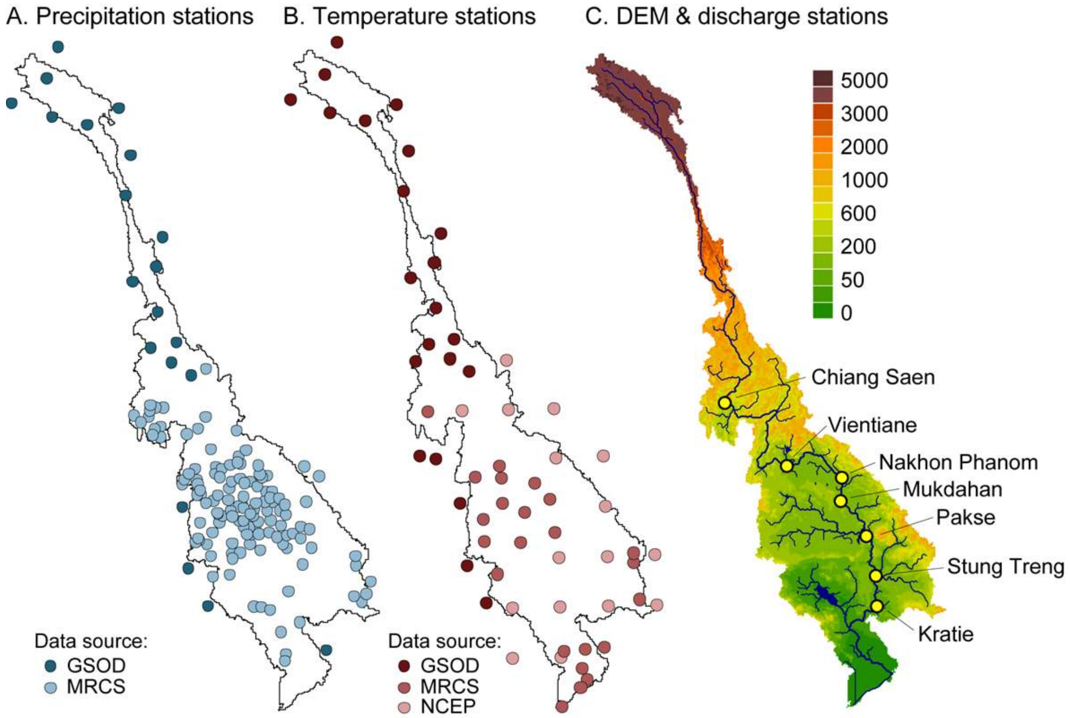

Fig. 1. Location of the hydrometeorological stations used in the study. **(A)** precipitation stations; **(B)** temperature stations; **(C)** main river discharge gauging stations over the DEM (digital elevation model). GSOD stands for Global Surface Summary of Day data (NCDC, 2010); MRCS stands for Mekong River Commission hydrometeorological database (Mekong River Commission, 2011); and NCEP for NCEP-DOE Reanalysis 2 data (NOAA, 2011).

the highly productive floodplains of Cambodia and Vietnam (Mekong River Commission, 2010c).

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 Mekong River Basin covers an area of 795 000 km^2, and has an average outflow of 15 000 $\mathrm{m}^3\,\mathrm{s}^{-1}$ (475 $\mathrm{km}^3\,\mathrm{yr}^{-1}$) (Mekong River Commission, 2005). The basin is usually divided geographically into the upper and lower parts, with the division point at Chiang Saen, Thailand, which is the closest discharge measurement station to the border with China (Fig. 1). The upper basin, from the headwaters to approximately Chiang Saen, is steep, and falls from elevations above 4500 m to about 500 m over a distance of 2000 km, with an average slope of 2 $\mathrm{m\,km}^{-1}$. In the lower basin, from Chiang Saen to Kratie, the river has a moderately steep slope, with an elevation drop from 500 m to a few tens of meters over a course of 2000 km, or about 0.25 $\mathrm{m\,km}^{-1}$ on average. Downstream from Kratie, on the Mekong floodplains and delta, the river bed is more or less flat, reaching the South China Sea after a distance of 500 km with a fall in elevation of 15 m, giving this section of the river an average slope of 0.03 $\mathrm{m\,km}^{-1}$ (Mekong River Commission, 2005).

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 km^2 (Armstrong et al., 2005).

Due to the monsoonal climate and the steepness of the riverbed in the upper and lower basin, the hydrograph of the Mekong River is single-peaked, with large differences between high and low flow values. At Stung Treng, where the river enters the Cambodian plains from Lao PDR, the average annual flow is about 13 000 $m^3 s^{-1}$, while the average annual maximum is 51 500 $m^3 s^{-1}$ and the minimum is 1700 $m^3 s^{-1}$ (computed from the years 1970–2002 observed data). Simulated annual runoff in the catchment varies from less than 100 $mm\,yr^{-1}$ in the eastern part of Thailand to over 2000 $mm\,yr^{-1}$ in the central part of Laos (computed from years 1982–1992 simulated data). Average annual runoff for the whole basin is about 600 $mm\,yr^{-1}$ (Mekong River Commission, 2005).

