Water Resour Manage
DOI 10.1007/s11269-012-0087-0

Downstream Hydrological Impacts of Hydropower Development in the Upper Mekong Basin

Timo A. Räsänen · Jorma Koponen · Hannu Lauri · Matti Kummu

Received: 15 November 2010 / Accepted: 5 June 2012

Abstract The Mekong River Basin in Southeast Asia is experiencing extensive hydropower development. Concerns have been raised about the consequences of the development for the ecosystems, livelihoods and food security in the region. The largest planned hydropower dam cascade in the basin, the Lancang-Jiang cascade, is currently under construction and already partly built into the Upper Mekong Basin, China. In this paper we assess the impact of the Lancang-Jiang cascade on downstream hydrology by using a combination of a hydrological model and a reservoir cascade optimization model. The hydrological changes were quantified in detail at the Chiang Saen gauging station in Thailand, the first gauge station downstream from the cascade, and in lesser detail at four other downstream locations in the Mekong mainstream. We found that on average the Lancang-Jiang cascade increased the December–May discharge by 34–155 % and decreased the July–September discharge by 29–36 % at Chiang Saen. Furthermore, the Lancang-Jiang cascade reduced (increased) the range of hydrological variability during the wet season (dry season) months. The dry season hydrological changes were significant also in all downstream gauging stations, even as far as Kratie in Cambodia. Thus the Mekong's hydrological regime has been significantly altered by the Lancang-Jiang cascade, but what the consequences are for ecosystems and livelihoods, needs further study.

Keywords Hydrological impact assessment · Hydrological modelling · Dynamic programming · Hydropower operation · The Mekong Basin · Yunnan

Electronic supplementary material The online version of this article (doi:10.1007/s11269-012-0087-0) contains supplementary material, which is available to authorized users.

T. A. Räsänen (✉) · M. Kummu
Water & Development Research Group, Aalto University, P.O. Box 15200, 00076 Aalto, Finland
e-mail: timo.rasanen@aalto.fi

J. Koponen · H. Lauri
Environmental Impact Assessment Centre of Finland Ltd., Tekniikantie 21 b, 02150 Espoo, Finland

Published online: 16 June 2012

1 Introduction

The Mekong River Basin is currently undergoing extensive hydropower development. The underlying drivers of the hydropower development are linked to the demographics, human development, water and food security, economic integration and climate change in the region (Grumbine et al. 2012). Currently there are 36 dams in the Lower Mekong Basin (LMB) while there may be 90 dams by the year 2030 and 136 by 2060 according to the Mekong River Commission (MRC) scenarios (MRC 2009a, 2011). Furthermore, there are currently at least five operational dams in the Upper Mekong Basin (UMB) and 24 planned or considered dams (HydroChina 2010; Grumbine and Xu 2011). If all the development plans are actualized, the total number of hydropower dams in the Mekong Basin will be 165.

The hydropower development in the Mekong is estimated to bring economic benefits to the region as it will increase the region's energy security, trade, foreign investments, and navigation and irrigation possibilities (ICEM 2010). However, hydropower development will also have adverse impacts on the region's ecosystems, social systems and livelihoods (ICEM 2010). One of the major concerns has been the adverse impacts of hydropower dams on fisheries. Over 56 million people in the region are dependent on fish and other aquatic animals (Hortle 2007), and the current development is expected to have major impacts upon fisheries (Dugan 2008; Dugan et al. 2010). Thus the hydropower development induced losses in ecosystem productivity are feared to negatively affect food security in the region (ICEM 2010; MRC 2010). Especially the planned dams in the mainstream of the Lower Mekong Basin are feared to cause significant negative impacts (Stone 2011).

A major impact of dam construction is the fragmentation of river systems (Nilsson et al. 2005) and its negative consequences for ecosystem productivity (Dugan et al. 2010). Dams also affect ecosystem productivity through alteration of flow regime, as it is the key determinant of physical habitats in streams and flood plains (Junk et al. 1989; Bunn and Arthington 2002). This is also the case in the Mekong Region. The Mekong's aquatic and riparian ecosystems have developed together with a flow regime that can be characterized as predictable monomodal food pulse (Junk et al. 2006; Lamberts 2008). River regulation or alteration of flow regimes does, therefore, have significant consequences for riparian (Nilsson and Berggren 2000) and aquatic ecosystems (Bunn and Arthington 2002). Furthermore, dams affect sediment transport (Kummu and Varis 2007; Kummu et al. 2010) and river morphology (Surian 1999).

When assessing the ecological impacts of flow regulation, a good understanding of the hydrological impacts is needed. In the Mekong Region hydrological impact assessments have been done with various modelling approaches with varying complexity (e.g. Adamson 2001; ADB 2004, 2008; World Bank 2004; MRC 2011). The modelling approaches in these cases vary from simple water reallocation methods to more complex models, such as river basin management, hydrological and hydrodynamic models. These impact assessments have been summarized and reviewed by Keskinen and Kummu (2010) and Keskinen et al. (2012), and the water resources modelling attempts broader in the Mekong by Johnston and Kummu (2012).

In this paper we focus on assessing the hydrological impacts caused by the Lancang-Jiang hydropower dam cascade using a combination of a distributed hydrological model and a reservoir cascade optimization model. The Lancang-Jiang cascade is located in the Mekong mainstream in the UMB, China. The Lancang-Jiang cascade includes eight dams, six of which will be operational by the year 2014 (MRC 2009a). Our assessment focuses on those first six dams as the planned operational years and technical details for the two lowest dams are uncertain. From here on, we will use the name Lancang-Jiang cascade for the first six dams. The cascade has raised debate in the region concerning its downstream impacts as the cascade has significant regulation capacity of 23 km^3 (ADB 2004) which is 40 % of the annual flow at the lowest dam of the cascade. One of the most recent heated discussion occurred during the 2010 dry season when the Mekong experienced exceptionally low water levels (e.g. Qiu 2010; Stone 2010). One major reason for the colourful discussion has been the lack of reliable data from the hydropower operations of the existing reservoirs.

The hydrological impacts of the Lancang-Jiang cascade have been estimated before by Adamson (2001) and Hoanh et al. (2010). Adamson's (2001) estimation is based on water balance calculations while the Hoanh et al. (2010) use the SWAT hydrological model and the IQQM water allocation model for their assessment. Both studies revealed relatively similar hydrological changes on seasonal scale: increased dry season flows and decreased wet season flows. The changes were not, however, addressed in detail in either one of the earlier studies. In this paper we assess the downstream hydrological impacts of the Lancang-Jiang cascade with more advanced methods, a better hydrometeorological dataset, and more detailed analysis compared to the earlier studies. Our main aim is to produce a scientifically solid and transparent estimation of the potential downstream hydrological impacts of the Lancang-Jiang cascade.

2 Study Area

The study area of this paper is the Mekong headwaters located in China and Myanmar, i.e. Upper Mekong Basin (Fig. 1a). The area of the Upper Mekong Basin is 190,000 km^2 of which 88 % resides in China and 12 % in Myanmar (MRC 2005). The whole Mekong River Basin covers an area of 795,000 km^2 and is also shared by Thailand, Lao PDR, Cambodia and Vietnam. The Mekong River is also called as Lancang-Jiang by the Chinese and Zachu by the Tibetans but in this paper we use the terms Mekong River and Upper Mekong Basin.

The Mekong River originates from the Tibetan Plateau (over 5000 masl) at China's Qinghai Province (MRC 2010). From there, the river flows south through the Tibetan Autonomous Region to an area where Mekong, Yangtze and Salween flow parallel in deep and narrow mountain gorges. In this area there are no significant tributaries. Further south, the Mekong River flows through China's Yunnan province, where mountain valleys broaden gradually but the mountains are still relatively high (2000–3000 masl) (MRC 2010). In Yunnan smaller tributaries start to develop. From Yunnan the Mekong River follows the border of Myanmar and Lao PDR and then enters Thailand. Here is where the UMB ends and the Lower Mekong Basin (LMB) begins. Altogether, the Mekong flows for 2200 km and decreases in altitude almost 4500 m before entering the LMB (MRC 2005).

