How well can Water Availability of the Regulated Mekong River Basin be Represented by Satellite Observations and Physical Models?

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Abstract

Currently there are 30 large dams in the Mekong River Basin (MRB), three of which are located on the main stem of the Mekong River in China. Understanding the impacts of these dams on the altered water availability on the MRB is therefore timely and essential. This study has two objectives that are as follows: 1) to identify if a widely-used macroscale hydrologic model (Variable Infiltration Capacity – VIC) can represent the hydrology of Mekong river basin in the absence of adequate in-situ data; 2) to explore how well satellite remote sensing can monitor the behavior of reservoirs and consequently improve physical hydrologic models for water regulation scenarios. The study shows that a macroscale hydrologic model like VIC can capture the seasonal and monthly variations in streamflow quite effectively for water management applications at planning scales. For flood forecasting or shorter applications, the use of satellite observations spanning visible, microwave and infrared imagery is found to yield accurate monitoring of reservoir dynamics at bi-weekly to monthly time steps. This study showed that it is possible to model water availability and reservoir behavior to a reasonable accuracy even under the circumstances of sparse in-situ data using satellite observations.

Key words: Mekong river, satellite observations, reservoirs, human alteration

INTRODUCTION

The Mekong Basin (Figure 1) is a fascinating international river basin (IRB) with many man-made and natural forces simultaneously at play. Among the man-made forces, increasing water and energy demand due to development pressures and hydro-political drivers are key (Zarfl et al., 2014). In hydro-political drivers, the riparian nations of China, Myanmar, Thailand, Vietnam, Laos and Cambodia are faced with increasing competition to develop their water resources through new dams for irrigation and hydropower development (Kummu and Sarkula 2008). Among the natural forces, a changing climate (e.g. a changing Monsoon) and rising sea level are perhaps the biggest threats (Syvitski et al., 2009).

Currently there are 30 large dams in the MRB (Figure 1), three of which are located on the main stem of the Mekong River in China (Keskinin et al. 2012). As of 2012, there were 14 dams currently under construction, with another 78 planned (Keskinin et al. 2012). More than 50 million people live in the Lower Mekong Basin alone, and 80% rely directly on the river for their food supply, primarily fish and floodplain agriculture. The Mekong River Commission (MRC) reported that planned dam development may potentially cause USD 476 million/year of damages on fisheries (International Center for Environmental Management 2010). Furthermore, the same dams are projected to inflict USD 25.1 million/year in lost agricultural land and USD 24 million/year in reduced nutrient loading to floodplain agriculture (International Center for Environmental Management 2010). Understanding the impacts of these dams on the altered water availability on the MRB is therefore timely and essential.

Some regions of the Mekong that are particularly critical for predicting water availability, are the low-lying deltas that are densely populated and extensively irrigated. For example, the Red River Delta (RRD) and the Mekong Delta (MD) are the largest deltas in Vietnam with population of about 36 million (about 40% of Vietnam's population). The groundwater wells in RRD and MD extract groundwater of about 2 million m^3/day and 1.2 million m^3/day, respectively (Pham, 2008). Studies indicate that land in the delta region may be sinking at a rate faster than the sea level rise (Syvitski et al., 2009). Overexploitation of groundwater in these low-lying regions can lead to a decline in groundwater levels, land subsidence, and increase the risk of flood damage coupled exacerbated by coastal sea level rise.

The vulnerability of such densely-populated low-lying deltas will only worsen due to uncoordinated human activity in the upstream regions, such as flow diversion and dam building. For example, a cascade of dams is being planned in upstream Mekong by China (Kuenzer et al., 2013). Laos PDR is considering the Don Sahong Dam on Mekong river (Baird, 2011) while the Thai government is planning a diversion from the Mekong River (Dore et al., 2012). Such heavy alteration of flows begs the question if physical hydrologic models, that traditionally lack a water management component, can adequately predict water availability for an increasingly regulated basin with the help of satellite observations of reservoir dynamics. It is quite well known that satellite remote sensing can be used to overcome the challenge of managing water supply in regulated IRBs in the absence of ground based measurements. Recent studies have correlated upstream river height measurements from satellite altimeters with downstream river heights for improved trans-boundary flood forecasting (Biancamaria et al., 2011; Hossain et al., 2013; Hossain et al., 2014). Another study developed a framework to incorporate observations from the forthcoming Surface Water and Ocean Topography Mission (SWOT) into the release operations of a dam in the Upper Niger River Basin (Munier et al., 2015). More recent efforts have combined altimetry with various methods of determining reservoir surface area. Birkett (2000) used TOPEX/POSEIDON altimetry measurements with NOAA/AVHRR radiometer images to build understanding of elevation and water surface extent of Lake Chad. Additionally, Gao et al., (2012) used the Moderate Resolution Imaging Spectro-radiometer (MODIS) along with satellite radar altimetry to estimate storage changes in 34 global reservoirs.