3 Data

For the basis of the distributed hydrological model of the Mekong basin used in this study, a 5 km × 5 km resolution raster dataset was constructed using SRTM 90 m elevations (Jarvis et al., 2008), Global Land Cover 2000 (GLC2000, 2003), and the FAO soil map of the world (FAO, 2003). The elevation data were first aggregated to 1 km × 1 km resolution, and land cover and soil data were aggregated by reclassifying the land-use data to nine classes, and the soil data to eight classes. After reclassification, all raster data were aggregated to 5 km × 5 km resolution and cropped using the Mekong catchment boundary (Mekong River Commission, 2010b). A 5 km × 5 km flow direction raster, required by the hydrological model, was computed separately by calculating the minimum elevation from the 1 km × 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 for reasons relating to data quality issues, the model was configured to compute soil surface water and energy balance using precipitation and daily minimum and maximum temperatures. 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 further supplemented with NCEP-DOE Reanalysis 2 data (NOAA, 2011) 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. (2012a).

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 the 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.

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 still being at the planning stage. As the MRC database includes only the reservoirs in the Lower Mekong Basin, 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 $2 \times 10^6\ m^3$; 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, including 110 tributary reservoirs and 16 mainstream reservoirs. Many of the reservoirs included still have a relatively small regulation capacity relative to river discharge, and therefore most likely only have a small impact 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, and were additionally checked against the MRC hydropower project location map (Mekong River Commission, 2008). 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 countries 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.

Table 1. Existing, under construction, and planned reservoirs in different Mekong countries, based on Mekong River Commission (2009) for the Lower Mekong Basin, and ADB (2004) for Chinese part of the basin. 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

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 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 the computed flow network. Manning's friction coefficients were estimated using the upstream watershed area of a specific grid cell 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.

Table 2. Downscaled GCMs (general circulation models), emission scenarios used, and spatial resolution of each GCM.

GCM	Emission scenarios	Spatial Resolution
CCCMA-CGCM3.1	A1b, B1	48×96 cells, $3.75° \times 3.75°$
CNRM-CM3	A1b, B1	64×128 cells, $\sim 2.8° \times 2.8°$
GISS-AOM	A1b, B1	60×90 cells, $3° \times 4°$
MPI-ECHAM5	A1b, B1	96×192 cells, $\sim 1.9° \times 1.9°$
NCAR-CCSM3	A1b, B1	128×256 cells, $\sim 1.4° \times 1.4°$

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 1 April, and finished 31 March, forming the hydrological year used in our analysis.

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 $1 + 0.0002\,h$, where h is the elevation difference in metres. For temperature, an additive correction with addition of $-0.006\,h$ 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 6.5 °C/1000 m 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 method (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