The climate in the northernmost parts of the UMB is defined as cold climate with cold and dry winters and cold summers while the climate in the lower parts of the UMB is defined as temperate climate with dry winters and hot summers (Peel et al. 2007). The annual average rainfall varies within the UMB from north 500 mm (GSOD station 561370 at Qamdo) to south 1600 mm (GSOD station 569540 at Lancang) (NCDC 2010; see station locations in Fig. 1b). The distinct dry and wet seasons combined with snowmelt from the higher elevation, create a seasonal flow regime where 76 % of the annual flow occurs between June and October (at Chiang Saen).

The Lancang-Jiang cascade (Fig. 1b) is planned to consist of eight dams (from upstream to downstream): Gonguoqiao, Xiaowan, Manwan, Dachaoshan, Nuozhadu, Jinghong, Ganlamba, and Mengsong. Three of the six most upstream dams (Xiaowan, Manwan, Dachaoshan) are completed while the rest are in various stages of implementation (MRC

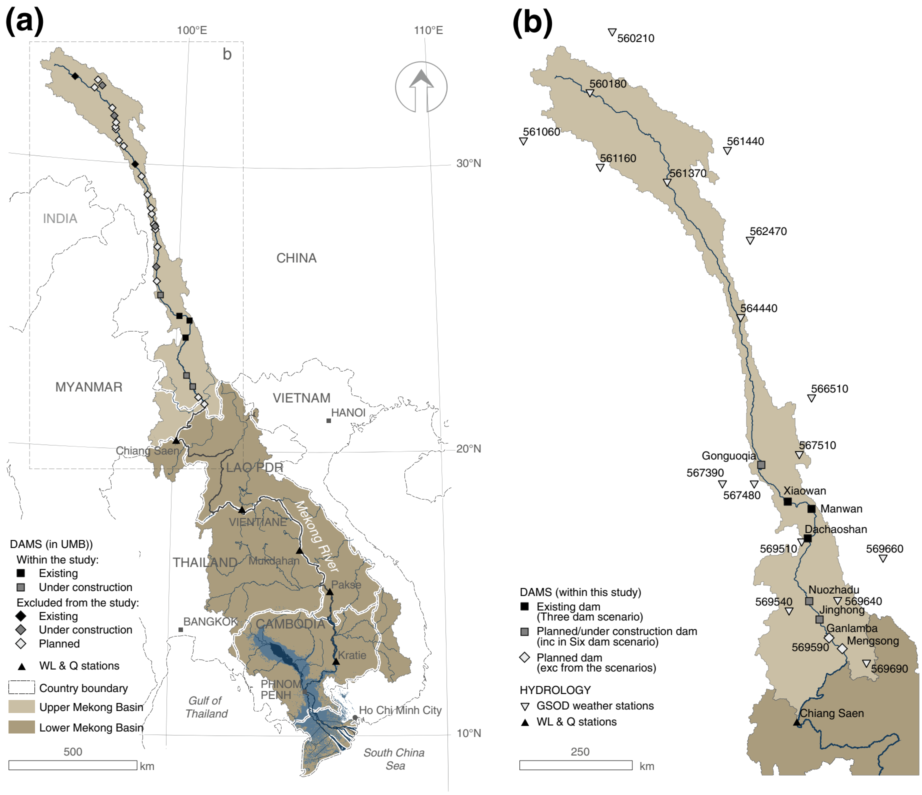

Fig. 1 Maps of the study area. **a** Dams in operation, under construction or planned in the Upper Mekong Basin (MRC 2009a; HydroChina 2010; Grumbine and Xu 2011) and mainstream gauging stations (WL & Q); b Lancang-Jiang cascade and GSOD (Global Summary of the Day) meteorological stations (NCDC 2010)

2009a). Once the first six dams are completed the cascade will have a regulation capacity of 23.2 km^3 that corresponds to 28 % of the annual flow at Chiang Saen in Thailand (see location in Fig. 1a), which is the first gauging station downstream from the cascade. The exact reservoir storages of Ganlamba and Mengsong are unknown but they are expected to be rather small (MRC 2009a). The details of the first six dams in the Lancang-Jiang cascade are presented in the Methodology and data sections. The planned and existing dams further upstream (HydroChina 2010; Grumbine and Xu 2011) were not considered in this study as there was no adequate information available on them and it is also expected that the Lancang Jiang cascade will have the most significant downstream hydrological impacts.

3 Methodology and Data

The methodology to assess future hydrological changes caused by the Lancang-Jiang cascade was based on simulations with the hydrological model VMod (Koponen et al. 2010) and the generalized dynamic programming package CSUDP (Labadie 2003). We used the hydrological model to define the baseline hydrology, reservoirs inflows and routed the reservoir releases downstream. The generalized dynamic programming package was used to simulate optimal reservoir cascade operations.

In the Lancang-Jiang cascade simulations three scenarios were considered: baseline, 3 dam and 6 dam scenario. The baseline scenario represents a period without any of the dams. The 3 dam scenario represents a situation when the Xiaowan, Manwan and Dachaoshan dams are operational while the 6 dam scenario includes all the six dams of the Lancang-Jiang cascade (Fig. 1b). The hydrological impacts of dam scenarios were assessed at Chiang Saen gauging station (Fig. 1b) below the dam cascade on daily, monthly and seasonal basis. The impacts of dam scenarios were assessed also at the four other downstream locations but in less detail. The time period for the dam scenario simulations was May 1994–April 2001. We used hydrological years in the simulations. The hydrological year was defined to start on the first day of May and end next year on the last day of April, following the definition by Kummu and Sarkkula (2008).

3.1 Hydrological Model, Model Setup and Model Validation

3.1.1 Hydrological Model

The VMod hydrological model can be classified as a distributed physically based hydrological model (Koponen et al. 2010). VMod is the hydrological part of broader IWRM model package but in this paper we have used only this hydrological part of the package. In the VMod, the modelled basin is divided into grid cells typically ranging from 0.01 to 5 km^2, and each grid cell has its own set of parameters such as ground slope and aspect, vegetation type and soil type. These grid values are obtained from the digital elevation model (DEM), land cover data and soil type data. The computed hydrological processes include precipitation, infiltration, snow hydrology, evapotranspiration, seasonal vegetation development, soil water balance, shallow groundwater flow, and soil water drainage into streams. Water flow in streams, rivers and lakes is computed using a dynamic river network model. Computation can be done at various time steps, e.g. 3 h, 6 h, daily. The VMod model is described in more detail in Koponen et al. (2010).

The VMod has been applied in the Mekong Region for several river basins e.g. the whole Mekong Basin (Sarkkula et al. 2010), Tonle-Sap sub-basin (MRCS/WUP-FIN 2003), Nam Songkhram (WUP-FIN 2008), Mae Cham (Sarkkula et al. 2010), and Khuwae Noi (Sarkkula et al. 2010) . These model applications have provided a strong background for the model development and therefore the VMod is well adjusted to fit the hydrological conditions of Southeast Asia.