This paper has two objectives that are as follows: 1) to identify if a widely-used macroscale hydrologic model (Variable Infiltration Capacity – VIC) can represent the hydrology of Mekong river basin in the absence of adequate in-situ data; 2) to explore how well satellite remote sensing can monitor the behavior of reservoirs and consequently improve physical hydrologic models for water regulation scenarios. The key question we ask in this paper is the title of the work - *"How well can water availability of the Mekong River Basin be represented by Physical Models and Satellite Observations?"*

STUDY REGION, DATA AND MODELS

The MRB has an area of 795,000 km^2 and the basin is made up of six nations of China, Myanmar, Laos, Thailand, Cambodia, and Vietnam. It has an average annual discharge of 457 km^3. The basin experiences a tropical monsoon climate where a majority of the precipitation arrives from May through October, resulting in a seasonal pattern in streamflow. In this this study, we focused on the 17 large reservoirs that are already as operational by the Global Reservoir and Dam (GRanD) Database (Lehner et al. 2011).

Table 1 lists the dam/reservoir name and identification number along with their capacity and degree of regulation (capacity divided by annual inflow), taken from the GRanD Database. The capacity of these reservoirs ranges from 22.8 million m^3 to 7030 million m^3 with an average of 961 million m^3. Degree of regulation (DOR) is the reservoir capacity as a percentage of the mean annual inflow into the reservoir.

For estimation of flow in the river systems of MRB, a 0.1 degree resolution Variable Infiltration Capacity (VIC) Model of the MRB was set up (Liang et al.1994). The VIC model was set up using land cover data from the Global Land Cover Characterization (GLCC) dataset and soil data prepared by the Harmonized World Soil Database (HWSD) (Siddique-E-Akbor et al., 2014). The Moderate Resolution Imaging Spectro-radiometer (MODIS) mission provided monthly leaf area index and albedo were provided while topography information was obtained from Shuttle Radar Topography Mission (SRTM). The VIC hydrologic model was run at the daily time step from 2002 through 2015 (14 years), and provided surface water fluxes for each 0.1 degree grid cell. The meteorological forcings such as temperature (minimum and maximum), wind speed and precipitation were obtained from 237 weather station records archived as Global Summary of the Day (GSOD) by National Climatic Data Center (NCDC) in a manner similar to Siddique-E-Akbor et al., (2014).

For modeling reservoirs, a combination of satellite altimetry or visible imagery and a satellite precipitation product was used to determine reservoir state (i.e, inflow, storage change and outflow), following the procedure outlined in Bonnema et al., (2016). This approach is based on the use of a simple mass balance between hydrologic controls (Equation 1) where reservoir outflow (O) is balanced by changes in reservoir storage (ΔS), precipitation induced runoff flowing into the reservoir (I), and evaporative losses (E). Due to the revisit period of the satellite observations being longer than a week, the mass balance can be resolved on approximately monthly time scales.

$$O = I - E - \Delta S \tag{1}$$

The total change in reservoir storage can be estimated from either radar altimetry measurement of height or satellite visible imagery (such as Landsat) measurements of reservoir surface area and applying the reservoir area-elevation relationship (Gao 2015; Bonnema and Hossain, 2016). To obtain reservoir-specific inflow, the modeled surface runoff was re-gridded to 0.01 degree resolution and applied through a streamflow routing model of the basin to obtain representative inflow into each reservoir (Lohmann et al. 1996). The re-gridding was necessary to simulate reservoir inflow at the appropriate resolution because some of the reservoirs are built on smaller rivers that would not appear in a flow direction network derived from 0.1 degree topography. The routing model used estimates of surface runoff from the VIC model and routed this water to river channels according to input topographical information. The daily flows were then aggregated into average monthly inflow to estimate reservoir behavior parameters such as outflow and storage change.

A long-term time series of reservoir storage change can help elucidate the effective rule curve or standard operating procedure (SOP) for the reservoirs studied. A point to note is that the VIC model represents natural stream flows and does not take the effects of reservoir operations into account. Hence, the satellite remote sensing-based reservoir modeling is a tool to supplement hydrologic models like VIC that lack a water management component to model the impact of human regulation of flow.

RESULTS AND DISCUSSION

VIC Model Calibration

In-situ discharge data were available at 13 different locations on the Mekong river (Figure 2). At each location, the water (river) level data were available from 1985 to 2013, while discharge data were available from 1985 to 2005 in most stations. Thus, a flow rating curve at each station was developed to generate the discharge data from 2005 to 2013 (Figure 3).

Six locations were selected for calibration of the VIC model, where the station discharge is significantly different from the neighboring upstream stations. The flows at these stations are shown in Figure 4.