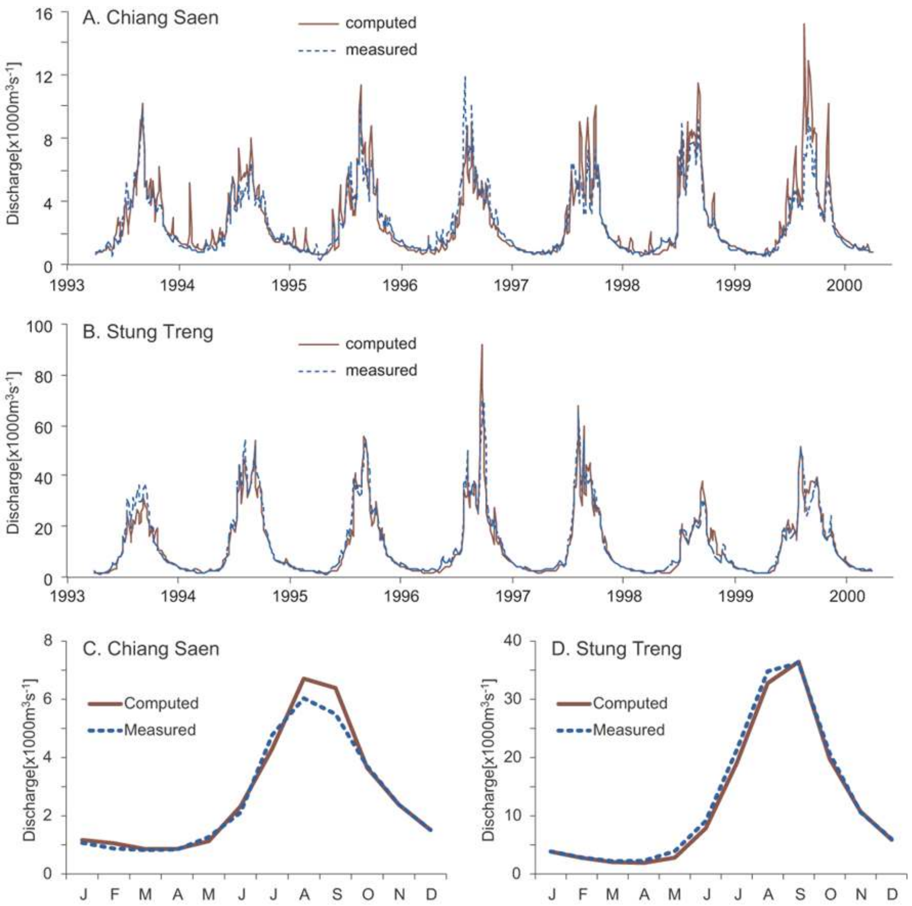

Fig. 2. Validation results of the VMod hydrological model. **(A)** Daily discharge at Chiang Saen; **(B)** daily discharge at Stung Treng; **(C)** monthly average discharge at Chiang Saen; and **(D)** monthly average discharge at Stung Treng. The validation period is 1993–1999. See Table 3 for efficiency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

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. A more detailed description of the evapotranspiration computation can be found in Sect. S2 of the Supplement.

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, it 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 in all six main river stations (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 (E ranging from 0.819 to 0.925) and validation periods (E ranging from 0.779 to 0.941) (Table 3).

4.3 Climate model downscaling

As the spatial resolution of GCMs is too coarse for basin-scale hydrological modelling, we downscaled the climate parameters (precipitation and temperature) using a delta method (see e.g. Diaz-Nieto and Wilby, 2005; Choi et al., 2009). Changes in the monthly GCM data between a climatic reference period (1981–2005) and future period were calculated using a moving window of 25 yr for each month (i.e. January, February, March, etc.). Delta factors were calculated using Eqs. (1) and (2):

$$\Delta_{\mathrm{TMP}} = \frac{\bar{T}_{\mathrm{series},\,i} - \bar{T}_{\mathrm{ref},\,i}}{\sigma_{\mathrm{ref},\,i}} \tag{1}$$

$$\Delta_{\mathrm{PRE}} = \frac{\bar{P}_{\mathrm{series},\,i}}{\bar{P}_{\mathrm{ref},\,i}}. \tag{2}$$

In Eqs. (1) and (2), $\bar{T}_{\mathrm{series},\,i}$ and $\bar{P}_{\mathrm{series},\,i}$ are the (25-yr) average for month i of a particular month in the GCM time series; $\bar{T}_{\mathrm{ref},\,i}$ and $\bar{P}_{\mathrm{ref},\,i}$ are the (25-yr) averages for temperature and precipitation for the reference period 1981–2005 for month i; and $\sigma_{\mathrm{ref},\,i}$ is the standard deviation of the monthly average temperature during the reference period for month i.

These delta factors were used to perturb a daily time series created by replicating the observed 25 yr. The delta factor for a specific month was used to adjust all daily data in that month. Temperatures were increased by the amount of standard deviations denoted by the delta factor and precipitation was multiplied with the delta factor. The average temperature, minimum temperature, and maximum temperature were all adjusted using the delta factor found in the GCM data for the average temperature.

4.4 Reservoir operation rules

To define reservoir operation, a linear programming (LP) optimisation (e.g. Dantzig and Thapa, 1997) was used to estimate monthly outflows for each reservoir separately. The LP is a well-known and most popular technique in reservoir optimisation (Rani and Moreira, 2010); some examples of the use of the method can be found, for example, from reservoir optimisation model reviews (Yeh, 1985; Labadie, 2004; Rani and Moreira, 2010). The aim of the LP objective function used is to maximise annual outflow from a reservoir through hydropower turbines, using the reservoir active storage, estimated monthly inflows, minimum outflow, and optimal outflow from the reservoir as parameters. An additional term was included into the objective function to force the filling of the reservoir during the wet season and emptying of the reservoir during the dry season. Constraints were also required to keep the reservoir outflow constant during the dry season.

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 simulated with daily time-step. 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

The monthly inflows for each reservoir, which are required in the optimisation, were estimated from computed 24-yr time series (April 1981–April 2005). The resulting operation rules aim to overestimate the reservoir usage and find an upper limit to the possible impact of reservoirs on Mekong discharges. Normal reservoir operation rules are often more careful and aim to make certain that the reservoir is filled up to full capacity each year.

The optimisation of all reservoirs was performed so that before optimising a given reservoir, all of the other reservoirs upstream from it were optimised. The inflows to the reservoir to be optimised were then computed with the upstream reservoirs being active. We first performed the reservoir optimisation procedure 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). An example of a reservoir regulation result is shown in Fig. S1 of the Supplements, which displays the water level of Chinese Xiaowan reservoir. The reservoir reaches full capacity on 17 of the 24 simulated years, and reaches the minimum operation level three times. A more detailed description of the method can be found in the Supplement S1.

