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Assessment of Flow Changes from Hydropower Development and Operations in Sekong, Sesan and Srepok Rivers of the Mekong Basin

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Abstract

The Mekong River supports unique biodiversity and provides food security for over sixty million people in the Indo-Burma region, but potential changes to natural flow patterns from hydropower development are a major risk to the wellbeing of this system. Of particular concern is the ongoing and future development of 42 dams in the transboundary Srepok, Sesan and Sekong (3S) Basin which contributes up to 20% of the Mekong's annual flows and provides critical ecosystem services to the downstream Tonle Sap Lake and the Mekong Delta. To assess the magnitude of potential changes, daily flows were simulated over 20 years using the HEC ResSim and SWAT models for a range of dam operations and development scenarios. A 63% increase in dry season flows and a 22% decrease in wet season flows at the outlet of the 3S Basin can result from the potential development of new dams in the main 3S Rivers under an operation scheme to maximize electricity production. Water level changes in the Mekong River from this scenario are comparable to changes induced by the current development of Chinese dams in the Upper Mekong Basin and are

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significantly higher than potential flow changes from the proposed 11 mainstream dams in the Lower Mekong Basin. Dams on the upper sub tributaries of the 3S Basin have very low impacts on seasonal flow regimes because most of those projects are run-of-river dams and have small reservoir storages. Impacts on hourly flow changes due to intra daily reservoir operations, sediment movement, water quality and ecology need further study. Strategic site selection and coordinated reservoir operations between countries are necessary to achieve an acceptable level of development in the basin and mitigate negative impacts to seasonal flow patterns which sustain downstream ecosystem productivity and livelihoods.

CE Database Subject Headings: Dam; Flow simulation; Flow pattern; Hydropower; Hydrologic model

Author keywords: Mekong; HEC-RESSIM; hydropower; dam operations; Asia

Introduction

The Mekong River and its tributaries form a dynamic hydro-ecological system supporting unique biodiversity and providing food security for more than sixty million people in the Indo-Burma region. The system is undoubtedly one of the world's most diverse river ecosystems (IUCN 2009; MRC 2010a). The Mekong River and its tributaries also have a large potential for hydropower generation (Figure 1). Rapid regional growth and energy demands from neighbouring countries have prompted plans to build numerous dams along the Mekong's mainstream and its tributaries (Kummu and Varis 2007; MRC 2010a). These plans have raised major concerns for the impact that changes in the flow regime from the dams could have on the livelihoods of rural people, the rich biodiversity of floodplain

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habitats, and productivity of fish and other aquatic organisms that are strongly related to the hydrological cycle (Halwart 2008; MRC 2010a).

Recent assessments of basin-wide development scenarios by the Basin Development Plan Phase 2 (BDP2) of Mekong River Commission (MRC) and others (Keskinen 2008; Campbell 2009; MRC 2011a) show development of storage dams will increase flows in the dry season and decrease flows in the wet season and thus reduce the amplitude of the flow pulse of the Mekong. It is also undeniable that where dams are constructed, their size, and how they are operated are key factors in determining flow changes and subsequent impact on downstream ecosystem services and biodiversity. Reduced seasonal fluctuations from high levels of dam development are likely to affect wetland habitats situated on the floodplains of the Mekong and adversely impact the natural flood pulse of the Tonle Sap (Cambodia's Great Lake) and the Mekong Delta, which are critical for food security in the region (Kummu and Sarkkula 2008; MRC 2011a).

Although Mekong mainstream dams have been the focus of much attention in the media and scientific literature recently (Hirsch 2010; ICEM 2010), tributary dam development is proceeding at a rapid rate and detailed studies on these developments are sparse. Of immediate concern is the development in the basin formed by the Sesan, Srepok, and Sekong (3S) Rivers. The basin drains 78,650 km^2, of which 33% is in Cambodia, 29% in Lao PDR, and 38% in Viet Nam (Figure 1b). Annual rainfall over the basin varies from 1,100 to 3,800 mm. Annual discharge from the 3S Basin represents approximately 17 to 20% of total annual flows of the Mekong mainstream (91,000 10^6 m^3 or an average of 2,886 m^3/s), making it the largest tributary contribution to the Mekong Basin and therefore of significant importance (Adamson et al. 2009). In addition to their hydrological significance, the 3S Basin also

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provide an important contribution of aquatic biodiversity and ecosystem services, especially with regards to fish habitats and migration routes (ADB 2010). The 3S Basin is also home to over 2.5 million people. Most people in Lao PDR and Cambodia still live close to the river system and remain highly dependent on natural resources and ecosystem services, while the central highlands of Viet Nam have a denser population and are undergoing a rapidly accelerating development.

Hydropower development, consisting of individual dams and cascade dams, is rapidly progressing in the 3S Basin, particularly in Viet Nam and Lao PDR as a result of economic growth and a need for security in electricity production. The total potential for hydropower in the basin is about 6,400 MW (MRC 2009). There are currently nine operating dams and 11 projects under construction with a total installed capacity of 3,643Mw (about 60% of the potential) and a total live storage of 6,196 10^6 m^3 (Figure 1b). Twenty one other projects are at various levels of planning stages. The key characteristics of all these hydropower projects, which include storage and run-of-river dams, are summarized in Table 1. Existing dam operations in the Sesan River cause high fluctuations of water levels downstream, and have already caused changes in water quality, a major decline of fish populations and species, and the loss of livelihood and economic security (Grøner 2006). Understanding the impact of flow changes due the operation of individual and cascading dams is therefore critical to address transboundary issues, from power generation to potential alteration of downstream ecosystem productivity.