The VIC model was calibrated using four different soil parameters: the variable infiltration curve parameter (b_{inf}); maximum velocity of baseflow (Dsmax); fraction of Dsmax (Ds) and soil moisture (Ws) where non-linear base flow occurs. The calibrated model parameters are shown in Table 2. Besides the soil parameters of VIC, the cell impulse response function (i.e., UH file) of the route model was also calibrated. Calibration of the UH file is required where the daily discharge information is important (i.e., not monthly discharge). Three different cell impulse response functions were tested for Mekong River, and the UH.2 was selected as the calibrated function (Figure 5).

The model was simulated from 2002 to 2015. The output of the first year (i.e., 2002) was excluded to avoid any spin up error. The calibration period was set from 2003 to 2008, while the validation period was 2009-2013 (for the same six locations). The calibration and validation plots are shown in Figure 6. The error metrics of the simulated flow before and after calibration along with the validation period are shown in Table 3.

Model Validation at Independent Locations

In addition to the six stations that were used for calibration of VIC model parameters, there were four additional but completely independent locations where the model's capability to simulate flow was tested. Table 4 and Figure 7 summarize the flow simulation accuracy at these four locations (e.g. Chiang Khan, Mukdahan, Khong Chiam and Stung Treng). These locations provide a more robust test of how well VIC model can indeed simulate surface water availability patterns. When compared with the performance at calibrated locations it is very clear that VIC model can maintain a similarly high standard of skill in predicting flow at those locations at weekly to monthly scales needed for water management. However, water availability prediction at shorter timescales, such as for daily applications (municipal/irrigation water supply or forecasting floods), is seen to often miss the peaks in flow (Figure 7). We attribute this partially to the human regulation of flow by dams that the VIC model cannot simulate (see next section).

Satellite Observation of Reservoir Behavior

By applying the modeling technique based on mass balance and using satellite observables of reservoir height or surface area, the typical behavior of the 17 Mekong reservoirs (dams) was identified according to Bonnema and Hossain (2016). Figure 8 reproduces from Bonnema and Hossain (2016) how well satellite observations are able to capture the reservoir storage change, as an example, for the Sirindorn reservoir located in eastern Thailand. The good agreement with in-situ measurements indicate that the satellite observations (spanning visible, radar altimetry and passive microwave precipitation remote sensing) can indeed capture reservoir behavior well at monthly to bi-weekly timescales and could be used to model the management component for physical models like VIC. Figure 9 shows the reservoir volume (normalized to capacity) for all the 17 reservoirs averaged over 14 years of satellite observation as an 'effective' rule curve.

CONCLUSIONS

The ability to effectively predict stream flows in the Mekong river using physical hydrologic model supplemented with satellite-based monitoring of dam operations has wide reaching implications in trans-boundary water management. The Mekong river basin is vulnerable to water resources availability that often manifests as shortage (drought or upstream and unilateral extraction by dams and diversion projects), excess (floods) and crop damaging natural disasters (cyclones and river flooding) under an increasingly warming world. The vulnerability is felt more acutely downstream regions such as the Mekong delta due to the heavy population density and a water-intensive agricultural economy.

Among various options to build resilience against this vulnerability, one of the most cost-effective strategies with a proven benefit-to-cost-ratio is to institutionalize a physical modeling system that can monitor and predict ahead of time the changing dynamics of water cycle parameters as well as provide accurate human regulation of the waters by dams. Satellites with their vantage of space, sampling frequency and ability to distinctly measure complementary hydrologic variables with unprecedented accuracy, are uniquely positioned to meet this challenging requirement for the Mekong region. This study has shown that it is possible to model water availability and reservoir behavior to a reasonable accuracy even under the circumstances of sparse in-situ data using satellite observations. This ability should give water managers confidence that the future of planning and adaptation for precious water resources using physical models and satellite remote sensing is bright.