5 Results

The impacts of climate change, reservoir operations, 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. We were limited in the length of our baseline period because of some major dam constructions, like the Manwan dam (filled up 1993). We therefore selected 1982–1992 as the baseline period and 2032–2042 as the future time period, so that both periods were of equal length. The hydrological model runs, with their associated GCM, emission scenario, and reservoir configuration, are listed in Table 4.

5.1 Impact of climate change on temperature, precipitation, and runoff

The temperature, precipitation, and runoff of different model runs for the years 2032–2042 were compared to the baseline data (1982–1992) (Fig. 3; Table 5). Daily average temperature for the whole catchment, computed as the mean of minimum and maximum temperature, increased by 0.8–1.4 °C in the model runs using the A1b emission scenario, and 0.6–1.3 °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. 3a). 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.

For precipitation, all but one of the GCMs (cnA) project an increase in annual average precipitation (Table 5). Compared to temperature change, the spatial distribution of precipitation change differs much more between the model runs (Fig. 3b). In the runs using the A1b scenario, two different precipitation patterns can be identified: in the first pattern the middle part of the catchment receives the largest increase of precipitation (ccA, mpA and ncA); and in the second pattern the largest increases are in the northernmost and southern parts of the catchment (cnA and giA) (Fig. 3b). In the model runs using the A1b scenario, the precipitation increase ranges from 2.5 to 8.6 %, while in the runs using the B1 scenario the increase ranges from 1.2 to 5.8 % (Table 5).

The modelled runoff for the whole catchment increases in six model runs (ccA, mpA, ncA, ccB, mpB, ncB) and decreases in four runs (cnA, giA, cnB, giB) (Table 5). The spatial pattern of runoff change in the lower part of the catchment is somewhat similar for all hydrological model runs, but varies in the middle and upper part of the catchment (Fig. 3c). In the lower part there is a decrease in runoff in the west, and varying amounts of increase in runoff in the east. Under emission scenario A1b, in the middle part of the catchment three model runs (ccA, mpA, and ncA) show increasing runoff while two model runs (cnA, giA) show decreasing runoff. Also, in the uppermost part of the catchment the model runs disagree on the direction of change (Fig. 3c).

5.2 Impact of climate change on main river discharge

For the model runs using the A1b emission scenario, the wet season discharges at Kratie have more variation between the different runs than the dry season discharges (except for December) (Fig. 4c; Table S1 in the Supplement). For the wet season, computed monthly discharges show a consistent increase for two runs (ccA, ncA), a varying decrease or increase for two runs (giA, mpA), and a consistent decrease for one run (cnA). The increase of discharges is most pronounced at the end of the wet season/beginning of the dry season in September, October, and November. Even the direction of the change induced by climate change differs: the annual discharge change ranges from a 13.4 increase to a 10.6 % decrease in Kratie for the A1b runs (Table 5). In Chiang Saen, there is somewhat more variation between the different runs compared to Kratie (Fig. 4a; Table 5).

In the runs using the B1 emission scenario, the increase at Kratie in September–October compared to baseline is smaller than in the runs using the A1b scenario (Fig. 4d; Table S1). There is also a decrease in monthly average discharge during June and July, which is not present in the runs using the A1b scenario. The range of annual discharge change for the runs using the B1 scenario is from −6.9 to +8.1 % (Table 5). At Chiang Saen, the average monthly discharge decreases throughout almost the entire year in most of the runs using the B1 scenario, staying at the baseline level only during May and June (Fig. 4b; Table S1). The largest decrease takes place in August.

5.3 Impact of reservoir operations on main river discharge

To investigate the impact 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. 5a–d, respectively. 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 (Fig. 5d), whereas the relative decrease during the wettest month is largest at the upstream part of the catchment at Chiang Saen (Fig. 5a).