3.1.2 Hydrological Model Setup

The geospatial data for the construction of the hydrological model included the following datasets: Soil type data, land use data, DEM, Mekong river catchment boundary, and river and lake shore data. The Mekong River Basin has 12 major soil types (FAO 2003), and for the hydrological model setup soil types were reclassified into seven soil types according to similarities in hydrological behaviour. The new classification was based on Driessen et al. (2001). Driessen et al. (2001) also list data on soil textural classification for sample soil profiles for 30 world reference base soil types. The soil textural classes were used to calculate the hydraulic properties of the soil types. The calculation was done with the

Hydraulic Properties Calculator (Saxton and Rawls 2006). The land use classes in the Mekong River basin were reclassified from 22 classes (GLC2000 2003) to 9 classes according to their similarities. The SRTM data were used for the DEM (Jarvis et al. 2008).

All geographical data were converted into 5 km resolution grid files. For the DEM, the average elevation value from the 90 m resolution raster values within the model grid box was used for the final grid box elevation. For soil and land use types, the most common type within the grid box was selected for the final grid box. Once the 5 km grid datasets were ready, the Mekong River Basin area was extracted according to the Mekong River Catchment boundary (MRC 2009c). The river data in the model grid were created according to river and lake shore data (MRC 2009c) while the smaller river networks were calculated according to the lowest neighbour principle.

The meteorological input data for the hydrological model were derived from the Global Summary of the Day (GSOD) dataset, which is an online dataset distributed by the US National Climatic Data Center (NCDC 2010). Altogether 18 stations (Fig. 1b) with least missing data in the period January 1985–May 2010 were selected for the study. The data from the GSOD stations included daily precipitation and daily average, minimum and maximum temperatures. The original datasets were examined for missing data and errors. On average, the precipitation data had 1.9 % missing data values and 12.1 % possibly incomplete data. Missing precipitation data were filled using the Normal Ratio Method (see e.g. Dingman 2002) with two or three neighbouring stations. The missing values after the year 1998, which could not be filled with neighbouring stations, were filled with daily data from the Tropical Rainfall Measuring Mission (NASA 2010). Daily temperature data had on average 0.8 % missing data, which were filled similarly to the Normal Ratio Method with two or three neighbouring stations. The hydrological model simulations revealed that the years 1992, 1993 and 1999 may still have errors in the precipitation data. The Mekong mainstream flow data at Chiang Saen station were obtained from the Mekong River Commission's HYMOS database for the period January 1985–May 2010. The flow data was quality controlled by the MRC.

3.1.3 Model Calibration and Validation

The initial parameterization for the VMod hydrological model was obtained from previous model applications used in the Mekong Region. The model used for this study was initially calibrated for the whole Mekong River Basin using observed flows from the period 1990–2000 (Sarkkula et al. 2010). The current model was recalibrated for the UMB using the observed flows at Chiang Saen during the period 1990−2000 and validated using the period 2001–2008.

3.2 Reservoir Simulation Model and Model Setup

3.2.1 Reservoir Simulation Model

CSUDP is a generalized dynamic programming package that uses discrete dynamic programming to find optimal decision policies for sequential multi-stage decision problems (Labadie 2003). The use of CSUDP requires the user to develop C functions, which describe the nature of the problem as well as the objective functions, which are used to solve the problem with minimum costs or maximum benefits. CSUDP allows the use of user-defined constraints on decision and state variables, which guide the optimal decision policy. CSUDP is described in more detail by Labadie (2003).

The major benefit of discrete dynamic programming is that it optimizes simultaneously multi-stage problems such as multiple dams and their operations as part of a cascade. Thus the dynamic programming has been a popular method for optimizing various water resource planning and management problems, such as reservoir cascade operations, and is more widely discussed together with other optimization and simulation methods by Labadie (2004) and by Rani and Moreira (2010). A study done by Yi et al. (2003) is also an example of the application of CSUDP for solving complex hydropower operations.

3.2.2 Reservoir Operation Model Setup

The simulation of the Lancang-Jiang cascade was based on three main principles: i) minimum allowed reservoir water levels, ii) head-energy production relationship, and iii) maximization of annual energy production of the entire cascade. The simulation of the dam cascade was purposefully kept rather simple, as adequate data were not available for further refinement of the method. Therefore, a more detailed simulation method would not have made the results more accurate or reliable. The method we used, however, is intended to give a reasonable understanding of the hydrological changes. The cascade optimization approach was adapted from the Mahaweli example problem included in the CSUDP program package. The main characteristics and assumptions of the model setup are presented here and more detailed information can be found from the Online Resource.

To run the CSUDP model, we first defined the natural inflows at the exact location of each of the six dams (see locations in Fig. 1b) with the VMod hydrological model. The average flows from the hydrological model at the dam sites correspond reasonably well to the average flows given in ADB (2004). CSUDP was operated with a weekly time step and thus, we combined the daily flows into weekly inflows to the dam sites. The inflow into the most upstream dam was the simulated natural flow at the dam site while the flow into the lower dams was defined as the release of the upstream dam added with the surface and subsurface flows into the stream between the dams derived from the VMod hydrological model. This maintained the water balance and took into account the runoff to the river between the dams.

The minimum allowed water levels, i.e. lower boundaries, were defined by using the active storage part of the total reservoir storage. Active storage is the part of total reservoir storage that is used for regulation. The purpose of the lower boundary is to prevent the active storage from emptying too early in the dry season and to ensure that the active storage will be filled up in the wet season (see Fig. S4 and Fig. S5 in the Online Resource for the lower boundaries of Xiaowan and Nuozhadu reservoirs). The lower boundaries were defined with maximum constant wet and dry season releases which could be held during the driest year in record. Wet season release was defined to start when the natural discharge reached long-term average and the dry season release was defined to start when the natural discharge fell below the long-term average. For the driest year we used average hydrographs at the dam sites which were scaled to the level of the driest year in the study period. The average hydrographs were obtained from the hydrological model for each of the dam sites.

3.2.3 Optimisation Process

The energy produced by a hydropower dam is dependent on the hydraulic head and turbine flow at a specific moment. For the energy production simulation we defined the shape of the reservoir to estimate the elevation-volume relationship of the reservoir. The reservoir elevation-volume relationship was calculated for each dam using the SRTM DEM with 90 m resolution (Jarvis et al. 2008) and the dam and reservoir characteristics (Table 1). This method produced the relationship of elevation-volume-energy rate, which was needed in the optimization process (see also Online Resource for more details on reservoir shape calculation and energy rate function).

The optimization process was based on maximization of an objective function that calculated the total annual energy production of the cascade. Different objective functions could have been used but this objective function was considered to provide the most realistic estimate of the dam operations as in the currents situation there was no information of the operational goals of the simulated dams. Thus the combination of dynamic programming and the objective function used optimized simultaneously the operations of all dams so that the annual energy production of the entire cascade is maximal (see also Online Resource for more details on objective function and energy calculations).

After the optimization process the weekly releases of the lowest dam in the cascade were interpolated to a daily time step. Interpolation was done so that the weekly flow sum was divided into equal amounts for each day of the week. The daily regulated flows were then used as an input for the validated hydrological model. The hydrological model then routed the dam releases and added other hydrological components to downstream flows.