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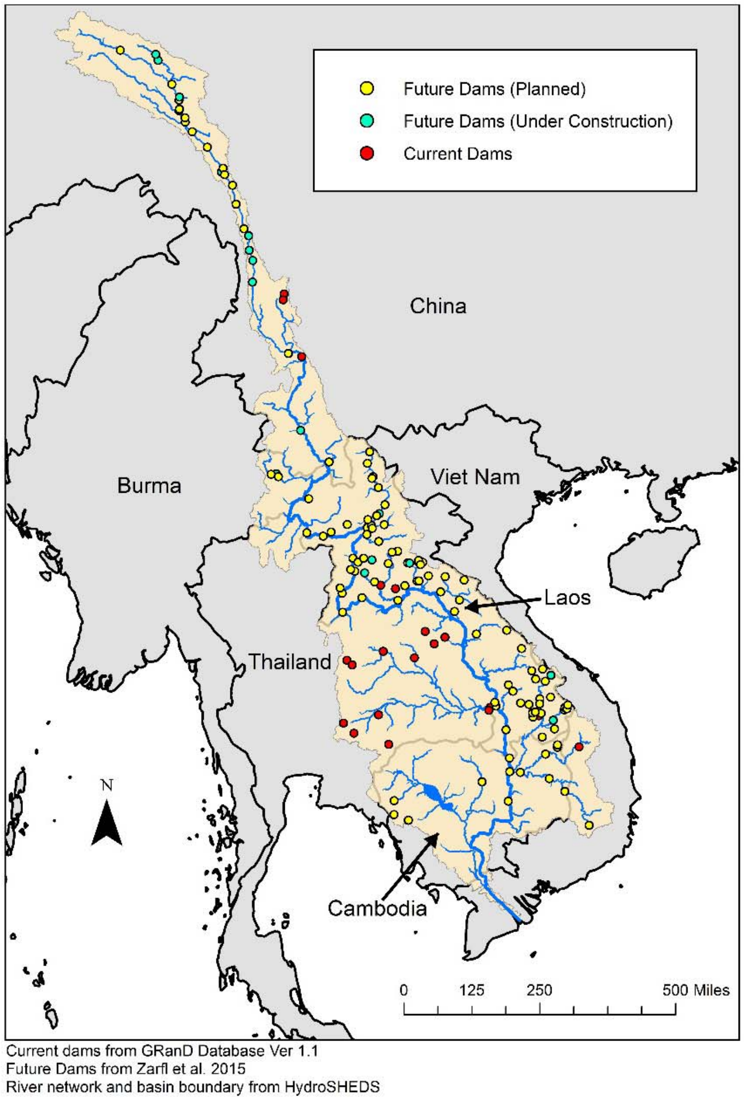

Figure 1. The Mekong River Basin (MRB) showing location of current and planned dams. *After Bonnema and Hossain, 2016*

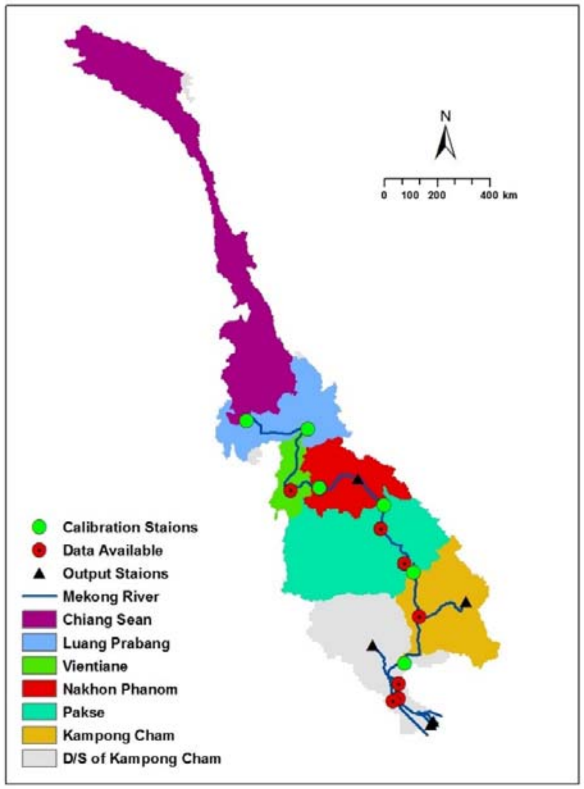

Figure 2. Mekong river basin, showing the location of calibration stations with the additional stations were discharge data are available. Basin segment (i.e., sub-basin) of each calibration station is shown by different color.

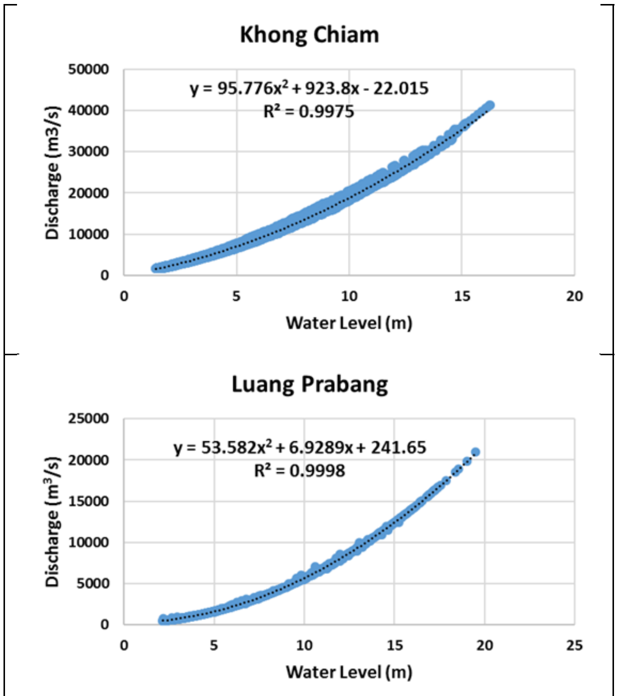

Figure 3. Sample of flow rating curves at two different locations on the Mekong river.