The main objective of this study is to assess how existing and future hydropower development and operations in the Sesan, Srepok and Sekong Rivers can change flow regimes at critical points in the 3S Basin. Potential flow changes from various operations and development scenarios are presented and discussed so that strategic options for dam development and operations in the 3S Basin can be considered. Changes in water levels in the Mekong induced by development in the 3S Basin are also compared with changes induced by the current development in the Mekong Basin and by proposed mainstream dams in the Lower Mekong Basin.

Methodology

The impact of hydropower development and operation on river flows in the 3S basin was examined through simulations using the Soil and Water Assessment Tool (SWAT) and the US Army Corps of Engineers-HEC ResSim models. The simulations were based on observed daily climatic data from the 1987 to 2006(20 years). These climate datasets were input to the SWAT model for simulating daily flows at numerous points along the 3S basin's rivers. The output flows from the SWAT model were feed into the HEC ResSim model to simulate regulated flows and power production for different levels of hydropower development scenarios and different operation rules. Changes in flow patterns and hydropower production of each scenario were compared against the baseline scenario without hydropower power projects.

Input data sources

Spatial information for hydrological modelling was extracted from satellite imagery, a 50 m grid cell size resolution digital elevation model (DEM) generated by the MRC from topographic maps (scales 1:50,000 and 1:100,000) and land surveys (MRC, 2003), land cover maps, and soil maps. Six climate stations were selected to obtain weather data including evaporation, humidity, wind speed and solar radiation. Rainfall data was obtained from 35 stations distributed around the basins and measured flow was obtained from 6 stations in the 3S Basin (MRC 2011b). The physical and operational characteristics of hydropower projects (dam height, width, installed capacity, spillway capacities, power plant discharges associated with reservoir levels and tail water levels) were obtained from the MRC hydropower database (MRC 2009). Relationships for area, storage and elevation for each reservoir were extracted from individual dam feasibility studies or calculated from the 50m DEM using spatial analyst tools. The reach properties (slope and cross-section) for channel routing were computed from spatial analysis of the 50m DEM and satellite imagery using ArcGIS and some cross-sections were verified with field survey.

Hydrologic and reservoir simulation modeling

The Soil and Water Assessment Tool (SWAT) model was chosen for simulating flows in the 3S Basin. SWAT is a physically based model which uses climate information, 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 modelled. The model can be separated into two major components. The first component models the land phase of the hydrologic cycle by dividing the landscape into hydrologic response units (unique combinations of sub-basins, land use, and soil type) to calculate water yields to the main channel from each sub-basin. The second component is the water routing phase, which can be defined as the movement of water through the channel network to the watershed's outlet (Winchell et al. 2009). Apart from its proven ability to simulate flows, SWAT was chosen because it is a model already used by the MRC and is part of the MRC's modeling Toolbox

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(MRC 2010b). Between 2010 and 2011, the model was calibrated for the 3S Basin using actual flow and rainfall measurements from 1987 to 2006 (MRC 2011b).

Results from SWAT were then used as inputs to the hydropower operations model HEC-ResSim developed by the US Army Corps of Engineers (USACE). HEC-ResSim is a well-established and widely used model for simulating reservoir systems within basins (USACE 2007; Minville et al. 2010). Given its capabilities to model detailed operations of individual and cascading hydropower schemes, the model was deemed suitable for application in the 3S Basin to study hydropower reservoir plans and potential operating policies (Cochrane et al. 2010). The model consists of three components: watershed, reservoir network, and simulation (USACE 2007). Stream alignment and hydropower project configurations are defined with the watershed component. Spatial connectivity parameters, physical parameters, and operational information on hydropower projects, reaches and diversions are added in the reservoir network component. Configuration and computations of the different hydropower scenarios is done through the simulation component. Physical characteristics including dam height and width, spillways and power plant release capacities were defined for each dam. The Muskingum-Cunge method was selected for channel routing in which channel cross-section geometry was defined by eight points (USACE, 2000). A schematic of the 41 hydropower projects, including eight flow diversions, modeled using HEC-ResSim is presented in Figure S1.

Simulated scenarios

A baseline scenario, a definite future scenario, and two hydropower development scenarios were simulated to access the degree of changes in flows and elucidate discussion on potential environmental, social and economic impacts. Each scenario is described below and a complete list of the current status of hydropower projects is given in Table 1.

1) ***Baseline scenario (BL):*** reference river flow scenario resembling natural conditions. No hydropower projects are included in this scenario.
2) ***Definite future scenario (DF):*** includes existing and ongoing hydropower construction projects that are expected to occur in the near term (next 5 years). This scenario includes 19 projects (8 existing and 11 projects under construction).
3) ***Development on main tributaries scenario (DMT):*** future hydropower development on the main 3S Rivers (Mekong tributaries) that countries have considered for study or development. This scenario comprises the developments in the DF plus the proposed developments on the main 3S Rivers, totalling 28 projects (8 existing, 11 under construction and 9 proposed projects).
4) ***Development on main and sub tributaries scenario (DMST):*** all current and proposed hydropower development on the main 3S Rivers and sub tributaries. This scenario comprises the developments in the DMT plus the proposed developments on the sub tributaries, totalling 41 projects (8 existing, 11 under construction, 9 proposed projects on the main 3S Rivers and 13 proposed projects on the sub tributaries).