5.4 Cumulative impact of climate change and reservoir operations 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

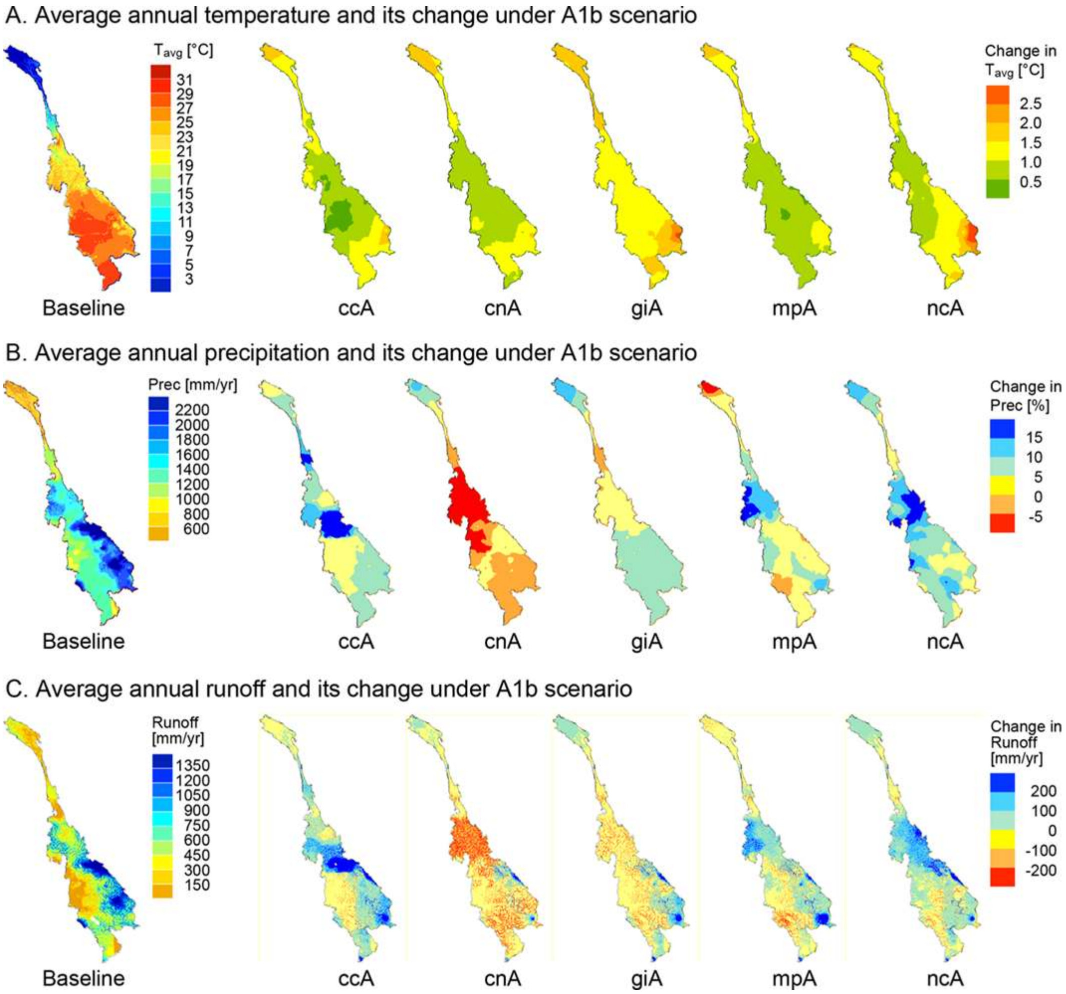

Fig. 3. Baseline results (1982–1992) and impact of climate change (2032–2042) on those under A1b scenario. **(A)** Average annual temperature (T_{avg}; °C). **(B)** Annual precipitation (mm yr^{-1} for baseline and % for change). **(C)** Average annual runoff (mm yr^{-1}). Abbreviations for used GCMs are stated in Table 4.

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)

Table 5. Variation in the estimates for the impacts of climate change: changes in average annual precipitation (prec.), maximum temperature ($T_{\max}$), minimum temperature ($T_{\min}$), and runoff; and annual discharges in Kratie and Chiang Saen for different model runs. Scenario years 2032–2042 are compared to baseline period 1982–1992.

Model run	Prec. (%)	$T_{\max}$ (°C)	$T_{\min}$ (°C)	Runoff (%)	Discharge Kratie (%)	Discharge C. Saen (%)
A1b scenario						
ccA	7.8	1.09	0.72	9.7	13.4	4.9
cnA	−2.5	1.20	0.80	−13.9	−10.6	−15.5
giA	5.2	1.65	1.10	−3.5	−0.9	−5.1
mpA	5.6	0.93	0.62	2.5	7.1	6.7
ncA	8.6	1.41	0.96	6.9	10.9	11.0
B1 scenario						
ccB	5.8	0.86	0.59	5.7	8.1	1.2
cnB	1.2	0.85	0.57	−3.5	0.1	−11.8
giB	1.4	1.58	1.04	−10.2	−6.9	−6.3
mpB	3.7	0.68	0.44	1.7	2.0	−4.4
ncB	4.7	1.05	0.72	1.0	4.2	−5.7

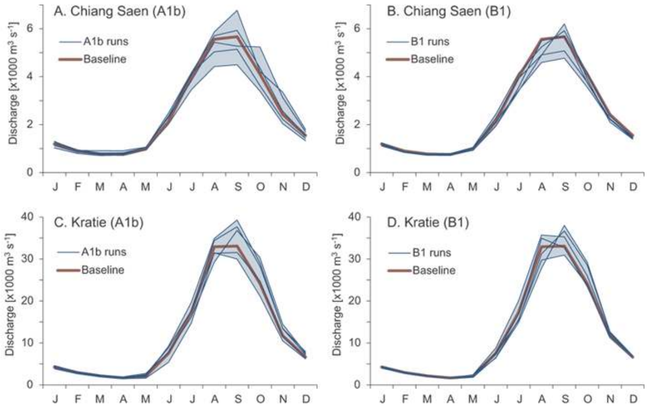

Fig. 4. Impact of climate change on Mekong main river discharge. Monthly average discharges of the model runs under emission scenarios (2032–2042) compared to baseline (1982–1992). **(A)** Chiang Saen under A1b emission scenario; **(B)** Chiang Saen under B1 emission scenario; **(C)** Kratie under A1b emission scenario; and **(D)** Kratie under B1 emission scenario. See Tables S2 and S3 in the Supplement for tabulated data. Note the differing discharge scales.