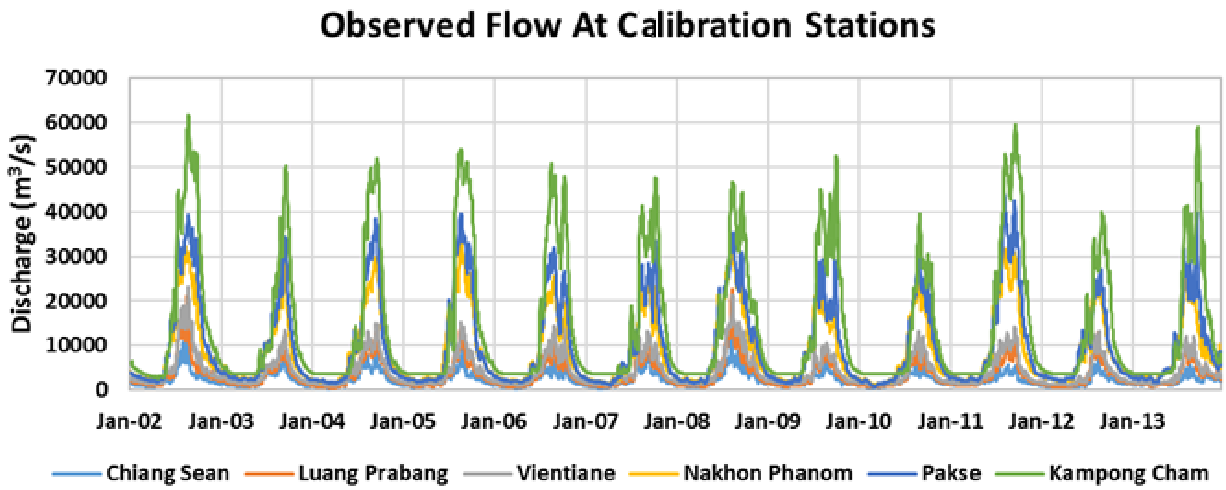

Figure 4. Flow at the selected discharge stations on the Mekong river used for calibration of the VIC model.

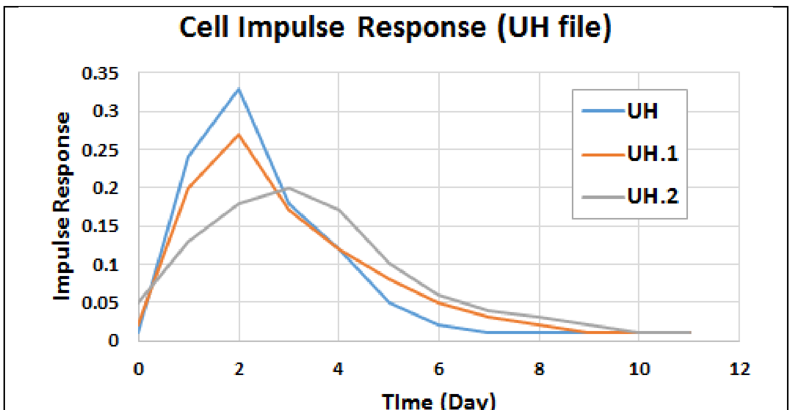

Figure 5. Three cell impulse response functions used in the route model of the Mekong river; UH.2 was selected as the calibrated function.