In addition to the level of dam development, three operation rules which define target water levels for each reservoir were modelled to compare resulting changes in power plant releases and downstream flows: i) seasonal variation, ii) full level and iii) low level (Figure 2). These scenarios aim to show the possible range of dam operations and their effect on electricity production, power plant releases and flow patterns.

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The seasonal variation operation rule consists of setting seasonal water release targets from the reservoir. The rule allows drawdown of the reservoir in order to maximize seasonal energy production, avoid running the reservoir dry before the end of the dry season, and minimize the risk of excess spillage due to the reservoir being full before the end of the wet season. The seasonal variation rule was defined as the default operation scheme as it is normally used during dam feasibility studies. The water release decision of this operation is dependent on the reservoir target level and the physical plant release capacities related to the reservoir levels. If the water levels in the reservoir are lower than target levels, the dam operator will stop flows through the turbines to raise water levels in the reservoir.

The full level rule keeps reservoirs at the maximum active storage level throughout the year. The dam operator will stop releasing flow through the turbines if the water level in the reservoir is below the full level. When the dam is full, it will be operated like a run-of-river dam were water outflows are close to inflows. This is analogous to a more conscious transboundary management of dams.

The low level operation rule is an example of an operation rule to allow for flood control where the water levels in the reservoir are targeted to be kept low throughout the year. Water is therefore released through the turbines as much as possible to reserve water storage space for potential flood flows. The release, however, is constrained by the power plant's physical release capacity. If inflows are greater than power plant's release capacity, the surplus water will be stored in the reservoir.

Assessment of flow changes

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The impact of dam development level and operation scenarios in the 3S Basin were modelled on a daily time step to quantify the magnitude of potential changes of flows using rainfall data from 1987 to 2006 (20 years). Flow results from the baseline scenario were compared against flows for each of the different development and operation scenarios to examine relative magnitudes of change. The results of the model simulations are provided for the 3S Basin outlet, outlets from each of the main tributaries (Sekong, Sesan and Srepok), and at country boundaries. Average wet and dry seasonal flows (6 months), average 7-day annual low and high flows, average daily flows, flow durations, and temporal shifts in peak flows were statistically compared. These flow change indicators are important for understanding potential short and long term changes to river morphology, disruption of habitat, change in fish community structure, navigation, and water availability.

Results and discussion

Impact of hydropower development level

Simulation results for each development scenario (BL, DF, DMT, DMST) were computed using the seasonal variation operation rule and orifice release at each of the 7 strategic sites (Figure 3). The average flows for the dry season (Dec. to May) and wet season (Jun. to Nov.) over the 20 years (1987-2006) were compared with average dry and wet seasonal flows of the Baseline scenario. As illustrated, the overall impact of the DF, DMT and DMST scenarios is the increase of dry season flows and decrease of wet season flows. In the DF scenario, average wet and dry seasonal flows in the Sesan River (sites 3 and 6) and upstream of the Srepok River (site 5) show significant changes due to the high level of hydropower development (existing and under construction) in the Viet Nam highlands. The average wet seasonal flows of sites 5 and 6 (country boundaries between Cambodia and Viet Nam in the Srepok and Sesan Basins) decreases 45 m^3/s (10%) and 72 m^3/s (22%), respectively while the average dry seasonal flows increases 35 m^3/s (18%) and 54 m^3/s (52%), respectively. The seasonal effects of the DF scenario are low at sites 4 and 7 in the Sekong River because all hydropower development is occurring on sub tributaries and total active storage for regulation is considerably small compared with the average annual flow at the outlet of the Sekong River (less than 10%). Overall, the level of hydropower development in the DF scenario is expected to modify the flow regime at the outlet of the 3S Basin (site 1) by increasing dry seasonal flows by 28% and decreasing wet seasonal flows by 4% compared to the BL scenario.

The development of proposed hydropower projects on the main 3S Rivers (DMT scenario) shows substantial changes in average seasonal flows in both wet and dry seasons, particularly in the Sekong River (sites 4 and 7), the outlet of the Srepok River (site 2), and the outlet of the 3S Basin (Figure 3). Most of the proposed hydropower projects are in Lao PDR (upstream of the Sekong River) and in Cambodia (downstream of Srepok and Sesan Rivers). The total active storage in the basin would increase to 22,845 10^6 m^3while the total active storage in the DF scenario is only 6,203 10^6 m^3 (Table 2). The total active storage in the DMT scenario is about ¼ of the average annual flow at the outlet of the 3S Basin (86,987 10^6 m^3). The average wet seasonal flows of site 7 (country boundary between Cambodia and Lao PDR in the Sekong Basin) compared with the DF scenario is estimated to further decrease by 317 m^3/s (21%) while the average dry seasonal flows will increase by 281 m^3/s (60%). Similarly, wet season flows decrease by 22% and dry season flows increase by 63% at the outlet of the basin. The additional 13 proposed hydropower projects on sub tributaries of the basin (the DMST scenario) do not cause significant changes to overall seasonal flows compared with

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the DMT scenario because most of these dams have small reservoir storages and were designed as run-of-river schemes.

