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Assessment of hydrological changes in the lower Mekong Basin from Basin-Wide development scenarios

T. Piman,[1]* T. Lennaerts[2] and P. Southalack[2]

[1] *University of Canterbury, Department of Civil and Natural Resources Engineering, Christchurch, New Zealand*
[2] *Mekong River Commission Secretariat, Vientiane, Lao PDR*

Abstract:

The Mekong is one of the world's great rivers. It has the greatest mean annual flow in the world for a river basin of comparable size. The flow regime, with very distinct wet and dry seasons, supports a rich biodiversity and the world's largest freshwater fishery. Given that at the present time the hydrological regime of the Mekong remains in its natural state, the accelerating pace of water resources development will induce hydrological change. The natural productivity of the system is therefore potentially jeopardized. This paper reports the findings of simulation studies of the potential hydrological impacts of water resource development scenarios over future planning horizons. In the Definite Future scenario (next 5 years), the seasonal redistribution of water by on-going hydropower development will increase the dry season flow by 40–60% in the upper portion of the basin and by 20–30% in the Mekong Delta. The Foreseeable Future scenario (next 20 years) and Long-Term Future scenario (next 50 years) will result in relatively small changes to the flow regime as further increases in dry season reservoir releases will be offset by planned increases in irrigation and other consumptive water demands. All scenarios were predicted to reduce the average wet season flows by 4–14%, flow reversal to the Tonle Sap Lake by 7–16%, flooded areas by 5–8% and salinity intrusion areas in the Viet Nam Delta by 15–17%. Predicted changes in Definite Future scenario will be irreversible, necessitating improved coordination between the LMB countries and cooperation with China in order to manage the risks and maximize the regional benefits. The scenario assessments highlighted the areas where research is necessary to mitigate and manage impacts in order to ensure the reasonable and equitable use of the Mekong basin's water resources. Copyright © 2013 John Wiley & Sons, Ltd.

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KEY WORDS Asia; Mekong Basin; hydrologic and hydraulic models; Tonle Sap: Hydropower

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INTRODUCTION

The Mekong has perhaps never been figured in popular imagination as one of the world's great rivers. The Amazon, which is alone responsible for 20% of global river runoff, the Nile because of its role in history, the Mississippi/Missouri and its role in popular culture and literature and the Congo which defines the dark heart of Africa all have a far higher profile. The Mekong is, after all, in terms of its drainage area only the 30th largest river basin in the world, a not particularly remarkable statistic. However, in terms of its mean annual flow volume to the South China Sea, it ranks 10th (Dai and Trenberth, 2002).

The Mekong has the greatest mean annual flow in the world for a river basin of comparable size. The mean annual flow is of the order of 457 km^3, much smaller than the Yangtze, for example at 900 km^3 but greater than that of the Indus at 207 km3 (Dai and Trenberth, 2002). It is a member of a family of large Asian river systems that flow through regions populated by almost 1/4 of humanity (Varis *et al*., 2012), which include the Indus, Yangtze, Yellow, Brahmaputra and Ganges. The population of the Mekong Basin is about 70 million (Pech and Sunada, 2008; Varis *et al*., 2012), a majority of whom depend upon the mainstream and its tributaries for their economic livelihood. The river supports the world's largest inland fishery and has a natural ecological biodiversity only rivalled by the Amazon and Congo (MRC, 2010a).

The division of the overall basin into 'upper' and 'lower' sub-basins is a logical expression of physical, climatic and hydrological and arbitrary differences (Carling, 2009). The Upper Mekong Basin (UMB) starts from China to Myanmar and the Lower Mekong Basin (LMB) begins from Lao PDR to the Viet Nam Delta. The hydrological boundary between the two is generally taken to be the hydrometric gauge on the mainstream at Chiang Saen (Figure 1). The UMB is narrow with no significantly large tributary systems. The LMB is wide with tributaries that are very large river systems in their own right. In terms of drainage area, the UMB accounts for 20% of the Mekong system total of 795 000 km^2 (MRC, 2005).To provide effective support for sustainable management and development of water and related resources in the LMB, the Mekong River Commission (MRC) was established by Lao PDR, Thailand, Cambodia and Viet Nam through an agreement in 1995.

The annual hydrological regime of the Mekong is clearly defined by its coherent seasonal monsoonal flood

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*Correspondence to: Thanapon Piman, Department of Civil and Natural Recources Engineering, University of Canterbury, Christchurch, New Zealand
E-mail: gamekung2@yahoo.com