3.2.4 Remarks on the Methodology

When interpreting the results of the reservoir simulations four issues need to be considered. First, the objective function maximizes annual energy production while a more realistic optimization target would have been economic return. Second, the dynamic programming method used here finds optimal decisions with perfect knowledge of future flows. In reality, however, there are no perfect streamflow forecasts. Third, other dam and reservoir operation or water allocations besides energy production were not considered in the simulations (e.g. flood protection). However, these reservoir operations could be added to simulations if those

Table 1 Dam, power plant and reservoir characteristics of the Lancang-Jiang cascade (ADB 2004)

		Gonguoqia	Xiaowan	Manwan	Dachaoshan	Nuozhadu	Jinghong	TOTAL
Completed	[year]	2011[a]	2012[a]	1993[a]	2003[a]	2014[a]	2013[a]	
Average inflow	[m^3/s]	985	1220	1230	1340	1750	1840	
Total storage	[km^3]	0.51	14.56	0.92	0.93	22.4	1.23	40.56
Active storage	[km^3]	0.12	9.9	0.26	0.37	12.3	0.25	23.19
Full supply level	[masl]	1319	1236	994	906	807	602	
Min. oper. level	[masl]	1311	1162	982	860	756	595	
Net head	[m]	77	248	89	80	205	67	
Dam height	[m]	130	300	126	110	254	118	
Plant capacity	[MW]	750	4,200	1,500	1,350	5,500	1,500	14,800
Energy production	[GWh]	4,670	18,540	7,870	7,090	22,670	8,470	69,310

[a] year of completion from MRC (2009a)

were known. Fourth, this approach does not consider the lag time of the water flow from one reservoir to the next. This does not introduce significant inaccuracies into the results as the time step used for reservoir simulations is 7 days, the reservoir distances are relatively short and the flow velocities are high. Regardless of these issues, our approach should be reasonable, given the data and information available, for estimating hydrological impacts of Lancang-Jiang hydropower cascade. The data required for reservoir operation simulation are drawn from the Asian Development Bank's Cumulative Impact Analysis (ADB 2004) and is presented in Table 1.

3.3 Assessing the Hydrological Impacts of Hydropower Cascade

Several methods were used to assess the impacts of hydropower operation on downstream hydrology. These are briefly introduced below. All assessments were done using the results from Baseline, 3 dam and 6 dam scenarios of the simulation period May 1994–April 2001.

First, we assessed how the daily flows and the range of daily hydrological variability of the Baseline scenario were affected by the 3 dam and 6 dam scenarios at Chiang Saen. The range of hydrological variability refers to the range how much the discharge of each day varied during the scenario simulations.

Second, we adapted the methods used by Kummu and Sarkkula (2008) in Tonle Sap Lake at Mekong in Cambodia to analyse the impact of Lancang-Jiang Cascade on the flood pulse (Junk et al. 1989; Junk and Wantzen 2004) at Chiang Saen. The flood pulse concept was originally developed for studying floodplain dynamics (Junk et al. 1989) but we consider the method appropriate also for describing the pulsing hydrology of a river environment. The flood pulse parameters that we used for characterizing the flood pulse were as follows: a) start and end date of the flood, b) flood duration, c) flood maximum date, d) flood amplitude, e) maximum water level. First we defined the start and end dates for the flood. The flood starts and ends on dates when the water level crosses the reference water level. The reference water level was defined as 1 m above minimum water level and minimum water level was taken according to a 31-day moving average (Kummu and Sarkkula 2008). The duration of the flood is the period between the start and end date of the flood. Flood maximum date is the date when the 31-day moving average reaches the maximum and flood amplitude is the height between the reference level and flood peak. Maximum water level is the actual maximum measured water level.

Third, we assessed the hydrological changes on monthly basis at four other downstream locations, Vientiane, Mukdahan, Pakse and Kratie (Fig. 1a) in addition to Chiang Saen. For this we used a simple water balance method. In this method the Lancang-Jiang cascade impacted flow at Vientiane was calculated in the following way: natural monthly flow at Chiang Saen was subtracted from natural monthly flow at Vientiane, and the regulated monthly flow at Chiang Saen was added to the flow at Vientiane. The flow changes were compared as changes in percentages from the flows of the Baseline period.

Fourth, we assessed how the range of monthly hydrological variability of the Baseline scenario changed under the 6 dam scenario at Chiang Saen. Here the range of hydrological variability refers to the range on how much the discharge of each month varied during the scenario simulations. We also calculated the average monthly discharge anomaly of the 6 dam scenario at Chiang Saen. The anomalies were calculated as average monthly discharge changes from the Baseline discharge.

Fifth, we examined how the driest year 1999 and wettest year 2001 of the simulation period affected the dam simulations and regulated flows at Chiang Saen. For this we calculated the natural monthly flow anomalies of the Baseline scenario and regulated monthly flow anomalies of the 6 dam scenario. All anomalies were calculated as differences from the average monthly flow of Baseline scenario. With this method we were able to compare how the combination of naturally dry and wet years together with dam operations affected the flows at Chiang Saen.

4 Results

4.1 Hydrological Model Calibration and Validation Results

The calibration results for the VMod hydrological model showed that the R^2 was 0.75 for the calibration period 1990–2000 (Fig. S2 in the Online Resource) while the R^2 was 0.86 for the validation period 2001–2008 (Fig. S3 in the Online Resource). The R^2 for the whole data period January 1985–May 2010 was 0.79. The lower R^2 in the calibration period was partly caused by suspected inaccuracies in precipitation data during the years 1992, 1993 and 1999. The average measured flow for the whole data period was 2660 m^3/s while the average computed flow was 2578 m^3/s.

4.2 Reservoir Simulation Results

The simulation results of the 3 dam and 6 dam scenarios showed significant changes in daily average flows at Chiang Saen (Fig. 2 and Fig. S8). In general, the average wet season flows decreased and the average dry season flows increased in both scenarios but the 6 dam scenario shows more substantial change. This is obvious as the total active storages used for regulation were 10.5 km^3 and 23.2 km^3 in the 3 dam and 6 dam cascade scenarios, respectively. In our simulations, on average 87 % of this active storage was used for regulation in the 3 dam scenario and 68 % in the 6 dam scenario (Fig. S4 and S5 in the Online Resource). The operation of the hydropower cascade in the 6 dam scenario resulted in significant flow increases in December–May (34–155 %) and flow decreases in July–September (29–36 %) at Chiang Saen (Fig. 3). The range of hydrological variability was also altered in both dam scenarios (Fig. 2 and Fig. 4a). In the 3 dam scenario the range of hydrological variability was reduced during July–August and in 6 dam scenario during May–September. The 6 dam scenario also increased significantly the hydrological variability during the dry season months. The ranges of hydrological variability during baseline and 6 dam scenarios are compared in Table 2.

The average monthly flow changes [%] in the 6 dam scenario were calculated at four other mainstream stations (Fig. 3). The monthly flow changes clearly illustrate that the relative changes in flows were greater in the dry season months and largest in March and April. In March the discharge increased on average by 49 % in Kratie by an impact of hydropower operation in Yunnan, which corresponds approximately to a 1.1 m increase in average monthly water level.

Our analysis of the flood pulse characteristics revealed that in scenario settings the flood duration, amplitude and maximum water level decreased, the timing of the flood start and peak dates delayed and the timing of flood end was advanced (Table 3). In the 3 dam scenario, flood duration decreased by 58 days and in the 6 dam scenario by 81 days from the total 214 days in the Baseline scenario (Table 3). In summary, the dam cascade operations led to a new hydrological regime with less seasonal variability in flows and water levels (Table 2).