The error bars in Figure 3 present standard deviations of average wet and dry seasonal flows over 20 years. An increase in dam development causes an observable reduction in dry season flow variations at the outlet of the 3S Basin and at the outlets of the individual 3S Rivers (sites 2, 3, and 4). Dam development, however, did not significantly alter the range of flow variations during the wet season over the 20 years of simulation.

Results showing the 7-day mean annual low and high flows, averaged over the 20 year simulation period of simulated scenarios, are presented in Table 3. T-tests, at 95% confidence interval, were used to examine whether there were significant differences between the sample means of the BL and the DF, DMT, and DMST scenarios. Results show that hydropower development (DF, DMT and DMST scenarios) will significantly increase the 7-day mean annual low flows at all sites. Conversely, the level of hydropower development in the DF scenario does not yield significant changes in the 7-day mean annual high flows in the Srepok, Sekong Rivers and the Basin outlet, except for the Sesan River. However, when the proposed hydropower projects in main and sub tributaries were included, their operations drastically decrease the 7-day mean annual high flows for all sites except site 5 (upstream of Srepok River in Viet Nam, Figure 3) because most hydropower projects upstream of site 5 are run-of-river schemes and have small storages.

Simulated daily flow results are presented for a rainy year (2000) and a dry year (1992) for the outlet of the 3S Basin (Figure 4) 4. The 3S outlet total annual runoff volume of the rainy year (116,428 10^6 m^3) was close to 100% larger than for the dry year (67,657 10^6 m^3). The

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peak flow during the rainy year (20,576 m^3/s) was 2.3 times larger than for the dry year (8,934 m^3/s). Average flows at the outlet of the 3S Basin doubled in the dry season of the dry year, and peak flows decreased by 13% in the rainy year when comparing the DF scenario to baseline flows. Greater changes occurred under the DMT scenario due to operations of large storage hydropower dams on main tributaries in Lao PDR in Sekong River (Xe Kong 3 up, Xe Kong 3 down, Xe Kong 4 and 5) and Cambodia in Srepok and Sesan Rivers (Lower Sesan 3, Lower Srepok 3 and 4 and Lower Sesan-Srepok 2), whose active storages are about 16,000 10^6 m^3. Dry season flows tripled in April for the dry year and the peak flow in the rainy year (20,576 m^3/s) was reduced by 50%. Only minor further changes occurred when all sub tributary dams were included. For all simulations, full hydropower development in the 3S Basin delayed flood peaks at the outlet by only one or two days. However, the timing of flood peaks could shift further from baseline conditions if dams are operated for flood control operations.

A comparison of flow duration curves of different hydropower development levels at the outlet of the 3S Basin is shown in Figure 5. The curves were derived from simulated daily flows over 20 years (1987-2006). Hydropower development will significant modify the flow duration curves for all the 3S Rivers, but particularly for the Srepok River under the DMT scenario. At high exceedance probability, low flows increase by two fold from baseline conditions in all sites when all hydropower projects were considered (DMST scenario). In contrast, at 10% low probability of exceedance, flows at the outlets of the 3S Basin, Srepok, Sesan and Sekong Rivers were reduced by 17%, 35%, 29% and 28%, respectively.

Impact of hydropower operations

Daily averaged flows for three operation rules at the outlet of the 3S Basin under the highest level of hydropower development (DMST scenario) were compared (Figure 6). The seasonal variation rule, which aims to maximize power production by storing excess flows in the wet season to allow for an increase in potential power generation in the dry season (Figure 7), results in the largest modification of seasonal flow patterns. On average, about 18,290 10^6 m^3 of water was stored in the reservoirs during the wet season, which is 20% of average annual flow at the 3S outlet (91,000 10^6 m^3). The rule to maintain the reservoir at the low level throughout the year also resulted in significant changes from baseline flows because this rule allows water levels in the reservoir to fluctuate from the low to full levels to mitigate floods (Figure 7). The resulting flow changes were only slightly smaller than changes induced by the seasonal variation rule. The full level rule resulted in minimum changes to natural or baseline flow patterns. This operation rule forces dams to act like weirs or run-of-river type schemes. When the reservoirs are full, excess inflows will be released through the power plant or the spillway because the operation will not allow reservoir levels lower than the full level or storage of water over the flood control level. This operation rule significantly restricts water level fluctuations in the reservoir.

The seasonal variation rule resulted in the highest electricity production (120 GWh/day) (Figure 6). The average energy production per day under the full level rule was reduced by 50% (59 GWh/day) of what the seasonal variation rule generated. Thus, operating dams to minimize seasonal variations will result in a significant reduction of potential income from electricity sales. While dam operators would tend to operate dams to maximize electricity generation, the ecosystem services offered by the natural flows of these rivers have a considerable value to the downstream beneficiaries, including agriculture, fisheries, wetlands, and biodiversity. The economic values of these services have been estimated for the LMB

(Constanza et at. 2011; MRC 2011a). Further work is underway to find operation rules that achieve an optimal balance between required electricity production, flood control, and maintaining important ecosystem services provided by natural flows of the 3S Rivers.