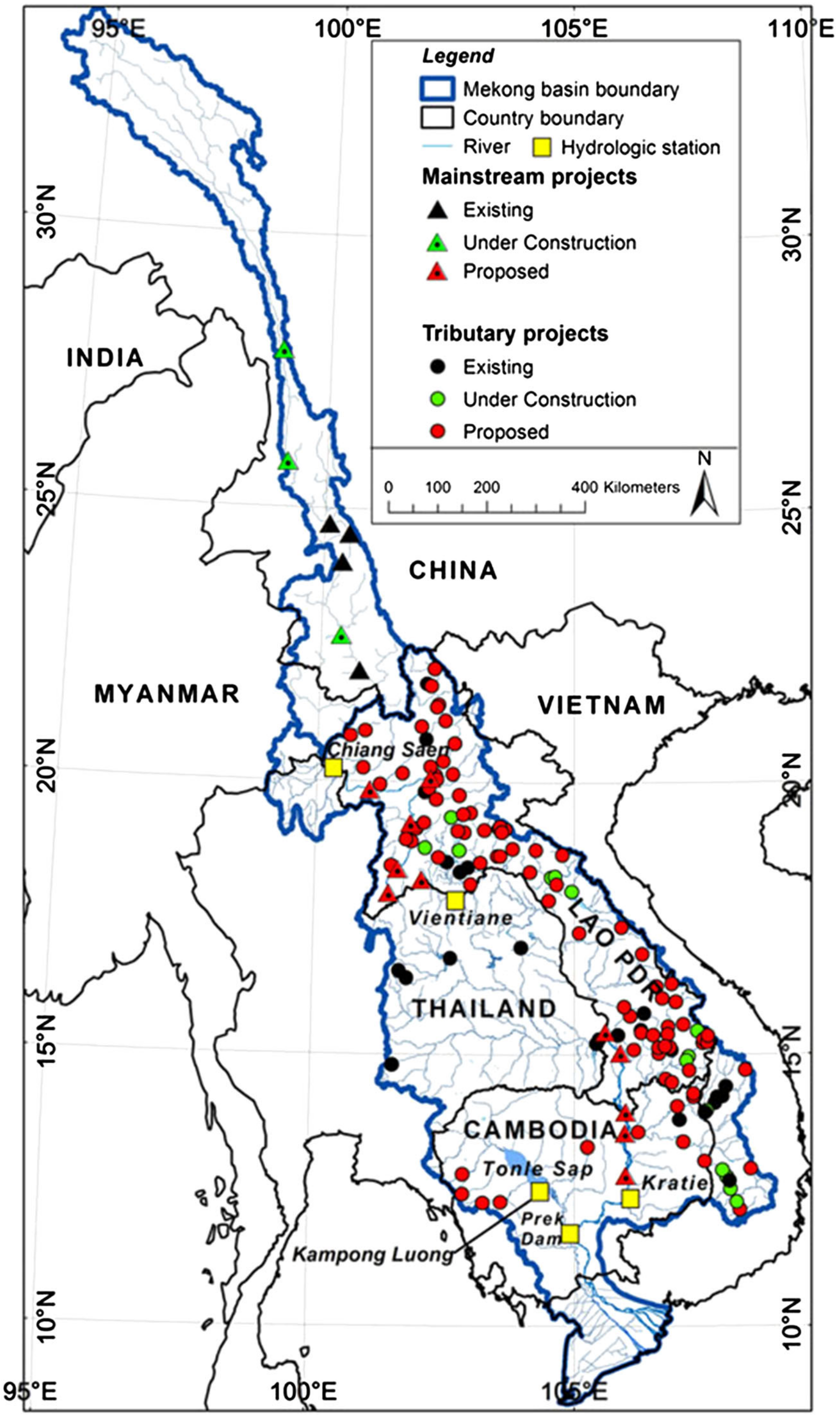


Figure 1. The Mekong River Basin and hydropower projects

with duration of five to six months between late June and late October. This annual mono-modal flood pulse is typical of large tropical rivers, including the Amazon and the Congo, and it is the dominant trigger in the annual cycle of ecological processes within the fluvial system, bringing about a distinct seasonality in the annual hydrobiological cycle between an aquatic phase and a terrestrial phase (Junk *et al.*, 1989). The understanding of relationships between the monsoon climate and variation of hydrology over the basin is increasing rapidly (Adamson *et al.*, 2009; Delgado *et al.*, 2010; 2012). As a consequence, there are highly seasonal biogeochemical cycles, growth rhythms and life cycles amongst the many species of ecosystem system biota such as algae, macrophytes, trees, fish and invertebrates (Junk, 1997). The extreme seasonality of flood pulsed monsoonal rivers such as the Mekong, where 75% of the annual flow in an average year occurs in the four months between July and October and where the average discharge in the peak flow month is a factor of 10 times larger than that in the month of minimum flow, is probably their defining hydrological feature (MRC, 2005). These vast seasonal differences in flow are associated with very large changes in mean monthly water level. For example, at Vientiane, the average water level in August is 9 m higher than that in April. At Kratie, the average seasonal change in water level is even greater at 14 m. The annual flood pulse and the associated flooding and drying create a rich ecology, a large diversity of fish and snails (Campbell, 2009), and a high aquatic ecosystem productivity (Lamberts, 2006; Hortle, 2007).

Despite strong economic growth over the past decade within the basin countries, the LMB remains among the world's poorest areas MRC (2010a). Governments thus believe that developing water resources will support basic needs for economic growth and reduce poverty as well as improve energy and food security (MRC, 2011a). Currently, all the LMB countries have water resources development strategies and sector plans in place that include water supply for drinking and irrigation, flood and drought management, hydropower generation and fisheries. Hydropower and agriculture are the two largest water resource sectors. It is acknowledged that these pose the greatest risks of trans-boundary environmental and social impacts (MRC, 2011a; 2011b).

Hydropower development is accelerating in China, Lao PDR and in the Viet Nam highlands. Currently, about 41 hydropower projects have either been built or are under construction in tributaries of the Mekong, which together with the dams already operating on the upper Mekong mainstream create 46 km^3 of active storage (MRC, 2011b). Over the next 20 years, an additional 30 tributary dams and 11 run-of-river dam mainstream dams are proposed, such that the total active storage will amount to about 16% of the mean annual flow (MRC, 2011b).

Water use in the agriculture sector is dominant in Thailand and in the Viet Nam Delta, whereas agriculture in Cambodia and Lao PDR is currently much less developed. Nevertheless, there are ambitious plans from the Lower Mekong countries to increase overall basin irrigation areas from 6.6 to 9.7 million ha (47%) in the next 20 years, with dry season irrigation being increased by 50% from 1.2 to 1.8 million ha (MRC, 2011b). However, some studies have found that irrigation expansion is potentially limited by the availability of suitable soils, physical conditions, high seasonal variation of rainfall, low flows in the dry season, and investment and maintenance costs (Nesbitt, 2005; Phengphaengsy and Okudaira, 2008).

The Mekong is considered one of the last unregulated great rivers of the world, the flow regime being still close to its natural state (Adamson *et al*., 2009; MRC, 2011a). However, there are increasing concerns about the potential impacts of large-scale water infrastructure projects and their cumulative impacts on the hydrologic cycle and the consequent ecosystem, social and economic impacts. Assessments of hydrological change in the basin have been undertaken over a wide range of spatial and temporal scales using hydrological, water balance and hydraulic models (ADB, 2004; Kummu and Sarkkula, 2008; ICEM, 2010; Arias *et al*., 2012; Piman *et al*., 2012).