The simulations revealed also that the dam regulations, and impact of those on hydrology, varied according to the inter-annual hydrological variation (Fig. S4, S5, S6 and S7 in the

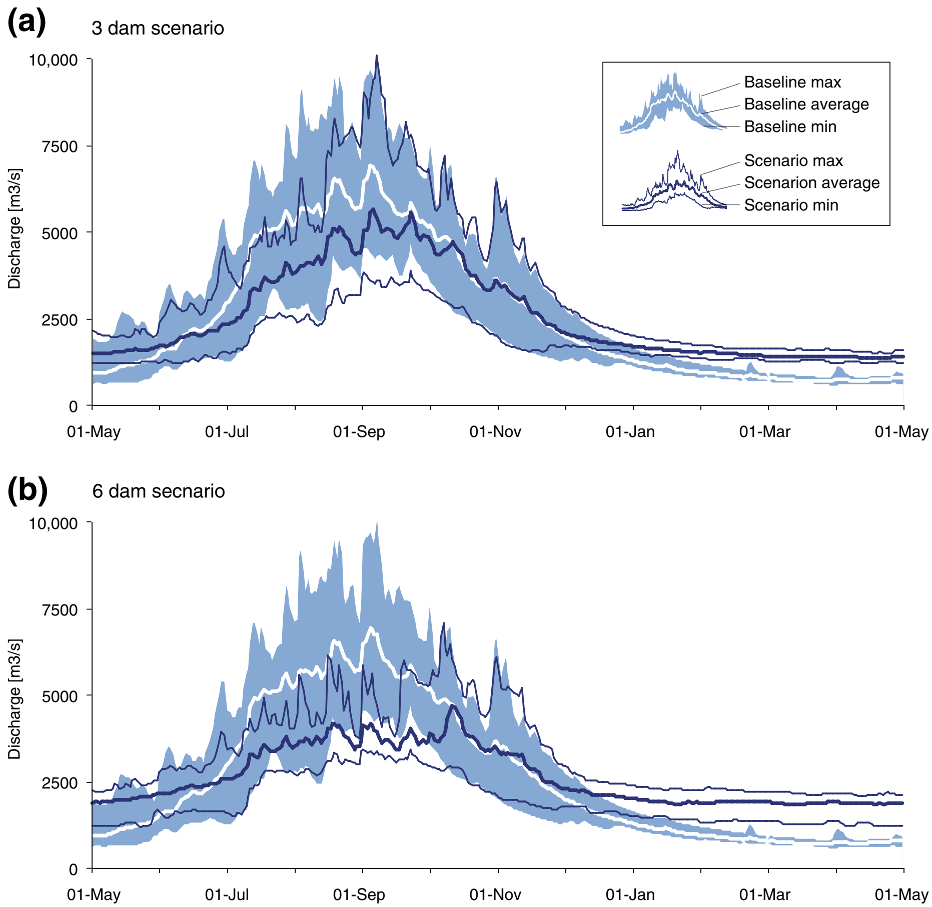

Fig. 2 Simulated daily average flows at Chiang Saen. **a** 3 dam scenario compared to the Baseline; **b** 6 dam scenario compared to the Baseline. The blue area represents the range of the natural hydrological variability without the dams with average flow shown by white line. The area between the darker blue lines represents the range of hydrological variability after the dam operations with the average regulated flow shown with thick dark blue line

Online Resource). During the dry years the reservoir water levels were kept higher and during the wet years the reservoir water levels were lower. The Fig. 4b shows how the prevailing hydrological conditions affected the reservoir operations and the flows at Chiang Saen on a monthly scale. The total wet season flow anomalies (i.e. the monthly flows of the 6 dam scenario compared to the average flows of the Baseline scenario) were found to be larger during the driest year 1999 than in the wettest year 2001, although the reservoirs used less of their storage capacity. Thus the combination of naturally drier wet season and hydropower operations led to larger wet season flow anomalies during the 1999 than in 2001. The dry season flow anomalies were then found to be larger during the year 2001 when the reservoirs used a larger proportion of their storage capacity. These findings highlight the fact that hydropower operation and consequently their impacts are closely linked to climate variations.

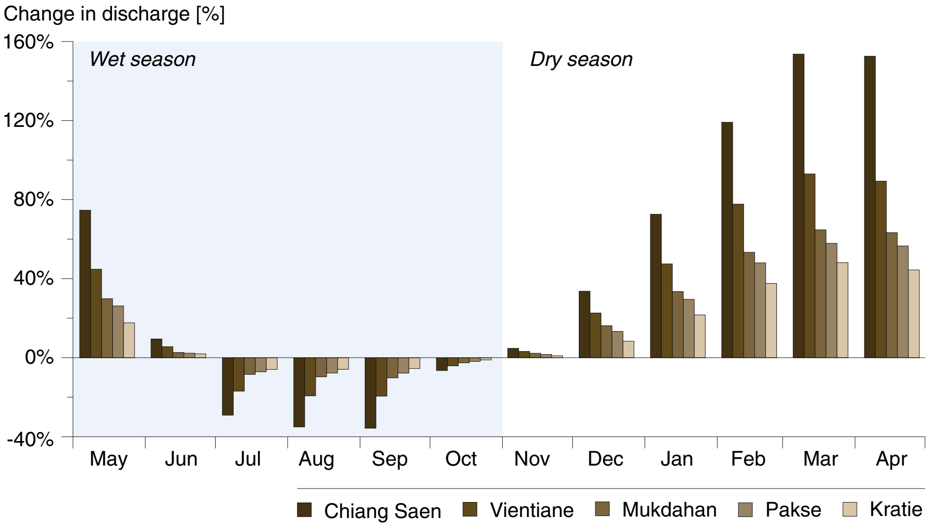

Fig. 3 Monthly average flow changes [%] caused by the 6 dams scenario of Lancang-Jiang cascade at five locations in the Mekong mainstream

4.3 Energy Production Estimations

The annual energy production of the 3 and 6 dam scenario simulations are shown in Fig. 5. The simulated energy productions were very close to the announced energy production figures (ADB 2004). For the 3 dam scenario the announced annual energy production was 33.5 TWh and the simulations produced on average 8.4 % more energy. Respectively for the 6 dam scenario the announced annual energy production was 69.3 TWh and the simulations produced on average 9.8 % more energy. Significant uncertainty for the energy production calculations in the simulations was the lack of information on the actual losses of the six hydropower projects. In our simulations the losses were assumed to be 10 %, which is quite reasonable for new hydropower projects.

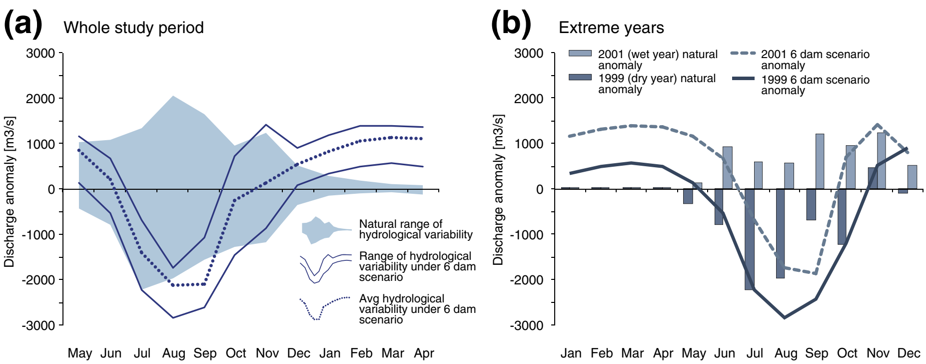

Fig. 4 The simulated monthly hydrological changes at Chiang Saen. **a** The range of hydrological variability of the 6 dam scenario compared to the range of natural hydrological variability in the Baseline scenario. **b** The natural monthly flow anomalies of the driest year (1999) and wettest year (2001) and the anomalies caused by the dam operations of the 6 dam scenario for the same years

Table 2 The monthly discharge anomalies and the range of hydrological variability of 6 dam scenario compared to Baseline scenario

Month	Average discharge anomaly under 6 dam scenario [m^3/s]	Range of hydrological variability under 6 dam scenario [m^3/s]	Range of hydrological variability under Baseline scenario [m^3/s]	Change in range
Jan	819	350…1181	−148…294	88.1 %
Feb	1052	499…1383	−91…183	222.9 %
Mar	1137	574…1406	−78…119	322.6 %
Apr	1115	504…1370	−125…96	292.9 %
May	848	137…1176	−426…1040	−29.1 %
Jun	212	−518…690	−778…1094	−35.5 %
Jul	−1392	−2213…−688	−2213…1338	−57.1 %
Aug	−2118	−2835…−1745	−1959…2069	−72.9 %
Sep	−2099	−2614…−1057	−1551…1658	−51.5 %
Oct	−242	−1456…726	−1259…954	−1.4 %
Nov	147	−851…1424	−1162…1251	−5.7 %
Dec	551	78…900	−342…525	−5.2 %

5 Discussion

In this paper we assessed the downstream hydrological impacts of the Lancang-Jiang cascade. Our findings are rather well in line with the two other studies done for the hydropower cascade (Adamson 2001; Hoanh et al. 2010), as presented in Fig. 6a and b. All three studies could be compared only at the seasonal scale, as the Hoanh et al. (2010) have not published monthly results for Chiang Saen. Hoanh et al. (2010) suggest that the June–November flows would decrease 17 % while Adamson (2001) and our study suggest 20 % and 22 % decrease (Fig. 6a). For the December–May months Hoanh et al. (2010) estimate a 60 % increase, Adamson (2001) a 74 % increase and this study a 90 % increase. Thus the Hoanh et al. (2010) results suggest the smallest hydrological impacts while this study suggests the largest impacts. At the monthly scale, the comparison of our results with those of Adamson (2001) shows a fairly similar monthly pattern of change, although the magnitude and timing of change differs (Fig. 6b).