Impact of hydropower development and operation in the 3S Basin on the Mekong mainstream

To analyze the impacts of the proposed 3S hydropower development and operation on the Mekong River, results of the DMST scenario were compared against a) an Upper Mekong Dam scenario in the Upper Mekong Basin (UMD-UMB) which includes all existing and under construction mainstream hydropower projects in China (Figure 1), b) Definite future scenario in the LMB (DF-LMB) which includes all existing and under construction hydropower projects in the LMB tributaries as well as present irrigation and water supply demands, and c) all 11 proposed LMB mainstream projects (MD-LMB). These 3 simulation scenarios were carried out by the MRC under BDP2 in 2010 (MRC 2011a).

Potential changes in water levels were also examined at Stung Treng, which is located on the Mekong mainstream at the downstream junction of the Mekong River and the outlet of the 3S Basin (Figure 8). Water levels were analyzed at this station because a well developed rating curve is available at this site. The DMST-3S scenario shows the most impact on annual daily maximum water levels compared with other scenarios. Maximum daily water levels between January and April increase 0.10 to 0.30 m from the baseline levels (2.30-3.00 m) and decrease 0.19 to 1.07 m in May-December from baseline levels (4.81-11.10 m). The proposed LMB mainstream dams, excluding the last dam (Sambor dam, Cambodia), have a small impact on monthly water levels at Stung Treng.

Incremental deviations from average monthly baseline flows on the Mekong mainstream at Kratie are presented in Figure S2 for all scenarios. Kratie is located downstream of the last proposed LMB mainstream projects in Cambodia, which is 200 km from the 3S outlet. Mainstream Chinese dams (UMD-UMB), which have a combined storage of 23,193 10^6 m^3, substantially modify seasonal flow patterns in the Mekong mainstream. Dry season flows increase in February by 812 m^3/s while wet season flows decrease in August by 1,807 m^3/s. Existing and ongoing development in the LMB (DF-LMB) which includes hydropower, irrigation and water supply also increase flows in dry season and reduce flows in wet season, but the magnitude of changes is about half of the impact from the UMD-UMB scenario. The total active storage of current and under construction hydropower projects in the LMB tributaries is only about 13,700 10^6 m^3. All changes induced by the UMD-UMB and DF-LMB scenarios on the Mekong's mainstream flow regime are expected to occur by 2015 when all projects are completed and operating (MRC 2011a).

The 11 proposed mainstream dams in the LMB, which are run-of river dams, will add 5,200 10^6 m^3 of water storage to the basin. The mainstream dams in the LMB would only have a marginal effect on monthly flows (Figure 8, MD-LMB scenario). The main changes could occur between April and July (transition period) by increasing flows in April and May about 200 m^3/s, and decreasing flows in June and July by about 400 m^3/s.

A significant relative change in monthly flow patterns in the Mekong River at Kratie was observed from the simulations of all proposed 3S hydropower projects (DMST-3S), which have a total active storage of 20,125 10^6 m^3. The impact of the DMST-3S scenario is similar to that of the UMD-UMB scenario because the total active storage for both scenarios is

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similar. Average flows at Kratie would increase to over 2,200 m^3/s in February from baseline flows and would decrease in August by over 4,000 m^3/s.

Conclusions and recommendations

Modelling of large-scale complex scenarios of hydropower development and operations are possible through a combination of SWAT and Hec-ResSim models. Changes in flows are dependent on the number, location, size, and operation of hydropower dams and reservoirs. Large storage reservoirs in downstream reaches, coupled with energy focused operation in the 3S Rivers system will significantly increase discharge flows in the dry season (Dec.-May) and reduce flows in the wet season (Jun.-Nov.). Current and under construction projects will also increase dry season flows by 28% and decrease wet season flows by less than 4% at the 3S outlet when compared to historical natural flows. Development of proposed new hydropower projects on the main Sekong, Sesan and Srepok Rivers will further increase flows by 63% in the dry season and decrease flows by 22% in the wet season at the outlet of the basin. Only minor additional changes of +7 and -3% in dry and wet season flows, respectively, occurred when the proposed projects on sub tributaries were included because these dams are mainly run-of-river schemes. The majority of flow changes can thus be directly attributed to a few large reservoirs if operated under a scenario to maximize energy production. Strategic selection of dams to be developed and a coordinated management of dams operated under a wider set of rules to minimize changes to natural flow pulses should be part of a strategy to maximize total economic return by including the value of downstream ecosystem services and livelihoods.

The development of all dams in the 3S Basin will also have a considerable impact on flows and water levels in the Mekong mainstream. The magnitude of flow changes at Strung Treng and Kratie from the development and operation of all dams in the 3S Basin is comparable to existing and under construction large mainstream hydropower projects in China and significantly larger than the magnitude of flow changes induced by the 11 proposed mainstream dams in the LMB. The narrowing of the range of flows over the year from full development in the 3S Basin is of great concern because it could impact habitat downstream by reducing wetland areas in the flood season, submerging sandbars, changing river morphology, and altering river bank vegetation. These changes, together with alteration of fish migration routes and sediment flows, could lead to a subsequent level of decrease of ecological and fish productivity in the Tonle Sap and enhance salt intrusion in the Mekong Delta. Applications of river and floodplain inundation models together with further information on ecological behaviour of the lower Mekong are needed to quantify impacts.

The assessment of changes in flows and water levels is essential, but it is only an initial step to examine impacts from hydropower development. Further research is needed to assess irrigation water abstractions, changes in sediment flows, water quality, and downstream ecosystem functions. Coordination and cooperation among countries is essential to build a comprehensive understanding of the importance of economic, environmental and social values and assets of the basin to provide more comprehensive strategic options for dam development and reduce risks of negative transboundary impacts.