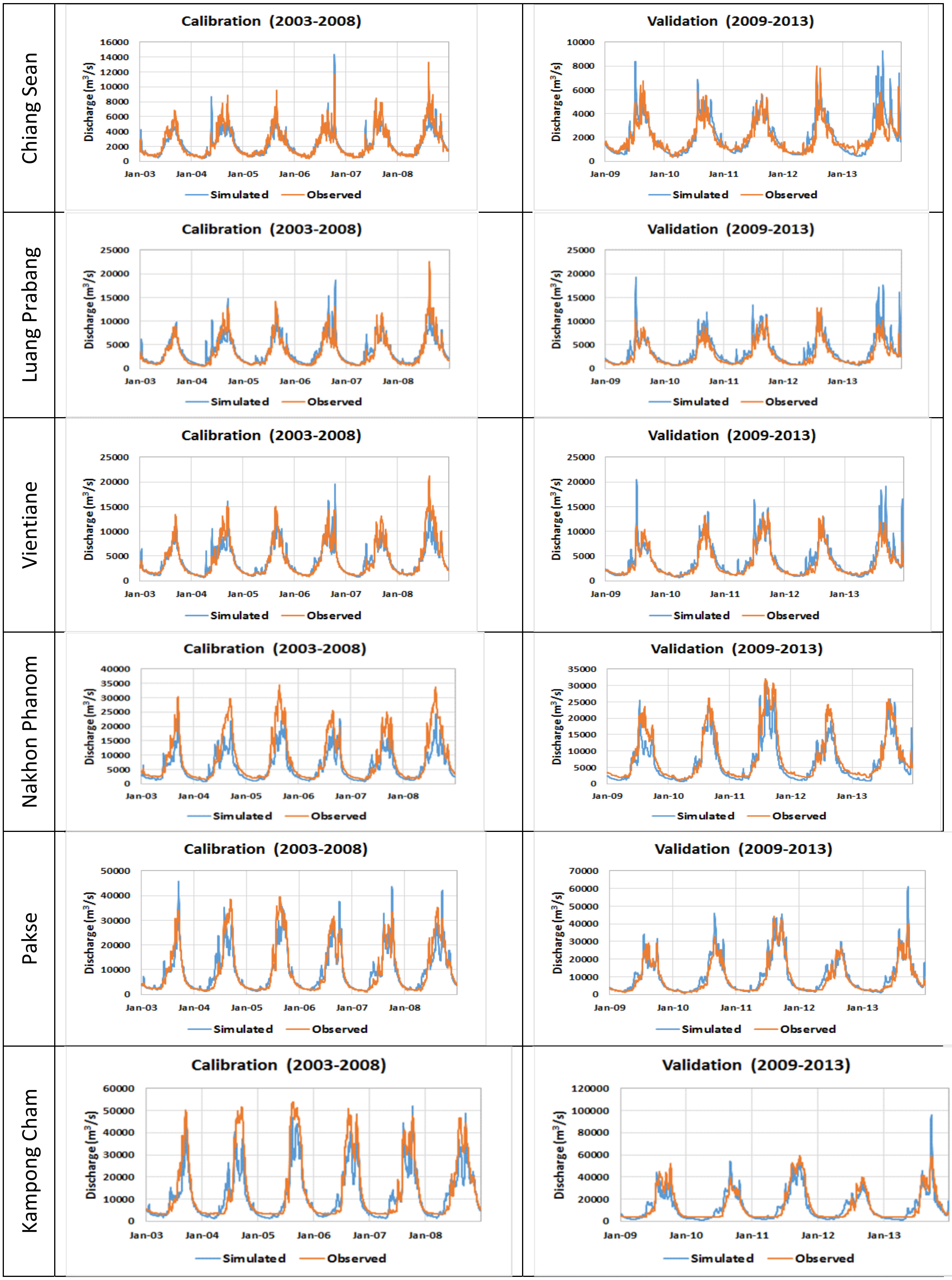

Figure 6. Calibration and validation plots at six different locations on the Mekong river.