The reasons for the differences in the results of the three assessments can be many. First, the methodologies for reservoir operation rule estimations are different: this study used dynamic programming for simultaneous optimization of all dams in order to maximize their total energy production, Adamson (2001) used a simple spread sheet model based for allocation of water from wet season to dry season and it did not consider hydropower

Table 3 Average flood pulse parameters of Baseline, 3 dam and 6 dam scenarios at Chiang Saen

Scenario	Flood start [date]	Flood end [date]	Flood duration [days]	Flood maximum [days]	Amplitude [m]	Maximum water level [m]
Baseline	26-May	25-Dec	214	29-Aug	4.64	7.24
3 dam	25-Jun	27-Nov	156	15-Sep	2.82	6.44
6 dam	6-Jul	15-Nov	133	5-Oct	1.53	5.74

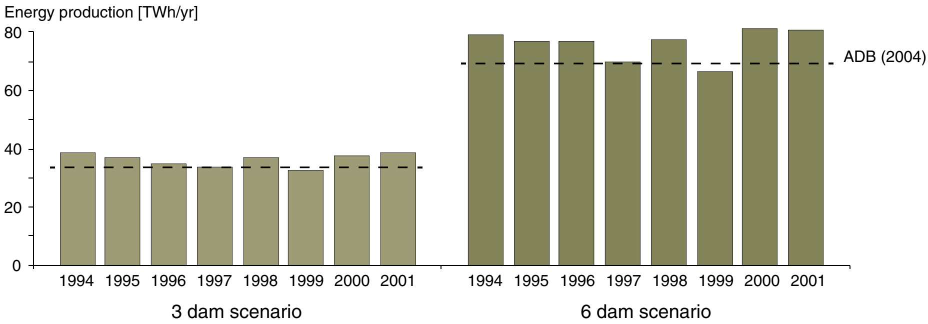

Fig. 5 Simulated annual energy productions of the 3 dam and 6 dam scenarios compared to the announced energy production (ADB 2004)

production, while the method used by Hoanh et al. (2010) remains somewhat obscure, due to lack of proper methodology section in their paper. Each of the three methodologies has varying assumptions on how the reservoirs would be operated. Furthermore, the hydrological baseline periods used in the three studies were different. This study used the period May 1994–April 2001, Adamson (2001) used the years 1960–1991 and Hoanh et al. (2010) used the years 1975–2000. The different baseline periods may also have caused some differences to the final impact assessment results. These differences in all three analyses clearly highlight the importance of transparency of the impact assessment processes and also the need for inter-comparison of alternative assessments.

5.1 Assessment Scales

This study and the two studies mentioned above (Adamson 2001; Hoanh et al. 2010) have examined hydrological changes only on coarse temporal scales (weekly, monthly and seasonal). The selection of scales determines what factors are considered and what are left out from the analysis and thus the selected scales affect also the interpretation of the results (Kummu 2008). For example the hydropower operations may vary greatly on hourly and daily basis and the impacts of these variations were not covered by the studies discussed in this paper. Furthermore, the impact assessments focusing on hydrological impacts of hydropower projects rarely cover the issue of more exceptional dam operations such as emergency spills. The analysis of these short-term impacts would require finer temporal scales and better information on actual dam operations.

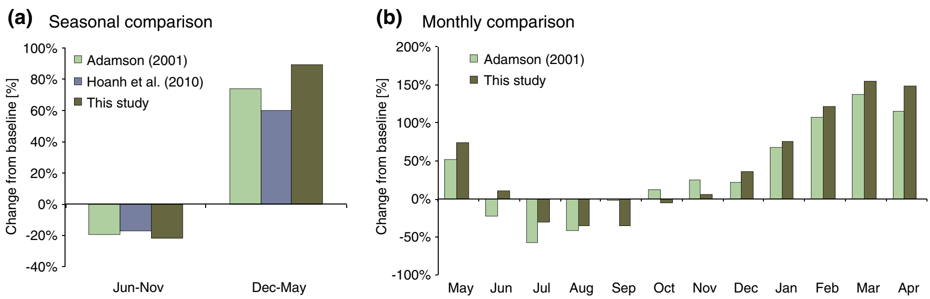

Fig. 6 Comparison of hydrological impact assessments of the Lancang-Jiang cascade by Adamson (2001) and MRC (Hoanh et al. 2010) to the results of this study on **a** seasonal, and **b** monthly scale

This study focused also only on the Lancang-Jiang cascade and did not account for the impacts of hydropower development further upstream in the UMB (see Fig. 1a). As we have shown, the Lancang-Jiang cascade changes significantly the hydrological regime and almost levels out the seasonality immediately below the cascade. The major hydrological impacts are, therefore, already caused by the Lancang-Jiang cascade and the dams upstream are not expected to cause further major hydrological changes. But in terms of sediments, the upstream dams may have additional impacts. The Lancang-Jiang cascade have been estimated to have the theoretical capacity to trap 94 % of the total suspended solids (Kummu and Varis 2007; Kummu et al. 2010) and the upstream dams will further reduce the sediment transport downstream.

To put the Lancang-Jiang cascade into basin-wide context, we compared the active storage of the cascade with those of MRC's hydropower development scenarios (MRC 2009a,b) in the Mekong Basin (Fig. 7). The active storage of 23.2 km^3 of the Lancang-Jiang cascade accounts for 32 % of the total storage capacity of all the reservoirs in the Foreseeable Future Scenario (year 2030) and 22 % of the Long Term High Development Scenario (year 2060). The total active storages of the hydropower scenarios are respectively 71.9 km^3 and 106.1 km^3, including the Lancang-Jiang cascade (MRC 2009a,b). Considering the estimations on the cumulative hydrological and sediment related changes caused by the Lancang-Jiang cascade together with further hydropower development, it is not difficult to foresee that the Mekong River Basin is subject to undergo massive changes. The hydropower development will have various negative but also positive impacts on multiple sectors (see e.g. Dugan 2008; Dugan et al. 2010; Lamberts 2008; Sarkkula et al. 2009; ICEM 2010; MRC 2010; Stone 2011; Grumbine and Xu 2011; Grumbine et al. 2012). It will be challenging task for the Mekong countries to balance between the pros and cons of the hydropower development.