This study was limited to daily flow simulations due to current constraints in the availability of detailed operation rules of the proposed hydropower projects and actual flow measurements. As more information becomes available, future studies should be conducted at hourly intervals to investigate flow changes from dam operations which may cause significant fluctuation in intra-daily flows and durations. Flood control operations for some of the large storage dams should also be simulated in greater detail as these will further delay and attenuate peak flows. The impact of climate change on hydrological flows also needs to be analyzed as part of an adaptation and strategic hydropower development plan for the 3S Basin.

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Supplemental Data

Figures S1 and S2 are available online in the ASCE Library (www.ascelibrary.org)

References

Adamson, P. T., Rutherfurd, I. D., Peel, M. C., and Conlan, I. A. (2009). "The Hydrology of the Mekong River." *The Mekong*, Academic Press, San Diego, 53-76.

ADB (2010). "Sesan, Srepok and Sekong River Basins Development Study in Kingdom of Cambodia, Lao People's Democratic Republic, and Socialist Republic of Viet Nam." Asian Development Bank, Manila, Philippines.

Journal of Water Resources Planning and Management. Submitted October 29, 2011; accepted May 16, 2012; posted ahead of print May 21, 2012. doi:10.1061/(ASCE)WR.1943-5452.0000286

Cochrane, T. A., Arias, M. E., Teasley, R. L., and Killeen, T. J. (2010). "Simulated changes in water flows of the Mekong River from potential dam development and operations on the Sesan and Srepok tributaries." *Proceedings of the IWA World Water Congress and Exhibition,* Montreal Canada, 7.

Campbell, I. (2009). "Development Scenarios and Mekong River Flows." *The Mekong*, Academic Press, San Diego, 389-402.

Constanza, R., Kubiszewski, I., Paquet, P., King, J., Halimi, S., Sanguanngoi, H., Nguyen L. B., Frankel, R., Ganaseni, J., Intralawan, A., and Morell, D. (2011). “Planning Approaches for Water Resources Development in the Lower Mekong Basin.” Portland State University/Mae Fah Luang University, Portland, USA.

Grøner, S. (2006). "Environmental Impact Assessment on the Cambodian part of the Sesan River due to Hydropower Development in Vietnam." Electricity of Vietnam, Hanoi, Viet Nam.

Halwart, M. (2008). "Biodiversity, nutrition and livelihoods in aquatic rice-based ecosystems." *Biodiversity Journal of Life on Earth*, 9, 36-40.

Hirsch, P. (2010). "The Changing Political Dynamics of Dam Building on the Mekong." *Water Alternatives*, 3(2), 312-323.

ICEM (2010). "Stategic Environment Assessment of Hydropower on the Mekong Mainstream." International Centre for Environmental Management, Hanoi, Viet Nam.

IUCN (2009). "Red List of Threatened Species." International Union for Conservation of Nature. www.iucnredlist.org

Keskinen, M. (2008). "Water resources development and impact assessment in the Mekong Basin: Which way to go?" *Ambio*, 37(3), 193-198.

Kummu, M., and Varis, O. (2007). "Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River." *Geomorphology*, 85(3-4), 275-293.

Kummu, M., and Sarkkula, J. (2008). "Impact of the Mekong River flow alteration on the Tonle Sap flood pulse." *Ambio*, 37(3), 185-192.

Minville, M., Brissette, F., and Leconte, R. (2010). "Impacts and Uncertainty of Climate Change on Water Resource Management of the Peribonka River System (Canada)." *Journal of Water resources Planning and Management*, 136 (3), 376-385.

MRC (2003). “MRC Information System (MRC-IS).” Information and Knowledge Management Programme, Mekong River Commission, Phnom Penh, Cambodia.

MRC (2009). "Hydropower Project Database." Basin Development Plan Programme, Mekong River Commission, Vientiane, Lao PDR.

MRC (2010a). "State of the Basin Report 2010." Mekong River Commission, Vientiane, Lao PDR.

MRC (2010b). “Stage 2 Development of MRC Toolbox: Final Report (WP016).” Information and Knowledge Management Programme, Mekong River Commission, Phnom Penh, Cambodia.

MRC (2011a). "Assessment of Basin-wide Development Scenarios." Mekong River Commission, Vientiane, Lao PDR.

MRC (2011b). "Application of MRC Modelling Tools in the 3S basin." Mekong River Commission, Phnom Penh, Cambodia.

USACE (2000). "Hydrologic Modeling System HEC-HMS. Technical Reference Manual." US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, Davis, California, USA.

USACE (2007). "HEC-ResSim, Reservoir System Simulation. User’s Manual, v.3." US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, Davis, California, USA.

Winchell, M., Srinivasan, R., Di Luzio, M., and Arnold, J. (2009). "ArcSWAT Interface for SWAT2009: User's Guide." Soil & Water Research Laboratory, Temple, Texas, USA.

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FIGURE CAPTION LIST

Figure 1. Hydropower projects in the Mekong Basin: a) existing, under construction, and proposed LMB mainstream projects, and b) existing, under construction, and proposed hydropower development in the 3S Basin.

Figure 2. Annual operation rules (full level, seasonal variation, and low level) for the Xe Kaman 1 hydropower dam.