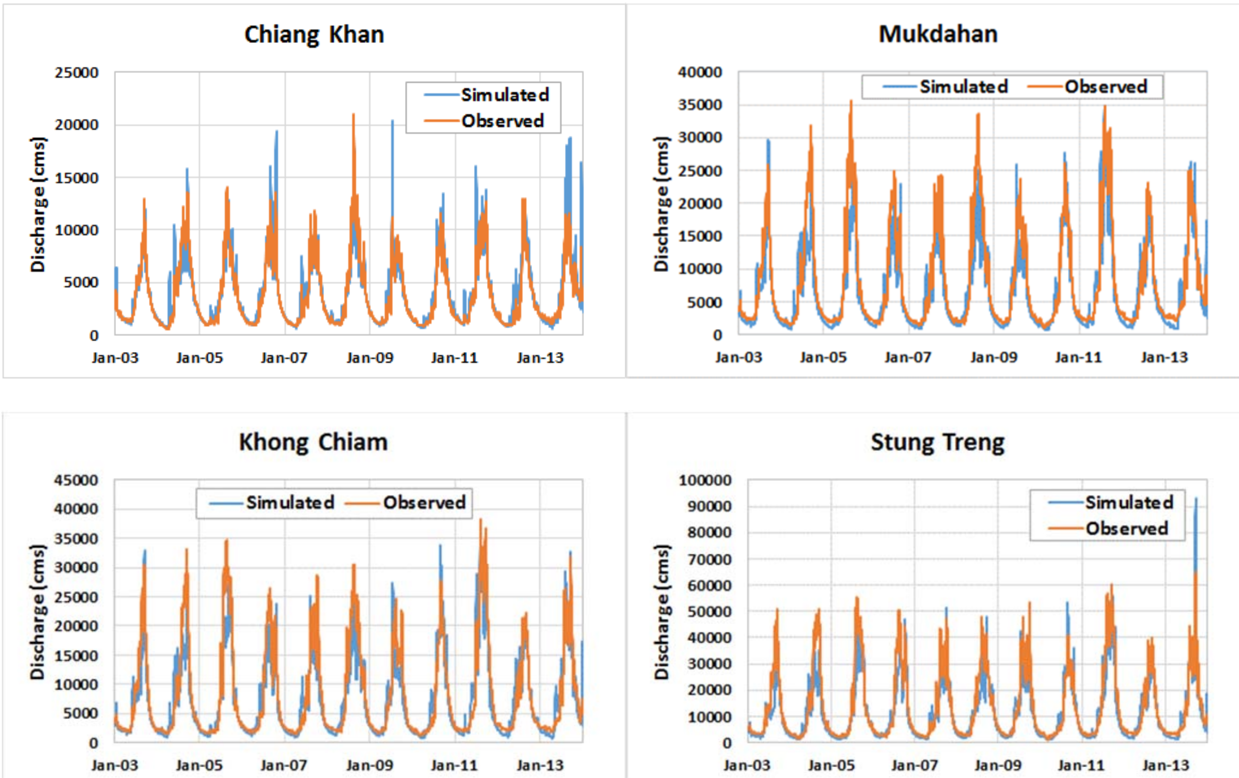

Figure 7. Validation of VIC simulated flow at locations not used for calibration.

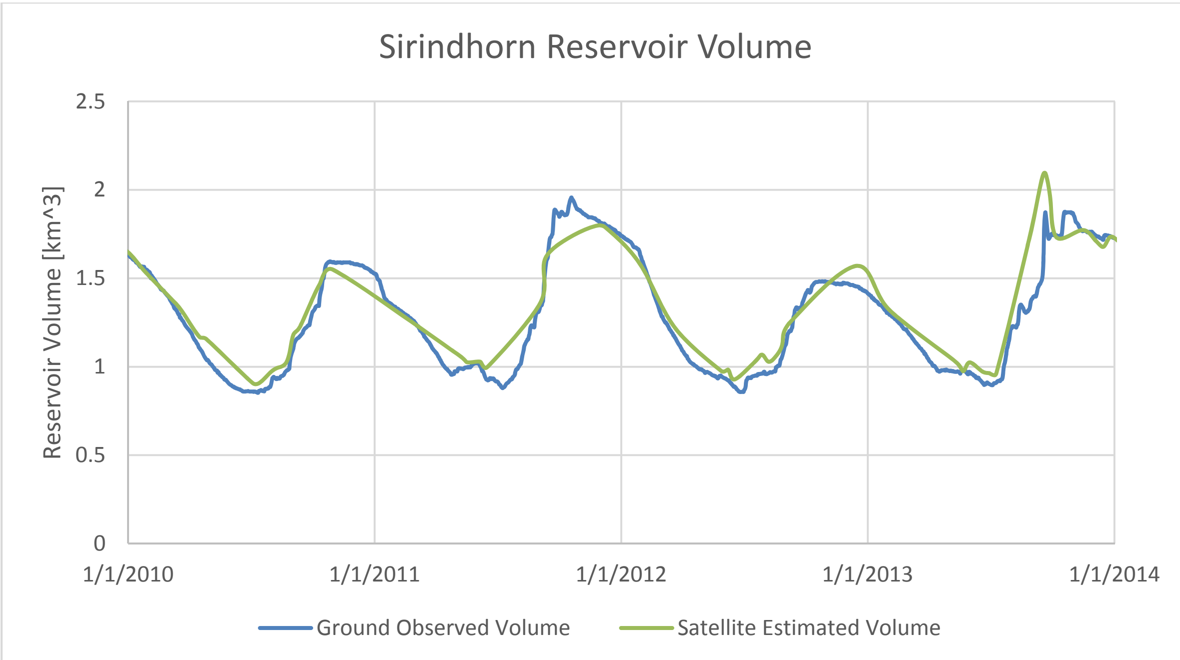

Figure 8. Comparison between ground observed and satellite estimated reservoir volume for the Sirindhorn Reservoir in Thailand. (reproduced from *Bonnema and Hossain, 2016*).