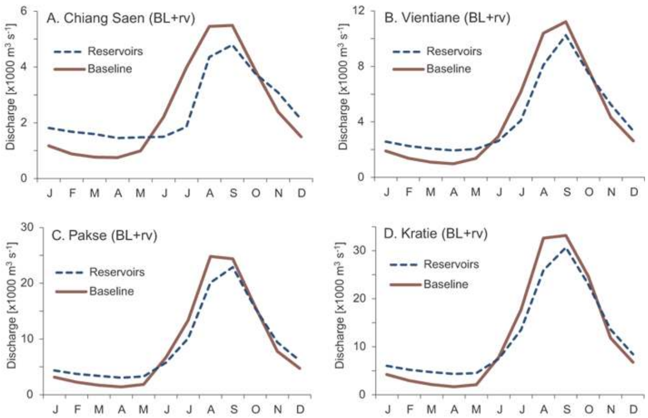

Fig. 5. Impact of reservoir operations on Mekong main river discharge. Monthly average baseline discharges (1982–1992) are compared with the discharge altered by reservoir operation at: **(A)** Chiang Saen; **(B)** Vientiane; **(C)** Pakse; and **(D)** Kratie. See Fig. 1c for the location of the stations. See Tables S4 and S5 in the Supplement for tabulated data. Note the differing discharge scales.

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. 6c). Similarly to the baseline with reservoirs (BL + rv) model run (Fig. 5d), 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–December, both the reservoir operation and climate change increase discharges, resulting in higher than baseline discharge values. The model runs using the B1 scenario 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. 6d).

In Chiang Saen, during the dry season and early wet season, the model runs using the A1b scenario and reservoirs follow the BL + rv results closely, except for the cnA + rv run, which has lower than average discharges (Fig. 6a). During August and September, there is a large variation between GCMs, with an average that is similar to the BL + rv run results (Fig. 5a). October and November discharges for the model runs using the 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. 6b).

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

The impact 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 impact 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. S2 of the Supplement. In the simulations without reservoirs there is a slight decrease of discharges in June and July for dry and wet years, and an increase of discharges in September and October for wet years in the majority of the model runs (Fig. S2a, c). The addition of reservoirs to the system for the dry year leads to a decrease in discharges in June and July and evens out the flood peak during August and September (Fig. S2b, d). For the wet year, the reservoirs reduce the discharge during June, July, and August, and are able to also reduce the peak flows during September. In October the reservoirs are full and do not affect the river discharge much.

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

The Mekong river flood pulse (Junk et al., 1989; Lamberts, 2006) at Kratie was in this study 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 selected flood pulse parameters for all model runs are shown in Table 6. In the climate change simulations without reservoirs, the flood peak discharge increases by 2 to 20 % (compared to baseline) in the runs using the A1b emission scenario, and 0 to 13 % for the ones using the B1 emission scenario. 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.

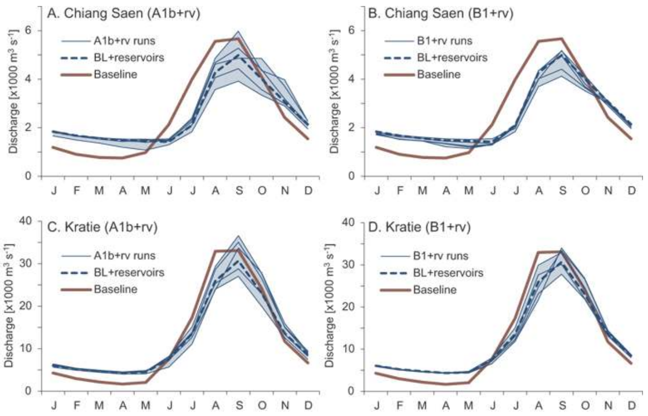

Fig. 6. Cumulative impacts of climate change and reservoir operations on Mekong main river discharge. Monthly average discharges of the model runs under emission scenarios (2032–2042) compared to baseline (1982–1992). **(A)** Chiang Saen using A1b emission scenario and reservoirs; **(B)** Chiang Saen using B1 emission scenario and reservoirs; **(C)** Kratie using A1b emission scenario and reservoirs; and **(D)** Kratie using B1 emission scenario and reservoirs. See Tables S4 and S5 in the Supplement for tabulated data. Note the differing discharge scales.

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 6). 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.

6 Discussion

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 support the planning of future hydropower dams. In Sects. 6.1–6.3, our findings are discussed and compared with those of other existing assessments, followed by a more general discussion about the remaining challenges and, consequently, future research themes.