Figure 3. Simulated average flow rates and standard deviations (error bars) for the wet (Jun-Nov) and dry (Dec-May) seasons based on 20 years of daily simulations for the baseline (BL), definite future (DF), dams on the 3S Rivers (DMT), and all dams in the 3S Basin (DMST) scenarios. Graphed results are shown for the 3S outlet (site 1), outlets of the main tributaries (sites 2, 3, and 4), and at the country boundaries (sites 5, 6, and 7).

Figure 4. Comparison of simulated daily flow hydrographs in wet and dry years (2000 and 1992) at the 3S outlet (site 1) for different levels of hydropower development.

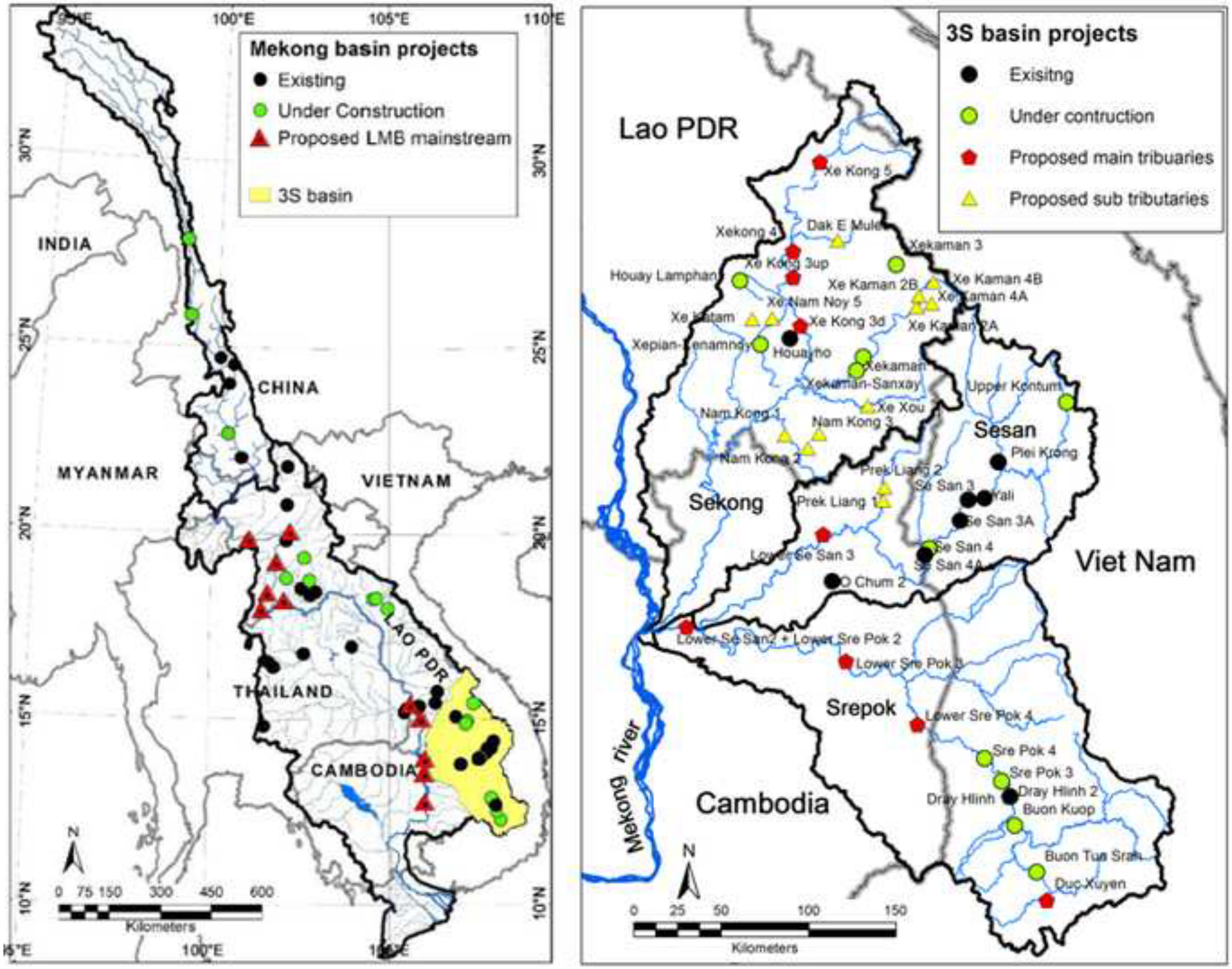
Figure 5. Comparison of flow duration curves at the 3S outlet (site 1) for different levels of hydropower development.

Figure 6. Comparison of simulated average daily flow hydrographs at the outlet of the 3S Basin and energy production under the seasonal variation, full level, and low level rules for simulation with all proposed dams in the 3S Basin (DMST).

Figure 7. Comparison of simulated storage at the Xe Kaman 1's reservoir under different operation rules between 1987 and 2006.

Figure 8. Cumulative maximum monthly water level deviation from maximum baseline water levels on the Mekong mainstream at Stung Treng from full development of all dams in the 3S Basin (DMST-3S), mainstream dams in the Lower Mekong Basin

(MD-LMB), definite future in the LMB (DF-LMB), and dam development in the Upper Mekong Basin (UMD-UMB).