Johnston and Kummu (2012) gave a comprehensive overview on the range of models used and their applications to assess hydrological change in work reported since 2000. The potential trends of hydrological change are relatively clear. Existing and planned water resource development will increase flows in the dry season, decrease flows in the wet season and reduce the amplitude of flood peaks. The wet season water levels in the Tonle Sap Lake were predicted to be reduced, while water levels in the dry season were predicted to increase. Nevertheless, the predicted magnitude of changes varies between studies. This is mainly due to assumptions made in simulating the future scenarios or projected water resources development levels. For an example, WB (2004) projected irrigation area and active storage of hydropower dams for the 20 year plan high development scenario in 2020 will be 11.3×10^6 ha and 49.5 km^3, respectively, while Hoanh, *et al*. (2010) propose that over a 20 year plan scenario to 2030, the irrigation area will expand to 8.2×10^6 ha, and hydropower dams' active storage will increase by 76 km^3.

Water resources development in the basin has accelerated over the last decade, and new information on existing and planned water infrastructure projects is available. Therefore, it is important for the MRC to regularly update basin-wide assessments. The updated assessment results serve as a technical basis for the Lower Mekong countries to discuss and negotiate mutually beneficial levels of water resources development and their associated levels of trans-boundary environmental and social impacts. The main objective of this paper is to present a recent assessment of how existing and future water infrastructure development may change hydrological characteristics, including flow regimes, flooding and salinity intrusion. Potential hydrological changes from various water infrastructure development scenarios are presented and discussed so that the trans-boundary implications of economic, social and environmental impacts can be considered.

METHODOLOGY

Basin-wide development scenarios were formulated to represent different combinations of nationally planned sector development, with a focus on active water use including domestic and industrial, irrigation and hydropower. Hydrological changes caused by each scenario were assessed through MRC's official suite of models, knowledge base and impact analysis tools, known as the Decision Support Framework (DSF). An assessment was made of the hydrological implications of the scenarios in relation to baseline conditions.

Basin-wide development scenarios

The six scenarios under consideration were consolidated into the four defined below (see also Table I).

1. **Baseline Scenario**: the reference hydrological condition against which future developments can be compared. This was agreed by the LMB countries to be the hydrological Scenario between 1986 and 2000

Table I. Description of the basin-wide development scenarios

No.	Short title	Full title	Development period	Interventions
Baseline Scenario				
1	BL	Baseline Scenario	Up to 2000	- 3.7 million ha irrigation areas - 15 hydropower dams in the LMB - Year 2000 water supply demands
Definite Future Scenario				
2	UMD	Upper Mekong Dam Scenario	2000 – 2015	- 3.4 million ha irrigation areas - 15 hydropower dams in the LMB + 6 hydropower dams in the UMB - Year 2015 water supply demands
3	DF	Definite Future Scenario	2000 – 2015	- 3.4 million ha irrigation areas - 41 hydropower dams in the LMB + 6 hydropower dams in the UMB - Year 2015 water supply demands
Foreseeable Future Scenario				
4	20Y Plan	LMB 20-Year Plan Scenario with LMB mainstream dams	2010 – 2030	- 5.3 million ha irrigation areas-82 hydropower dams in the LMB (including - 11 LMB mainstream dams) + 6 hydropower - dams in the UMB - Year 2030 water supply demands
5	20Y Plan w/o MD	LMB 20-Year Plan Scenario without LMB mainstream dams	2010 – 2030	- 5.3 million ha irrigation areas - 71 hydropower dams in the LMB (excluding 11 LMB mainstream dams) + 6 hydropower dams in the UMB - Year 2030 water supply demands
Long- Term Future Scenario				
6	VHD	the Foreseeable Future Scenario	2030 – 2060	- 8.4 million ha irrigation areas - 136 hydropower dams in the LMB (all) + 6 hydropower dams in the UMB - Year 2060 water supply demands

and the infrastructure of water resources development up to 2000.

2. **Definite Future Scenario**: the cumulative impacts of developments that are going to occur by 2015 (i.e. those built since 2000, under construction, or already firmly committed). The impacts of the mainstream dams in the UMB (Figure 1) were investigated individually.
3. **Foreseeable Future Scenario**: the cumulative impact of LMB countries' water resources development plans up to 2030. The scenarios in this Scenario investigate the impacts of these proposed developments, with and without mainstream dams (Figure 1).
4. **Long-term Future Scenario**: the cumulative impact of LMB countries' long term (2060) water resources development plans which will achieve a very high level of development.

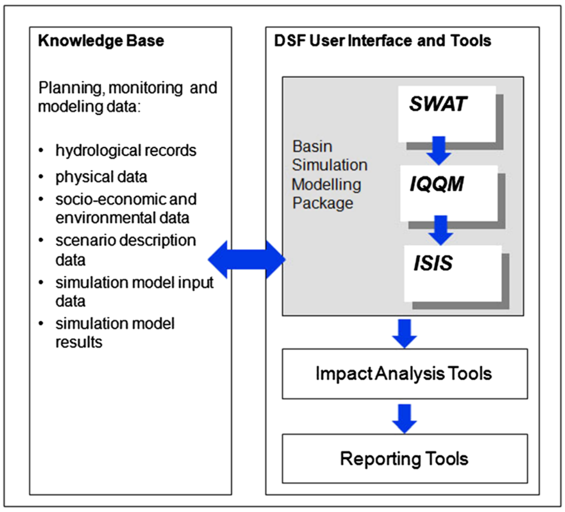


Figure 2. The MRC Decision Support Framework (DSF)

MRC DSF

The DSF was developed by the MRC for water resources planning in the LMB (Figure 2). The suite includes the SWAT, Integrated Quantity and Quality Model (IQQM) and ISiS hydrological, planning and resource simulation and hydraulic models. Quality assured input data were supplied by each member country and stored in a knowledge base. The model parameters were calibrated using a participatory approach involving extensive consultation with international experts and the four LMB countries (MRC, 2004). The models were used to simulate flows, water levels, flooding and salinity intrusion under different scenarios to assess hydrological changes from future scenarios against baseline conditions.

The Soil and Water Assessment Tool (SWAT) model, developed by US Department of Agriculture-Agricultural Research Service (USDA-ARS), was chosen for rainfall-runoff modeling. The SWAT model is a physically based model which uses climate information (rainfall, temperature and wind speed), soil properties, topography and land cover to simulate runoff and channel flows. It is a continuous simulation model that enables daily and long-term water yields to be estimated (Winchell *et al.*, 2009) at a daily time step.