Table 6. Flood parameters in Kratie for model runs computed as an average of 10 yr discharge data (2032–2041). Statistically significant ($p < 0.05$) changes compared to baseline (1982–1992) are marked with star (*). The flood volume is computed as the cumulative flow from the start of June to the end of December.

Model run	Peak-day	Peak 10^3 m^3 s^{-1}	Volume km^3	Model run	Peak-day	Peak 10^3 m^3 s^{-1}	Volume km^3
BL	245	47.5	379	BL	245	47.5	379
				BL + rv	248	42.7*	322*
A1b scenario							
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*
B1 scenario							
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*

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 on the relative change of precipitation compared to the change in evaporation. According to the downscaled results of the GCMs used in this study, both precipitation and temperature (i.e. evapotranspiration) in the Mekong region are generally projected to increase in the future (Table 5). However, the five GCMs used show large differences in how the Mekong's hydrology will change (Fig. 6; Tables 5 and 6), indicating high uncertainty in not only the magnitude, but also in 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 the 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 indicate more moderate impacts on hydrology due to climate change than the latter (Fig. S3 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 (ECHAM 4) as input to the hydrological model, and therefore we only compare our ECHAM5 results to their findings. It should be noted that the time horizons of these studies are different, and for climate change also relatively short: 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. S4 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. S4c 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. A more detailed comparison of the climate change impact assessments can be found in the Supplement S4.1.

6.2 Comparison: impact of reservoir operation on hydrology

Our results indicate similar changes in Upper Mekong Basin hydrology (with Chiang Saen as a reference location) compared to other studies (Adamson, 2001; Hoanh et al., 2010; Räsänen et al., 2012a). However, the magnitudes of the monthly changes do vary rather significantly between the studies (Fig. S5a in the Supplement). On a seasonal scale, however, our findings agree well with three other studies (Fig. S5b 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 Chiang Saen case (see Figs. S5 and S6 in the Supplement). Our results are well in line with the results of ADB (2004) on both the monthly and seasonal scale, but the comparison on seasonal scale shows that 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 a significant increase in irrigation in their basin wide analyses whereas the two other studies do not.

6.3 Comparison: cumulative impacts of climate change and reservoir operation on hydrology

In terms of policy relevance, among the most important findings of our study is that reservoir operations appear to have a larger impact on the hydrology of the Mekong's hydrology than climate change, at least in the near future studied in this paper (2032–2042). This is especially the case during the dry season. However, our projections including climate change show a large envelope between different GCMs, indicating high uncertainty in the future flow regime, especially during the wet season.

The comparison of our results of the cumulative impacts of dam operation and climate change on flow regime with the findings of Hoanh et al. (2010) and Mekong River Commission (2010c) is not straightforward for two reasons. Firstly, both Hoanh et al. (2010) and Mekong River Commission (2010c) incorporated irrigation development and inter-basin transfers in their study, while we did not take these into account. Secondly, while we used multiple GCMs, both Hoanh et al. (2010) and Mekong River Commission (2010c) used only one (ECHAM 4). Some level of comparison between these studies is, however, available in the Supplement.

6.4 Remaining challenges and future research themes

The scope of this paper is to assess hydrological impacts, which forms one of the first steps in impact assessment processes related to water development or to climate change. In order to understand the broader environmental, social, and economic impacts, further work is needed to assess the impact of the possible hydrological changes on ecosystems and water-related resources, and consequently, on people and their livelihoods and food security. For example, the Mekong River Commission (2010c) already provides a promising step forward in this regard. It is also important to note that even relatively small hydrological alterations in the flood pulse system may have significant impacts on ecosystem productivity (e.g. Lamberts, 2008). 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.

We acknowledge that the considered climate change and reservoir operations also impact on several other factors (e.g. Dugan et al., 2010; Kummu et al., 2010; Ziv et al., 2012), but in order to maintain focus we only examine the hydrological impacts. Moreover, although the analysed drivers (i.e. 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), they are not the only driving forces causing changes in the hydrology and water-related resources. Others include, for example, irrigation expansion, inter-basin water transfers, land use changes, and urbanisation (see also Pech and Sunada, 2008). 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). The impact of irrigation is expected to be opposite to the impacts of reservoir operation on stream flows during the dry season, which means that the irrigation may reduce the water level increase of dry season months caused by reservoir operations. 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).

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, we used one particular downscaling technique, whilst there are many other appropriate methods available, both statistical (e.g. Teutschbein et al., 2011) and dynamical (e.g. Giorgi, 2006). Yet, uncertainty resulting from different downscaling techniques is generally smaller than from different GCMs (Prudhomme and Davies, 2009). Furthermore, Delgado et al. (2010, 2012) and Räsänen et al. (2012b) report an increased likelihood of extreme floods and increased variance in the flows of the Mekong towards the end of 20th century, and that the levels of variance in the post-1950 period are unprecedented in at least the last 600 yr.