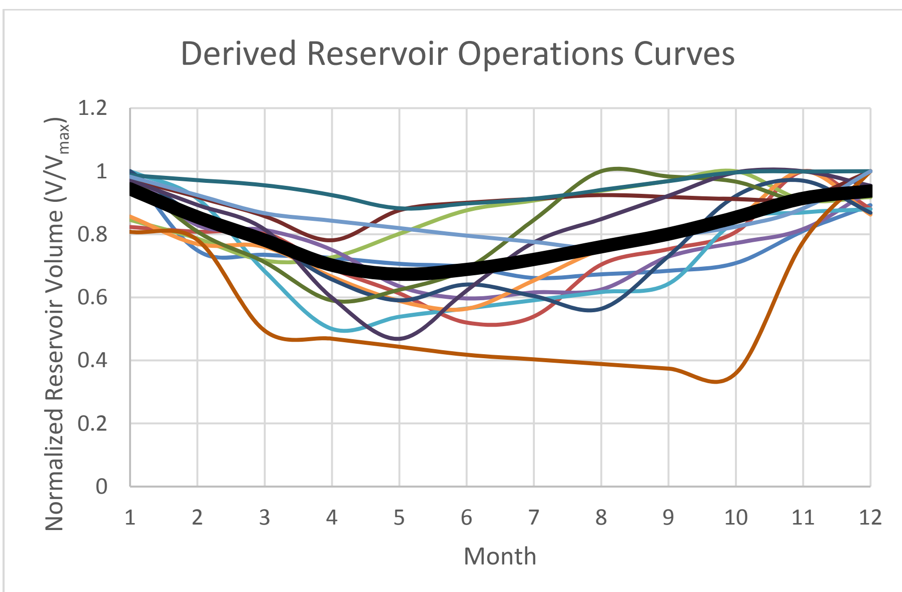

Figure 9. Derived reservoir operations curves (i.e. 'effective') for all 17 reservoirs, normalized by reservoir maximum volume. Average of all 'rules' shown in thick black. (reproduced from *Bonnema and Hossain, 2016*)

Table 1: List of dams examined in this study and their capacities and degrees of regulation (*after GranD dataset of Lehner et al., 2011*).

Dam/Reservoir Name	Capacity [million m^3]	Degree of Regulation (%)
Haixihai	61.9	197.7
Zibihe	93.2	131.6
Manwan	920	3.2
Nam Ngum	7030	87.5
Nam Leuk	185	72.3
Nam Oun	520	70.4
Nong Han Lake	1873.9	155.6
Nam Pung	165.5	102
Ubol Ratana	2263	83.2
Lam Pao	1430	48
Chulabhorn	188	198.1
Huai Kum	22.8	15.7
Lam Chang Han	26	156.4
Lamtakhong	310	189.8
Lamphraphloeng	152	86.7
Lamnangrong	150	161.6
Pak Mun	229	0.7

Table 2. Calibrated model parameters of each sub-basin

Sub-basin	INFILT (b_{inf})	Ds	Ds_MAX (mm/day)	Ws
Chiang Sean	0.1	0.3	No change	1
Luang Prabang	0.1	0.3	No change	1
Vientiane	0.1	0.3	No change	1
Nakhon Phanom	0.2	1	5	0.1
Pakse	0.1	0.8	No change	1
Kampong Cham	0.4	1	2	0.1
Kampong Down	0.4	1	2	0.1

Table 3. Performance metrics of the simulated discharge before (i.e., base) and after calibration. Validation is over the independent period of 2009-2013. NRMSE stands for Root Mean Squared Error (RMSE) of simulated flow normalized by observed flow and expressed as %. Efficiency pertains to the Nash-Sutcliffe measure.

Basin	Category	Mean Error (cms)	NRMSE (%)	Efficiency	Correlation
Chiang Sean	Base	-1274	70.6	0.64	0.80
	Calibration	-152	35.5	0.80	0.90
	Validation	171	42.5	0.57	0.87
Luang Prabang	Base	-1270	63.1	0.69	0.84
	Calibration	225	37.5	0.84	0.92
	Validation	792	52.8	0.70	0.92
Vientiane	Base	-1822	63.3	0.71	0.84
	Calibration	-206	35.3	0.84	0.92
	Validation	564	41.3	0.78	0.92
Nakhon Phanom	Base	-1822	63.3	0.71	0.84
	Calibration	-2536	52.4	0.78	0.93
	Validation	-1454	36.3	0.88	0.95
Pakse	Base	-1822	63.3	0.71	0.84
	Calibration	-316	38.7	0.86	0.93
	Validation	760	34.2	0.89	0.95
Kampong Cham	Base	-1822	63.3	0.71	0.84
	Calibration	-2349	45.3	0.84	0.93
	Validation	-597	40.9	0.85	0.92

Note: Base (2003-2008) is the model efficiency before calibration;
Calibration period is from 2003 to 2008 and Validation period is from 2009 to 2013

Table 4. Performance of the simulated flow at different (independent) locations on the Mekong river. Analysis period; 2003-2013. See Table 3 for definitions for NRMSE and efficiency.

Sub-basin	Remarkes	Mean Error (cms)	NRMSE (%)	Efficiency	Correlation
Chiang Sean	Calibration St.	-5.4	38.36	0.74	0.87
Luang Prabang	Calibration St.	482.7	44.07	0.79	0.9
Chiang Khan		164.2	34.25	0.83	0.91
Vientiane	Calibration St.	143.8	37.81	0.81	0.9
Nakhon Phanom	Calibration St.	-2044.5	46.24	0.82	0.93
Mukdahan		-1313.4	40.67	0.85	0.93
Khong Chiam		-811.7	37.26	0.86	0.93
Pakse	Calibration St.	173	36.79	0.87	0.93
Stung Treng		-1613.5	38.24	0.87	0.93
Kampong Cham	Calibration St.	-1552.8	43.44	0.84	0.92