SWAT model outputs are the natural flow conditions and provide the input to the IQQM, developed by the NSW Department of Infrastructure, Planning and Natural Resources, Australia (Podger and Beecham, 2003) to route the daily sub-basin flows through the river system. The IQQM model was used to estimate the impact of water diversions for irrigation, domestic and industrial demands and simulate reservoir systems and dam operations of the basin-wide development scenarios. Input data to the model consisted of daily inflows from the SWAT model, cropping patterns and cropping calendar, domestic and industrial water demands, dam's physical characteristics including dam height and width, spillways and power plant release capacities and dam operation rules. The outflows from the IQQM model define the modified hydrology given various levels of water resources development.

The ISiS hydrodynamic model, developed by HR Wallingford and Halcrow (Halcrow and HR Wallingford, 2001), was set up to represent the river system downstream of Kratie, including the Tonle Sap Lake in Cambodia and Mekong Delta (Figure 1). This hydrodynamic model represents the complex interactions caused by tidal influences, flow reversal in the Tonle Sap Lake and over-bank flows during the flood season with varying simulated upstream inflows at Kratie in Cambodia. Input to ISiS included simulated flows from the IQQM model under difference basin-wide development scenarios. ISiS generates hourly water levels and flows throughout the main channels and floodplain in the Tonle Sap Lake and Mekong Delta. The generated water levels, flows and tidal conditions were then used to simulate hourly salinity intrusion in the Viet Nam Delta during the dry season.

Model calibration and validation

To estimate model parameters, the SWAT and IQQM were calibrated together against observed flows at key stations both on the Mekong mainstream and its tributaries using the entire baseline period from 1986 to 2000, while the validation of both models was on the basis of determining how robust the models are over the calibration period. Upstream of Kratie, the models were calibrated in 28 gauged headwater catchments and at 16 in-stream reaches. Nine of the 16 calibrated in-stream reaches are located along the Mekong mainstream. Downstream of Kratie, measured gauge data is very limited such that only six stations were available for calibration. The calibrated model parameters in each headwater catchment show slightly different.

The performance of the SWAT and IQQM calibration was assessed by comparing simulated results at gauge nodes located at gauging station sites. Overall, the simulated flow volumes at stations upstream of Kratie were within 5% of the observed flows for most modelled catchments. The flow distribution is reproduced to within 10% for tributary gauges and within 3% for mainstream gauges. The calibrated flows at Chiang Saen, Vientiane and Kratie are presented in Figure S1. Although not all flow peaks are matched, which is related to the poor spatial coverage of rainfall data, the frequency and size of peaks are reproduced. The errors in flow volume were within 10% at most gauging stations downstream of Kratie, but some stations had flow duration errors of more than 10% due to the limited data availability.

In contrast to the approach taken for the SWAT and IQQM models, the ISiS model was calibrated only for the year 2000, which was the largest recorded flood in recent decades, and it was further verified using data from year 2001. These years were used because of data availability, representative high flood discharges and because the model is sensitive to the changes in water infrastructure, which would have occurred primarily after 2001. The model was calibrated against measured flows and water levels at 31 stations, which gave a reasonable coverage of all the main rivers and channels in the basin. In addition, further measurements such as maximum flood level and satellite data showing flood extent were also used. The model calibration goodness of fit was verified by comparing time series of recorded flows and levels against simulated values. Flood peaks were adequately simulated with 55% of all stations being within 0.1 m, 81% within 0.2 m and all others within 0.3 m for the 2000 event. Similar or better results were obtained for the 2001 flood season. The simulated water levels at Prek Kdam and Kampong Luong in the Tonle Sap compared with observed data in 2000 and 2001 are presented in Figure S2. The simulated flood extended area in Cambodia and the Viet Nam Delta from the calibrated model was also compared with satellite imagery for the peak month of October, 2000, which provided a good fit (Figure S3).

For salinity simulations, it was necessary to first ensure a good hydrodynamic calibration and then to calculate and test suitable dispersion coefficients for the main channels in the ISiS water quality model. When a satisfactory fit was attained for the main channels, the simulated maximum salinity in the smaller channels was compared with observed data. The data available for boundary conditions and for the calibration of salinity intrusion was limited. Only the dry season of 1998 was used to calibrate saline intrusion because this year represented a suitable drought year with low flows. The calibrated results at three main stations on the mainstream rivers in Viet Nam Delta were shown in Figure S4. The model shows reasonable results with measurements.

Reservoir operation guidelines

The information on how reservoirs might be operated for planned projects is normally absent so the RULE model (Dat, 2009) was developed using linear interpolation to determine monthly operation guidelines for each hydropower project. The objective functions for model optimization are:

i) to prevent the reservoir from emptying until the end of the driest season on record,
ii) to allow the reservoir to fill up by the end of the driest wet season on record and
iii) to maximize annual energy generation.

The first two objectives were met by designing a lower boundary (lower rule curve) to the fraction of live storage that must be maintained. This analysis involves knowledge of inflow water volumes and the live storage of the reservoir. The third objective was met by designing an upper boundary (upper rule curve) that balances the gains in energy production resulting from operating at high reservoir levels (higher head) and the losses of energy resulting from spilled water (lower turbine discharge). This analysis involves knowledge of the plant characteristics, specifically the reservoir volume–elevation relationship, the tail water level of the plant and the installed capacity and design discharge of the plants which are available in the MRC hydropower database (MRC, 2009a). In this study, the six dams on mainstream in China in Figure 1 (Gonguoqiaou, Xiaowan, Manwan, Dachaoshan, Nuozhadu Jinghong) were operated as a cascade, as is their purpose. The outflows from the upstream dam were used as inflows to the downstream dam to determine the operation rules. The remaining dams in the LMB were assumed to operate independently according to current information, thus the natural flows were used to determine the operation rule of each dam. For basin simulations, however, the operated flows of upstream dam were always the inflows to downstream dam.