Although globally climate change is known to have increased the number of extreme weather events (Coumou and Rahmstorf, 2012), it is not well understood what is the origin of these changes in variance in the Mekong. The flow variance in the Mekong has been linked to factors including the Western Pacific Monsoon (Delgado et al., 2012) and El Niño-Southern Oscillation (ENSO) (Ward et al., 2010; Räsänen and Kummu, 2012), both of which are known to be inter-related and vary on decadal scales (Torrence and Webster, 1999; Wang et al., 2008). There are also other factors affecting the hydrology in the region, such as Indian Ocean Dipole, Madden-Julian Oscillation, Quasi-Biennial Oscillation, decadal cycles, and tropical cyclones (Singhrattna et al., 2005; Yongqin and Chappell, 2009), but their role in the Mekong Region is less studied. Thus, the changes in variance and occurrence of extreme events raise an interesting question regarding the climate models: How well do they simulate changes in climate variability? For example, Allan and Soden (2008) reported that climate models might have underestimated the future projections of extreme weather events. Therefore, climate change projections based on GCMs could be analysed together with long- term historical data (e.g. paleoclimatological data) to provide new useful insights into future climate projections.

Our study included hydropower reservoirs that are existing, under construction, and planned, with the majority of the studied reservoirs being still at the planning stage (Mekong River Commission, 2009, 2010c). Hence, the estimated impact of the reservoir operations 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 reservoir operation 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 time frames, 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 all of the six main river stations used for calibration and validation, the simulated monthly averages show good agreement with the measured data, and for daily discharges the Nash-Sutcliffe efficiency varies between 0.779 and 0.941 for both the calibration and validation periods (see Table 3). Nevertheless, uncertainties caused by inaccuracies in model input data, model structure, and parametrisation remain in the model results. Uncertainty estimation of model parameters using known methods such as GLUE (Beven and Binley, 1992) was not performed. However, during the model calibration we noted that the most sensitive parameters of the model at the catchment scale were related to the evapotranspiration and overland flow computations. At the scale of tributaries, errors related to sparseness of precipitation data and inaccuracies in the model grid due to large grid cell size were also important. It is therefore likely that possible improvements of these computation methods and higher resolution data and model grid would increase the performance of the model.

7 Conclusions

In this paper we assessed the impact of climate change and reservoir operation on the hydrology of the Mekong River within the 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 may alter the discharge of the main river. We aimed to fill part of this knowledge gap by carrying out state-of-the-art hydrological modelling using multiple downscaled GCMs and reservoir operation optimisation algorithms. This allowed us to examine the impacts of climate change and reservoir operations, both separately and together.

We found that within the timescale used in our study (1982–1992 vs. 2032–2042), climate change is likely to increase basin precipitation and average temperature. The range between GCMs is, however, relatively large for both variables. We also found that under the two emission scenarios used, A1b and B1, there is a large variation in discharge results between the hydrological model runs using different GCMs. In some cases even the direction of climate change impacts on Mekong discharges remains uncertain. It thus seems possible that some of the flow-related impacts of climate change are similar – not opposite, as the majority of studies have so far suggested – to the flow-related impacts of reservoir operation. This highlights the importance of using multiple GCMs when estimating the possible climate change impacts on Mekong discharge.

Our study also shows that, at least within the studied timeframe, the impacts of the reservoir operations on selected flood pulse parameters (such as relative changes in monthly discharges) are clearly larger than the effects of climate change. These reservoir operation impacts result in higher dry season flows and lower flood peaks in Kratie, and particularly affect 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 operations alone. Hence, climate change increases the uncertainty of the estimated reservoir operation impacts, emphasising the importance of looking at these impacts in a cumulative manner. It should be noted, however, that the reservoir operations do not significantly impact the total discharge over a year, while climate change causes changes in annual runoff variation of between -13.9 and 9.7 %.

The impact of reservoir operations on hydrology depends largely on the operation rules applied and, naturally, on the actual number and location of the dams. Consequently, collaboration with dam planners and dam operators to minimise the impact of the reservoirs 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 discharge varies greatly 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.net/16/4603/2012/hess-16-4603-2012-supplement.pdf.

Acknowledgements. This work was part of the "Exploring Mekong Region Futures" project's local study for the Tonle Sap area. The project was funded by CSIRO AusAID Research for Development Alliance. GCM downscaling was funded by Maa-ja vesitekniikan tuki ry. Hans de Moel also received funding from the Dutch research programme "Knowledge for Climate" (KvK Theme 1) and the CcASPAR project (IWT Flanders); Philip J. Ward received funding from the Netherlands Organisation for Scientific Research (NWO; VENI grant); Timo A. Räsänen received funding from RYM-TO doctoral school; Marko Keskinen received funding from Academy of Finland (#133748), and Matti Kummu received funding from the postdoctoral funds of Aalto University. We thank our colleagues at Water & Development Research Group, particularly Aura Salmivaara and Olli Varis, and our long-term collaborators with the Mekong studies Jorma Koponen and Juha Sarkkula, for their support and helpful comments. The constructive and thoughtful comments of the two anonymous reviewers are highly appreciated.

Edited by: W. Buytaert

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