5.2 Climate Variability and Climate Change

Our analysis on the cascade operations during the wet and dry years also highlights the importance of the climate variability and climate change in the impact assessment of hydropower operations. In our case, the natural hydrological variability affected the dam operations and the downstream impacts. Thus the potential changes in the future climate may also affect the hydropower operations and their impacts. Some studies (e.g. Västilä et al. 2010; Hoanh et al. 2010) have suggested that the potential climate change impacts in the Mekong region are opposite to the hydropower impacts found in this study, although there are considereable uncertainties on the direction of climate change impacts (Kingston et al. 2011). It is also important to acknowledge that the timescales of the impacts can be very

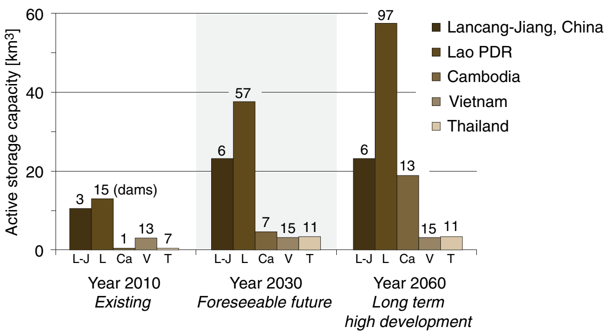

Fig. 7 Active storage of Lancang-Jiang cascade compared with the total active storages of hydropower development scenarios by country in the Lower Mekong Basin (MRC 2009a,b). The number of dams in each country is indicated above the columns

different. The impacts of hydropower development will be experienced in the coming years or decade while climate the change impacts will most likely be experienced over a longer time span (Keskinen et al. 2010). However, there is already some indication of the increased hydrological variability in the flows of the Mekong (Delgado et al. 2010, 2012). The potential changes in climate and hydrology can have consequences to existing planned hydropower projects, as they have to be able to adjust to the new hydrological conditions.

The combination of climate events and hydropower operations, have already raised discussion in the Mekong (see e.g. Qiu 2010; Stone 2010). During the dry season of 2010 parts of the Mekong experienced exceptionally low water levels and the discussions on the reasons behind the low water levels addressed the possible filling of a new reservoir of Xiaowan dam in Lancang-Jiang cascade. According to our analyses, a major factor behind the low water levels was the significantly lower rainfall during the last months of wet season (Fig. S10 in the Online Resource). The rainfall of September and November in 2009 were both the second driest September and November months during the period of Jan 1985–May 2010. Furthermore, the rainfall during the dry season months December–February in 2010 were lower than average. But how the filling of Xiaowan reservoir contributed to the dry water levels is still an open question. This case may potentially be an example for future water conflicts related to development and climate.

6 Conclusions

In this paper we assessed the hydrological impacts for the Mekong mainstream caused by the Lancang-Jiang hydropower cascade in China. We used a combination of a hydrological model and a dynamic optimization model to conduct the study. We found that the operation of the hydropower cascade would significantly alter the flow regime of the Mekong. In our estimations the December–May discharge increased by 90 % while the June–November discharge decreased by 22 % at Chiang Saen, the closest gauging station downstream from the dam cascade. General features of the changes in the flood pulse characteristics were that the duration and amplitude of flood pulse would decrease, and the timing of the flood maximum would be delayed. Furthermore, the Lancang-Jiang cascade reduced (increased) range of the hydrological variability during the wet season (dry season) months. The hydrological changes during the dry season were also significant as far as Kratie in Cambodia, where the discharge was around 40–50 % higher than the baseline during March and April. The most important uncertainties in this study come from the estimated reservoir operations. If more information were available on operational targets and goals, the uncertainties could be reduced.

On the basis of the understanding gained in studying the hydrological impacts of the Lancang-Jiang cascade, it is clear that basin-wide hydropower development will have considerable consequences on the Mekong's flow regime. The new flow regime may have significant implications for mainstream and floodplain ecosystems (e.g. Tonle Sap Lake), livelihoods and even food security in the region, but the significance of these implications needs to be addressed in separate studies. This study also shows the importance of the inter-comparison of various hydrological assessments and their methodologies in the Mekong. The inter-comparison of three different assessments suggested different hydrological changes with particular differences in the magnitudes of change. The reason for these differences needs to be openly discussed together with the uncertainties in the methodologies used in the assessments. This is important especially when the assessment results are being used to support planning and decision-making.

Acknowledgments The authors would like to thank the Mekong River Commission for providing the discharge data for the study. The authors are grateful to Prof. Olli Varis, Dr. Marko Keskinen, Aura Salmivaara and Mirja Kattelus for their support. Timo Räsänen received funding from the RYM-TO Graduate School and Maa- ja Vesitekniikan Tuki ry. and Matti Kummu received funding from the postdoctoral funds of Aalto University. The research was also supported by Academy of Finland (project 133748).

References

Adamson P (2001) The Potential impacts of hydropower developments in Yunnan on the hydrology of the lower Mekong. International Water Power and Dam Construction 53:16–21

ADB (2004) Cumulative impact analysis and Nam Theun 2 contributions: Final report. Prepared by NORPLAN and EcoLao for Asian Development Bank (ADB).http://www.adb.org/Documents/Studies/Cumulative-Impact-Analysis/default.asp. Accessed 16 September 2010

ADB (2008) Lao People's Democratic Republic: Preparing the Cumulative Impact Assessment for the Nam Ngum 3 hydropower project. Prepared by Vattenfall Power Consultant AB in association with Ramboll Natura AB and Earth Systems Lao for Asian Development Bank (ADB).http://www.adb.org/Documents/TARs/LAO/40514-LAO-TAR.pdf. Accessed January 2012

Bunn S, Arthington A (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ Manag 30:492–507

Delgado J, Apel H, Merz B (2010) Flood trends and variability in the Mekong river. Hydrol Earth Syst Sci 14:407–418

Delgado J, Merz B, Apel H (2012) Climate-flood link for the lower Mekong River. http://www.hydrol-earth-syst-sci.net/16/1533/2012/. Hydrol Earth Syst Sci 16:1533–1541

Dingman S (2002) Physical hydrology, 2nd edn. Waveland Press, Illinois, 600

Driessen P, Decker J, Spaargaren O, Nachtergaele F (eds.) (2001) Lecture notes on the major soils of the world. Food and Agriculture Organization of United Nations (FAO)

Dugan P (2008) Mainstream dams as barriers to fish migration: international learning and implications for the Mekong. Catch Culture 14:9–15

Dugan P, Barlow C, Agostinho A et al (2010) Fish migration, dams, and loss of ecosystem services in the Mekong Basin. Ambio 39:344–348

FAO (2003) WRB map of world soil resources. Food and Agriculture Organization of United Nations (FAO), Land and Water Development Division.

GLC2000 (2003) Global Land Cover 2000 database. European Commission, Joint Research Centre

Grumbine R, Xu J (2011) Mekong hydropower development. Science 322:178–179

Grumbine R, Dore J, Xu J (2012) Mekong Hydropower: drivers of change and governance challenges. Front Ecol Environ 10:91–98

Hoanh C, Jirayoot K, Lacombe G, Srinetr V (2010) Impacts of climate change and development on the Mekong flow regime, First assessment - 2009. MRC Technical Paper No. 29 Mekong River Commission, Vientiane, Lao PDR.http://www.mrcmekong.org/assets/Publications/technical/tech-No29-impact-of-climate-change.pdf. Accessed January 2012

Hortle K (2007) Consumption and the yield of fish and other aquatic animals from the lower Mekong Basin. Mekong River Commission Technical Paper 16, Mekong River Commission, Vientiane. http://www.mrcmekong.org/assets/Publications/technical/tech-No16-consumption-n-yield-of-fish.pdf. Accessed January 2012

HydroChina (2010) Map of planned and existing hydropower projects. http://www.hydrochina.com.cn/zgsd/images/ziyuan_b.gif. Accessed 16 September 2010

ICEM (2010) MRC Strategic Environmental Assessment (SEA) of hydropower on the Mekong Mainstream. Hanoi, Viet Nam. http://www.mrcmekong.org/news-and-events/consultations/strategic-environmental-assessment-of-mainstream-dams. Accessed January 2012