Irrigated crop water usage

The irrigated crop demand model in IQQM was used to calculate water demand for irrigation areas. The first step in the simulation was to assign a specified area to one or more types of crop. The calendar date at which these crop types are planted was determined by the month when the crop factor for that crop is non-zero. The model estimates soil water level every day of the simulation. During the non-irrigation season, rainfall infiltration and bare soil evaporation rates determine the soil water balance. From the date a crop is planted the model starts estimating the amount of water needed to bring the soil moisture, or the water level in the rice bay, up to a target water level. The next part of the calculations is estimating how much water needs to be extracted from the river to meet this irrigation requirement by taking into account of irrigation efficiency and pumping capacity. A detailed description of the crop model is given in the IQQM Reference Manual (DLWC, 1995). The irrigation data for existing and planned projects were obtained from the MRC irrigation database (MRC, 2009b). The irrigation projects were then grouped into the IQQM sub-basins to calculate total irrigation areas. In each IQQM sub-basin, an irrigation node was created to extract water from river for supplying irrigation demand. The return flows to river system from the irrigation areas were assumed to be between 15 and 20% of the diverted water, based on selected field observations.

Assessment of hydrological changes

The impact of the basin-wide development scenarios on flows and water levels were modeled on a daily time step from 1986 to 2000 (15 years) to quantify the magnitude of changes at key monitoring stations on the Mekong mainstream. Flow reversal to the Tonle Sap Lake was examined in terms of changes in timing and volumes. Changes in maximum flooded areas in the LMB in the wet season were investigated for average, wet and dry years. Similarly, the assessment of changes in salinity intrusion in the Viet Nam Delta was considered in the dry season of an average, a wet and a dry year (1999, 2000 and 1998, respectively). Results from the baseline scenario were compared against results for each of the different basin-wide development scenarios to examine relative magnitudes of change. Results in this paper are only presented for Vientiane, Kratie and Prek Kdam which represent three key locations along the Mekong River; however, the DSF can simulate results at many other stations along the river.

RESULTS

Changes in flows and water levels

Daily data were extracted and averaged to obtain monthly flows for each scenario at Vientiane and Kratie (Figure 1), and these were compared with the Baseline flows (Figures 3a and 3b). Overall, the impact of all simulated scenarios is an increase in dry season flows and a decrease in wet season flows due to the redistribution of water from the wet season to the dry season by hydropower dam operations. Results from all mainstream stations follow a similar trend. In terms of seasonal flows and water levels (Table II), it is observed that the greatest change will occur under the Definite Future Scenario. A further change in flows and water levels occurs under the Foreseeable Future Scenario. The Long-Term Future Scenario shows marginal changes in the mainstream flows and water levels over and above the changes caused by the Foreseeable Future Scenario.

At Vientiane, the dry season flow volume simulated in the Definite Future Scenario increased by 41% from the baseline and increased a further 10% under the LMB 20-Year Plan Scenarios, which include additional tributary and mainstream dams in the LMB as well as increased irrigation including a diversion of Mekong flow to the northeast of Thailand. The water level in April is predicted to increase about 1.2 m in the near future and increase by an additional 0.4 m in the next 20 years. Average wet season water levels are reduced by 10% (0.4 m) in the Definite Future Scenario, and further small reductions occur in the LMB 20-Year Plan Scenarios.

At Kratie, the dry season flow volume in the Definite Future Scenario is estimated to increase by 22% and average wet season flow volumes to decrease by 4% from the baseline. There is a further 5% increase in dry season flows and a further 4% decrease in wet season flows under the LMB 20-Year Plan Scenarios. Similarly, water levels in April will increase by 0.9 m from the baseline and water levels in September are reduced by 0.3 m in the Definite Future Scenario. The peak season flows at Vientiane in September were decreased by 1050 m3/s (0.64 m) in the Definite Future Scenario and a further 244 m3/s (0.18 m) in the LMB 20-Year Plan Scenarios. Likewise, the September flows at Kratie were reduced by 1490 m3/s (0.33 m) and 912 m3/s (0.20 m) in the Definite Future and the LMB 20-Year Plan Scenarios, respectively. Changes in flow regime reduce gradually along the Mekong mainstream due to additional flows from tributaries.

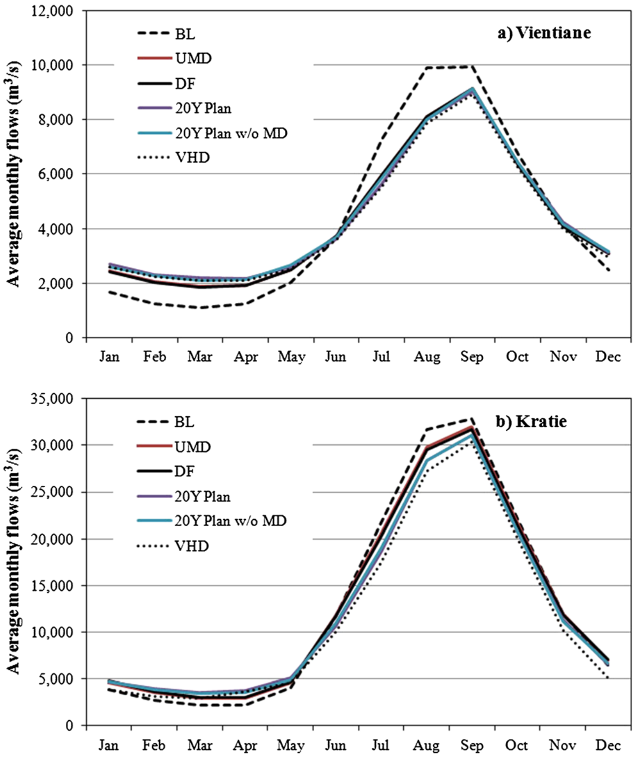


Figure 3. Changes in average monthly flows from the basin-wide development scenarios at Vientiane and Kratie

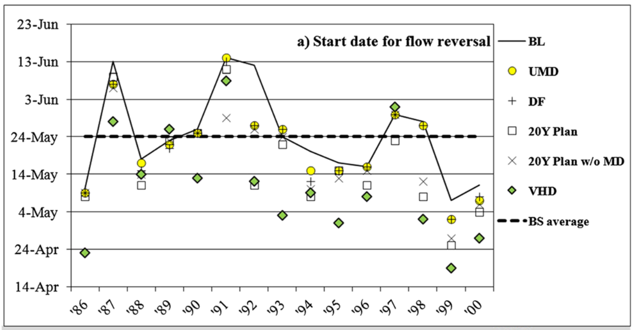
Changing in reverse flows of the Tonle Sap Lake

Flow reversal occurs in the Tonle Sap River when water levels in the mainstream exceed those in the Tonle Sap Lake, causing the river to reverse its flow into the lake. Flow reversal will therefore be affected by potential decreases in peak wet season flows as a consequence of basin-wide development. The timing of when the flow reversal occurs and the changes in flow volumes to the lake were analyzed at the Prek Kdam monitoring site (Figure 1) for the various development scenarios.

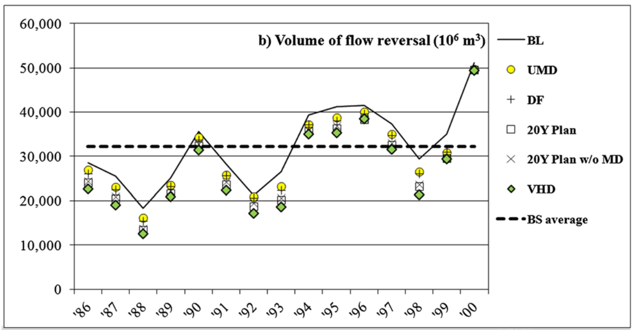
The reverse flow in the Tonle Sap normally starts in mid-May and finishes in mid-September. The dates when flow reversal occurs have been abstracted for each year for each scenario modeled and averaged. In comparison to the baseline, reversal occurs slightly earlier for each increasing development scenario. Under the Definite Future Scenario, the reversal would occur 3 days earlier (with a variability of +/−19 days within the 15 year simulation period). Under the LMB 20-Year Plan Scenarios, with all mainstream dams and with no mainstream dams, the reversal would occur 6 to 8 days earlier, respectively (with variability of +/− 21 and +/− 24) and under the LMB Very High Development Scenario, the reversal would occur 13 days earlier (with variability of +/− 25 days) (Figure 4a). A similar analysis was done on the average volume of flows during the flow reversal period. The average flow reverse of the Baseline Scenario is 32.3 km^3. Under all scenarios there was a predicted decrease in flow reversal volumes of 7–8% in

Table II. Changes in average seasonal flows and average monthly flows in April and September from the basin-wide development scenarios at Vientiane and Kratie

Scenario	BL	UMD	DF	20Y Plan	20Y Plan w/o MD	VHD
Average season flows (km^3)						
Vientiane						
Dry season	25.7	36.6	36.3	39.9	39.3	38.2
Change from the BL (%)		*42%*	*41%*	*55%*	*53%*	*48%*
Wet season	110.4	99.3	99.2	98.3	99.0	95.4
Change from the BL (%)		*−10%*	*−10%*	*−11%*	*−10%*	*−14%*
Kratie						
Dry season	56.9	67.7	69.6	72.8	71.3	73.0
Change from the BL (%)		*19%*	*22%*	*28%*	*25%*	*29%*
Wet season	349.4	338.5	334.6	319.6	321.2	304.9
Change from the BL (%)		*−3%*	*−4%*	*−9%*	*−8%*	*−13%*
Average monthly water levels (m)						
Vientiane						
April	0.65	1.85	1.85	2.21	2.16	2.07
Change from the BS (m)		*1.20*	*1.20*	*1.56*	*1.51*	*1.42*
September	8.31	7.89	7.89	7.89	7.89	7.76
Change from the BS (m)		*−0.42*	*−0.42*	*−0.42*	*−0.42*	*−0.55*
Kratie						
April	6.24	7.03	7.15	7.81	7.60	7.67
Change from the BS (m)		*0.79*	*0.91*	*1.57*	*1.36*	*1.43*
September	18.59	18.36	18.28	18.12	18.12	17.93
Change from the BS (m)		*−0.22*	*−0.30*	*−0.47*	*−0.46*	*−0.66*



Scenario	BL	UMD	DF	20Y Plan	20Y Plan w/o MD	VHD
Average start date	24-May	21-May	21-May	16-May	18-May	11-May
Days earlier against BL	0	3	3	8	6	13
Variation of start date (days)	+/- 19	+/- 22	+/- 21	+/- 24	+/- 20	+/- 25



Scenario	BL	UMD	DF	20Y Plan	20Y Plan w/o MD	VHD
Average volume (10^6 m^3)	32,259	30,145	29,740	27,993	28,358	27,008
Volume decrease against BL	0%	-7%	-8%	-13%	-12%	-16%

Figure 4. Changes in flow reversal to the Tonle Sap Lake from the basin-wide development scenarios; a) change in start date and b) change in reverse flow volumes

the Definite Future Scenario, 12–13% in the LMB 20-Year Plan scenarios and 16% in the LMB Very High Development Scenario (Figure 4b). By comparison, natural flow volume variation in the Lake over the baseline period (1986 – 2000) annually varied between 15 and 70 km^3 (or more than 300%). Nevertheless, the changes in flow rates, and the peak extent of the floodplain inundation under the considered scenarios could be significant.

The simulated water levels at Kampong Luong station (Figure 1) show that in April, water levels in the Tonle Sap Lake will increase by only 8 cm in Definite Future Scenario due to the increases of the dry season flows along mainstream and a further 2–5 cm in the LMB 20-Year Plan scenarios. In the peak flood month (October), the average water levels for the next 5 and 20 years are estimated to decrease by 22 and 39 cm from the baseline, respectively.