Jarvis A, Reuter H, Nelson A, Guevara E (2008) Hole-filled SRTM for the globe Version 4. CGIAR-CSI SRTM 90 m Database

Johnston R, Kummu M (2012) Hydrological modelling in the Mekong Basin: a review. Water Resour Manag 26:429–455

Junk W, Wantzen K (2004) The flood pulse concept: New aspects, approaches and applications – An update. In: Welcomme R, Petr T (eds.) Proceeding of international symposium on the management of large river for fisheries. RAP Publications 2004716, FAO, Bangkok 2:117–140

Junk W, Bayley P, Sparks R (1989) The flood pulse concept in river-floodplain systems. In: Dodge D (ed.) Proceedings of the international large river symposium (LARS). Canadian Special Publication of Fisheries and Aquatic Sciences 106:110–127

Junk W, Brown M, Campbell I et al (2006) The comparative biodiversity of seven globally important wetlands: a synthesis. Aquat Sci 68:400–414

Keskinen M, Kummu M (2010) Impact assessment in the Mekong: review of strategic environmental assessment (SEA) & cumulative impact assessment (CIA). Water & Development Publications, Aalto University. TKK-WD-08. 48 p. http://www.wdrg.fi/publications/water-development-publications/impact-assessment-in-the-mekong. Accessed January 2012

Keskinen M, Chinvanno S, Kummu M, Nuorteva P, Snidvongs A, Varis O, Västilä K (2010) Climate change and water resources in the Lower Mekong River Basin: putting adaptation into the context. J Water Clim Change 1:103–117

Keskinen M, Kummu M, Käkönen M, Varis O (2012) Mekong at the crossroads: next steps for impact assessment of large dams. Ambio 41:319–324

Kingston D, Thompson J, Kite G (2011) Uncertainty in climate change projections of discharge for the Mekong River Basin. Hydrol Earth Syst Sci 15:1459–1471

Koponen J, Lauri H, Veijalainen N, Sarkkula J (2010) HBV and IWRM Watershed Modelling User Guide. MRC Information and Knowledge management Programme, DMS – Detailed Modelling Support for the MRC Project. http://www.eia.fi/index.php/support/download. Accessed January 2012

Kummu M (2008) Spatio-temporal scales of hydrological impact assessment in large river basins: the Mekong case. PhD Thesis, Water Resources Research Unit, Helsinki University of Technology. 92+ app. p 112

Kummu M, Sarkkula J (2008) Impact of Mekong River flow alteration on Tonle Sap flood pulse. Ambio 3:185–192

Kummu M, Varis O (2007) Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. Geomorphology 85:275–293

Kummu M, Lu XX, Wang JJ, Varis O (2010) Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong. Geomorphology 119:181–197

Labadie J (2003) Generalized dynamic programming package: CSUDP. Documentation and user guide, version 2.44. http://modsim.engr.colostate.edu/csudp.shtml. Accessed January 2012

Labadie J (2004) Optimal operation of multireservoir systems: state of the art review. J Water Resour Plann Manag 130:93–11

Lamberts D (2008) Little impact, much damage: the consequences of Mekong River flow alterations for the Tonle Sap ecosystem. In: Kummu M, Keskinen M, Varis O (eds.) Modern myths of the Mekong. Water & Development Publications, Helsinki University of Technology, pp. 3–18

MRC (2005) Overview of the hydrology of the Mekong Basin. Mekong River Commission (MRC), Vientiane, Lao PDR

MRC (2009a) Economic, environmental and social impact assessment of basin-wide water resources development scenarios, Assessment methodology. Mekong River Commission (MRC) technical note, Vientiane Lao PDR. http://www.mrcmekong.org/assets/Other-Documents/BDP/Tech-Note2-Scenario-assessment-methodology-complete-Report091104.pdf. Accessed January 2012

MRC (2009b) Hydropower dam database. Mekong River Commission (MRC), Vientiane Lao PDR.

MRC (2009c) Mekong river basin 1:50'000 vector data. Mekong River Commission (MRC), Vientiane Lao PDR

MRC (2010) State of the basin report 2010. Mekong River Commission (MRC), Vientiane, Lao PDR. p 232

MRC (2011) Assessment of basin-wide development scenarios, Basin Development Plan Programme, Phase 2. Mekong River Commission (MRC), Vientiane, Lao PDR http://www.mrcmekong.org/assets/Other-Documents/BDP/Assessment-of-Basin-wide-dev-Scenarios-MainReport-110420.pdf. Accessed January 2012

MRCS/WUP-FIN (2003) Modelling Tonle Sap for environmental impact assessment and management support. Final report, WUP-FIN Phase I, Mekong River Commission and Finnish Environment Institute consultancy consortium, Phnom Penh. http://www.eia.fi/wup-fin/Reports/wup-fin1/WUP-FIN_FinalDraft.pdf. Accessed January 2012

NASA (2010) Tropical rainfall measuring mission (TRMM). NASA, Goddard Space Flight Center.

NCDC (2010) Global Surface Summary of the Day (GSOD). US National Climatic Data Center.

Nilsson C, Berggren K (2000) Alterations of riparian ecosystems caused by river regulation. BioScience 50:783–792

Nilsson C, Reidy C, Dynesius M, Revenge C (2005) Fragmentation and flow regulation of the world's large river systems. Science 308:405–408

Peel M, Finlayson B, McMahon T (2007) Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci 11:1633–1644

Qiu J (2010) China drought highlights future climate threats. Nature 465:142–143

Rani D, Moreira M (2010) Simulation-optimization modeling: a survey and potential application in reservoir systems operation. Water Resour Manag 24:1107–1138

Sarkkula J, Keskinen M, Koponen J, Kummu M, Richey J, Varis O (2009) Hydropower in the Mekong region: what are the likely impacts upon fisheries? In: Molle F, Foran T, Käkönen M (eds) Contested waterscapes in the Mekong region - Hydropower, livelihoods and governance. Earthscan. pp. 227–249

Sarkkula J, Koponen J, Lauri H, Virtanen M (2010) IWRM modelling report. Detailed Modelling Support (DMS), Information and Knowledge Management Programme, Mekong River Commission. http://www.eia.fi/DMS/DMS_IWRM-Report_24December2010_v4.pdf Accessed January 2012.

Saxton K, Rawls W (2006) Soil water characteristic estimates by texture and organic matter for hydrological solutions. Soil Sci Soc Am J 70:1569–1578

Stone R (2010) Severe drought puts spotlight on Chinese dams. Science 327:1311

Stone R (2011) Mayhem in the Mekong. Science 333:814–818

Surian N (1999) Channel changes due to river regulation: the case of Piave River, Italy. Earth Surf Process Landforms 24:1135–1151

Västilä K, Kummu M, Sangmanee C, Chinvanno S (2010) Modelling climate change impacts on the flood pulse in the Lower Mekong floodplains. J Water Clim Change 1:67–86

World Bank (2004) Modelled observations on development scenarios in the Lower Mekong Basin, Mekong Regional Water Resources Assistance Strategy. Prepared for the World Bank with Mekong River Commission cooperation. p. 142. http://ns1.mrcmekong.org/download/free_download/LMB-Development-Scenarios.pdf. Accessed June 2012

WUP-FIN (2008) Hydrological, environmental and socio-economic,modelling tools for the Lower Mekong Basin impact assessment. WUP-FIN Phase II, Mekong River Commission and Finnish Environment Institute consultancy consortium, http://www.eia.fi/wup-fin/Reports/wup-fin2/wup-fin2_Model-Report.pdf. Accessed January 2012

Yi J, Labadie J, Stitt S (2003) Dynamic optimal unit commitment and loading in hydropower systems. J Water Resour Plann Manag 129:388–398