Changing in floodplains

Flooding in the Mekong Basin occurs primarily on the Cambodian floodplain, around Tonle Sap Lake, and the Viet Nam Delta. The attenuation of flood season flows due to increasing amounts of storage within the basin and decreasing of the wet season flows under the different basin-wide development scenarios would have a consequential effect on year-to-year average flooding. Changes in flooding during an average, dry and wet year, as a function of basin-wide development, are presented in Table III. The total area inundated by the mainstream flooding in an average hydrological year is reduced from

Table III. Changes in maximum flooded areas from the basin-wide development scenarios in the average, wet and dry years

Scenarios	Average year					Wet year					Dry year				
	L	T	C	V	LMB	L	T	C	V	LMB	L	T	C	V	LMB
BL (10^6ha)	0.41	0.37	2.18	1.80	4.76	0.45	0.40	2.55	1.83	5.24	0.39	0.35	1.95	1.74	4.43
DF (10^6ha)	0.34	0.30	2.08	1.79	4.51	0.46	0.41	2.53	1.83	5.22	0.39	0.34	1.87	1.73	4.34
Change from the BS (%)	*−15.8*	*−18.6*	*−4.8*	*−0.6*	*−5.2*	*1.5*	*1.8*	*−1.0*	*−0.1*	*−0.3*	*−1.4*	*−1.9*	*−3.9*	*−0.5*	*−2.2*
20Y Plan (10^6ha)	0.33	0.29	2.04	1.79	4.45	0.45	0.40	2.53	1.83	5.21	0.38	0.34	1.77	1.71	4.21
Change from the BS (%)	*−18.6*	*−21.8*	*−6.5*	*−0.9*	*−6.6*	*0.5*	*1.1*	*−1.0*	*−0.1*	*−0.4*	*−2.2*	*−2.7*	*−9.2*	*−1.5*	*−5.0*
20Y Plan w/o MD (10^6ha)	0.33	0.29	2.05	1.79	4.46	0.46	0.41	2.51	1.81	5.19	0.38	0.34	1.77	1.70	4.20
Change from Baseline (%)	*−18.4*	*−21.8*	*−5.9*	*−0.9*	*−6.3*	*1.5*	*1.8*	*−1.6*	*−0.9*	*−0.8*	*−2.1*	*−2.7*	*−9.1*	*−2.3*	*−5.3*
VHD (10^6ha)	0.33	0.29	1.98	1.77	4.37	0.45	0.40	2.51	1.81	5.18	0.38	0.34	1.71	1.68	4.11
Change from the BS (%)	*−19.1*	*−21.8*	*−9.3*	*−1.7*	*−8.2*	*0.3*	*0.7*	*−1.6*	*−1.0*	*−1.0*	*−2.5*	*−2.6*	*−12.5*	*−3.4*	*−7.3*

Note: L = Lao PDR, T = Thailand, C = Cambodia, V = Viet Nam

4.76 to 4.45 million ha (6.6%) going from the Baseline to the LMB 20-Year Plan Scenario. In percentage terms per country, changes are biggest in Thailand (21.8%) and Lao PDR (18.6%), are moderate in Cambodia (6.5%) and small in Viet Nam (0.9%) (Table III). Under the LMB Very High Development Scenario, the flooded areas decreases by a further 8.2% compared with the Baseline Scenario.

Reductions of flooded areas in Lao PDR, Thailand and Viet Nam, during a typical dry year, were estimated to range from 0.5 to 3.5% for all scenarios; whereas in Cambodia, the flooded area decreases from 3.9% to 12.5%. Overall, in a typical dry year, flooded areas in the LMB decrease from 4.43 million ha under the Baseline Scenario to 4.11 million ha (7.3%) under the LMB Very High Development Scenario. In a wet year, the total flooded area under the Baseline Scenario in the LMB is about 5.2 million ha. Less than a 1% change in the LMB's flooded area was observed during a wet year under the Very High Development scenario when compared to the Baseline Scenario. The LMB mainstream dams under the LMB 20-Year Plan Scenario show little impact on flooding in Cambodia and Viet Nam when compared with the LMB 20-Year Plan Scenario without all mainstream dams.

Changing in salinity intrusion

Saline intrusion occurs naturally each year in various branches of the Mekong in the Viet Nam Delta. The stronger the freshwater flows from the Mekong River, the less salinity intrusion there is. In the dry season, high salinity levels in the river channels are observed up to 80 km inland from the coast. The DSF models were used to predict the extent of saline intrusion from different basin-wide development scenarios. Assessments were also made for average, wet and dry years during the months between February and June. Salinity intrusion areas were identified as having salinity concentration levels above 1.3 g/l as this concentration level will damage crops (MRC, 2010b). An analysis of simulation results is given in Figure 5.

The salinity affected areas under the Baseline Scenario during average, wet and dry years are 1.85, 1.56 and 1.93 million ha, respectively. Increase of the upstream dry season flows shows that the area potentially affected by salinity intrusion in an average year were reduced by 15% (271 943 ha) under the Definite Future Scenario, by a further 2% (36 600 ha) under the LMB 20-Year Plan Scenarios (both with and without mainstream dams), and a less than 1% further increase under the Very High Development Scenario. In wet and dry years, the basin-wide development scenarios had a lower effect (4.7 to 9.3%) in reducing saline intrusion areas compared with the average year under different scenarios. Moreover, the simulated results showed that the extension of salinity intrusion will be reduced by 5 to10 km as a result of an increase in dry season flows.

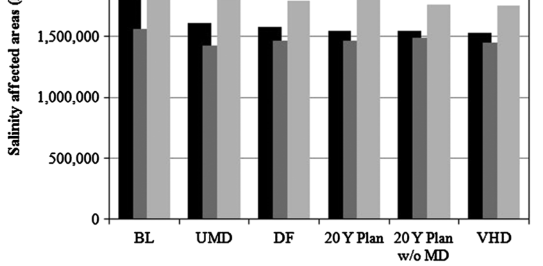


Figure 5. Changes in salinity affected areas in the Viet Nam Delta from the basin-wide development scenarios in the average, wet and dry years

DISCUSSION

In the Definite Future Scenario, the flow and water level changes are mainly due to the operations of the large two storage dams (Xiaowan and Nuozhadu) in the UMB, which have a combined active storage of 22.2 km^3. Small additional changes in flow under the Foreseeable Future Scenario compared to the Definite Future Scenario were observed, even though large irrigation and hydropower projects were included. The main reason for the relatively small change is that the proposed irrigation diversions for the next 20 years seem to offset the large increases in storage and dry season releases from hydropower development. Furthermore, only small percentage differences were found in both wet and dry season flows and water levels when the results between 20-Year Plan Scenarios with and without mainstream dams in the LMB were compared. The reason for this is that all planned LMB mainstream dams are currently designed as run-of-river schemes with small storage reservoirs, which add only 5.2 km^3 of water storage to the basin.

Although the development of hydropower mainstream dams in the LMB will not significantly redistribute water from the wet to the dry season, there are expected to be significant local impacts from raising water levels in upstream reservoir areas and the timing of releases of water downstream. Furthermore, mainstream dams will also create trans-boundary impacts with regard to sediment transport, nutrient loads and fish migration patterns (ICEM, 2010; MRC, 2011b; Lauri *et al.*, 2012).

The predicted seasonal flow changes reported here were compared with earlier studies (ADB, 2004; WB, 2004; Hoanh *et al.*, 2010; Lauri *et al.*, 2012), and we found that the trends of seasonal flow changes are in agreement. However, the degree of change, particularly the percentage increase of dry season flows, is significantly different. ADB (2004) and Lauri *et al.* (2012) predicted dry season flows under the full hydropower development scenario will increase by as much as 70% from the baseline while WB (2004), Hoanh *et al.* (2010) and this study indicate increases of dry season flows of 30–40%. A reason for this large difference is most likely that ADB (2004) and Lauri *et al.* (2012) did not include water use from future irrigation in their assessment. Their aim was to assess the impact from hydropower development independently. In contrast, this assessment includes large-scale irrigation schemes planned for operation in both the wet and dry seasons. Thus, the predicted increases in dry season releases from hydropower flow redistribution are partially offset by planned irrigation schemes by approximately 30–40%. Moreover, the results also indicate that full hydropower development in the basin could compensate for the increased abstractions from planned irrigation in the dry season without any reduction of baseline dry season flows.

Moreover, predicted changes in reverse flows of the Tonle Sap Lake from our study indicate similar seasonal tendencies as maybe observed in other existing studies (Adamson, 2001; ADB, 2004; Arias *et al*., 2012), but the changes in water levels are less pronounced. ADB (2004), for example, predicted average water levels in the lake during the dry season will increase 54 cm and decrease 60 cm in the wet season. The differences seem to be primarily a result of using different levels of future water development for the simulations.

Increases in the dry season flows and reduction in the extent and duration of saline intrusion provide opportunities for irrigation, water supplies and navigation downstream, but sandbars and river bank vegetation may be submerged (MRC 2011b). Decreases in the wet season flows could be beneficial for flood mitigation, but there will be an increase risk to biodiversity, ecosystem services, wetlands habitats, fishery production and livelihoods, which are strongly related to the natural annual flood pulse (Kummu *et al*., 2006; Lamberts and Koponen, 2008; Ziv *et al*., 2012). Increase of the dry season water levels and decrease of wet season water levels in the Tonle Sap Lake will affect flood duration and flooded areas and consequently vegetation around the lake, particularly flooded forest and inundated grasslands (Arias *et al*., 2012).

The floodplain in the Mekong Delta is very large and dynamic. Rapid developments, particularly in the Viet Nam Delta such as channels, embankments, roads, bridges and culverts are also affecting the flow of water across the floodplain. These changing environments and the limitations of current data make it difficult to maintain a calibrated hydrodynamic model to represent a long-term period. The hydrodynamic and salinity models in our study were then calibrated only for the wettest year and the driest year, respectively, as the snapshot of the situations based on the latest knowledge. The calibrated model parameters may not able to represent a wide range of situations thus using the models to simulate a range of dry and wet years may increase uncertainty and reduce accuracy of simulations. However, these are basin-wide scale models and perceived weaknesses may not be as significant at this scale.

Conclusions and recommendations

The impacts of the Definite Future Scenario, when compared to other future scenarios, cause a substantial change on the natural flow regime on the Mekong mainstream by increasing dry season flows, decreasing wet flows, reducing flood peaks and changing salinity intrusion patterns. Changes in the Definite Future Scenario depend mainly on the operation rules of the large storage hydropower dams on the mainstream in the UMB. These projects are either completed or are in progress so predicted changes will be irreversible. Reservoir operation rules used in this study were only targeted to maximize energy production; however, the dams in the UMB are not only designed for energy generation, but also navigation purposes (ICEM, 2010). Detailed studies and monitoring programmes on dam operations, modifications to sediment transport, sub-daily water level fluctuation and subsequent downstream impacts to livelihoods and ecosystems are necessary. Coordination between LMB countries and cooperation with China should be prioritized to maximize opportunities from the expected increase in dry season flows and to ensure the risks of planned projects will be cooperatively managed.

Numerous large-scale hydropower projects and irrigation schemes in the LMB were included in the LMB 20-Year Plan Scenarios (with and without the Lower Mekong mainstream dams). These result in further modification of the Mekong River flow regime and consequently a reduction of flow reversal to the Tonle Sap Lake, as well as a reduction in flooded areas and salinity intrusion in Delta. We found that the degree of change under the LMB 20-Year Plan Scenarios was smaller than the Definite Future Scenario because the increase of storage and dry season flows from hydropower development over this period was offset by proposed large-scale irrigation diversions in next 20 years. Large increases in irrigation areas, particularly, in Lao PDR and Cambodia represented in the LMB 20-Year Plan Scenarios are very ambitious compared to current development progress (ADB, 2004); therefore, the potential of future irrigation development and investment in the LMB needs further revision. The interaction between hydropower and irrigation operations in terms of timing and location needs further detail studies. Our study also shows that the proposed 11 mainstream dams in the LMB cause small changes in flow patterns because these dams are designed as run-of-river schemes, which have low capacity to redistribute flow from the wet season to the dry season. Other factors, such as blocking of fish migration routes and changes in sediment transport, need to be considered through more detailed studies.

Although this was a comprehensive undertaking to model a large and complex basin, there are a range of uncertainties associated with the accuracy of predicted changes. These are linked to the accuracy of information, and analytical tools employed the manner and timing of project implementation, operational issues and insufficient knowledge with regard to the processes associated with sediment transport, ecological change, climate change and ground water use. These uncertainties need to be taken in to account in both water resources development and management plans. Furthermore, simulated changes were spatially and temporally variable across the basin, and therefore, detailed studies on the impact of water resources development in the key Mekong sub-basins such as Sekong, Sesan and Srepok Basins (Piman *et al*., 2012) are necessary to improve the understanding of the interrelated impacts between the Mekong mainstream and its tributaries.

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