Mekong basin projects
● Existing
● Under Construction
▲ Proposed LMB mainstream
3S basin
95°E
100°E
105°E
110°E
30°N
25°N
20°N
15°N
10°N
INDIA
CHINA
MYANMAR
VIETNAM
LAO PDR
THAILAND
CAMBODIA
N
0 75 150 300 450 600
Kilometers
3S basin projects
● Exisitng
● Under contruction
⬟ Proposed main tribuaries
△ Proposed sub tributaries
Lao PDR
Viet Nam
Cambodia
Sekong
Sesan
Srepok
Mekong river
Xe Kong 5
Dak E Mule
Xekong 4
Xekaman 3
Xe Kong 3up
Houay Lamphan
Xe Kaman 2B
Xe Kaman 4B
Xe Kaman 4A
Xe Nam Noy 5
Xe Katam
Xe Kong 3d
Xe Kaman 2A
Xepian-Xenamnoy
Houayho
Xekaman 1
Xekaman-Sanxay
Upper Kontum
Xe Xou
Nam Kong 1
Nam Kong 3
Nam Kong 2
Plei Krong
Prek Liang 2
Prek Liang 1
Se San 3
Yali
Se San 3A
Lower Se San 3
Se San 4
Se San 4A
O Chum 2
Lower Se San2 + Lower Sre Pok 2
Lower Sre Pok 3
Lower Sre Pok 4
Sre Pok 4
Sre Pok 3
Dray Hlinh
Dray Hlinh 2
Buon Kuop
Buon Tua Srah
Duc Xuyen
N
0 25 50 100 150
Kilometers

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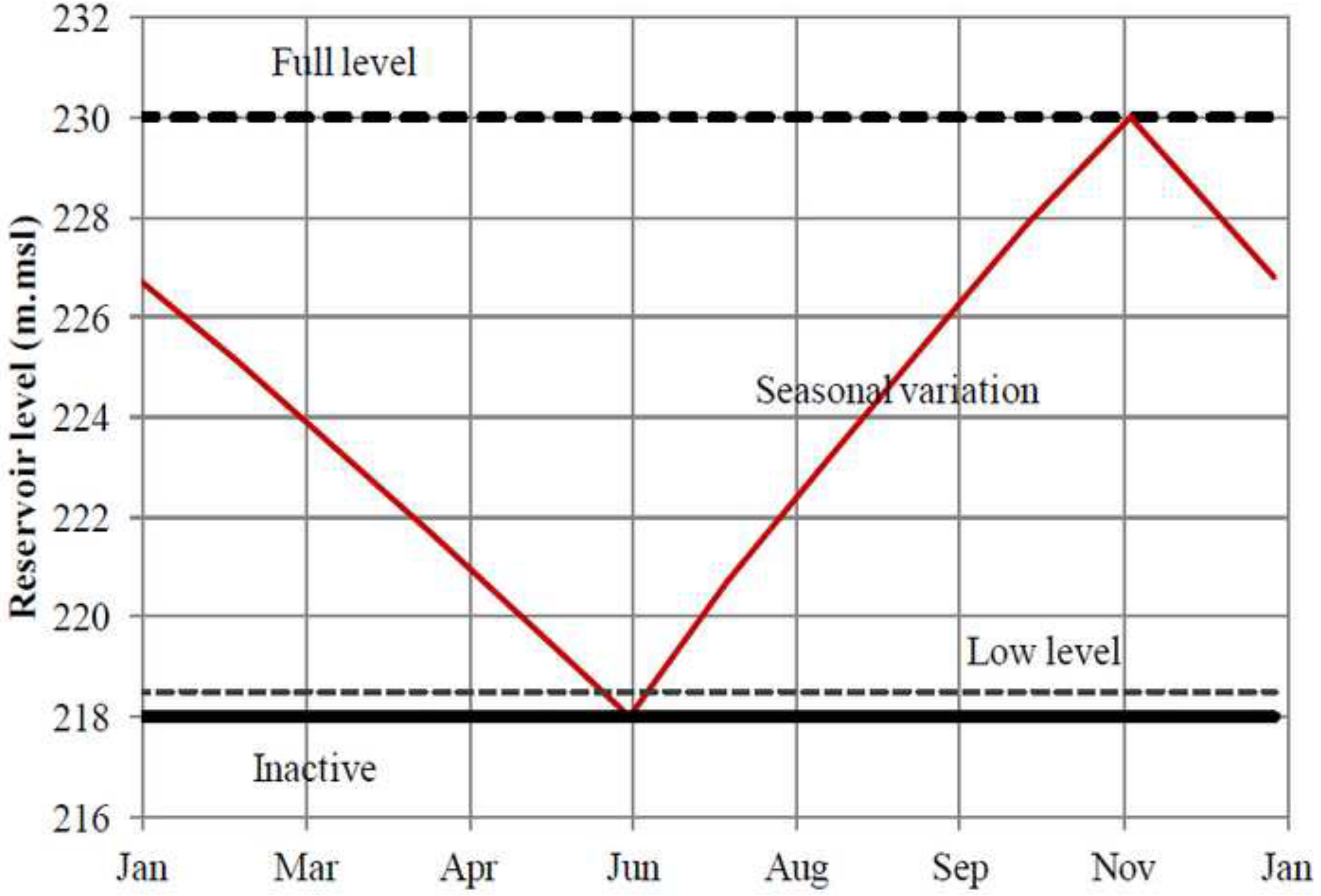

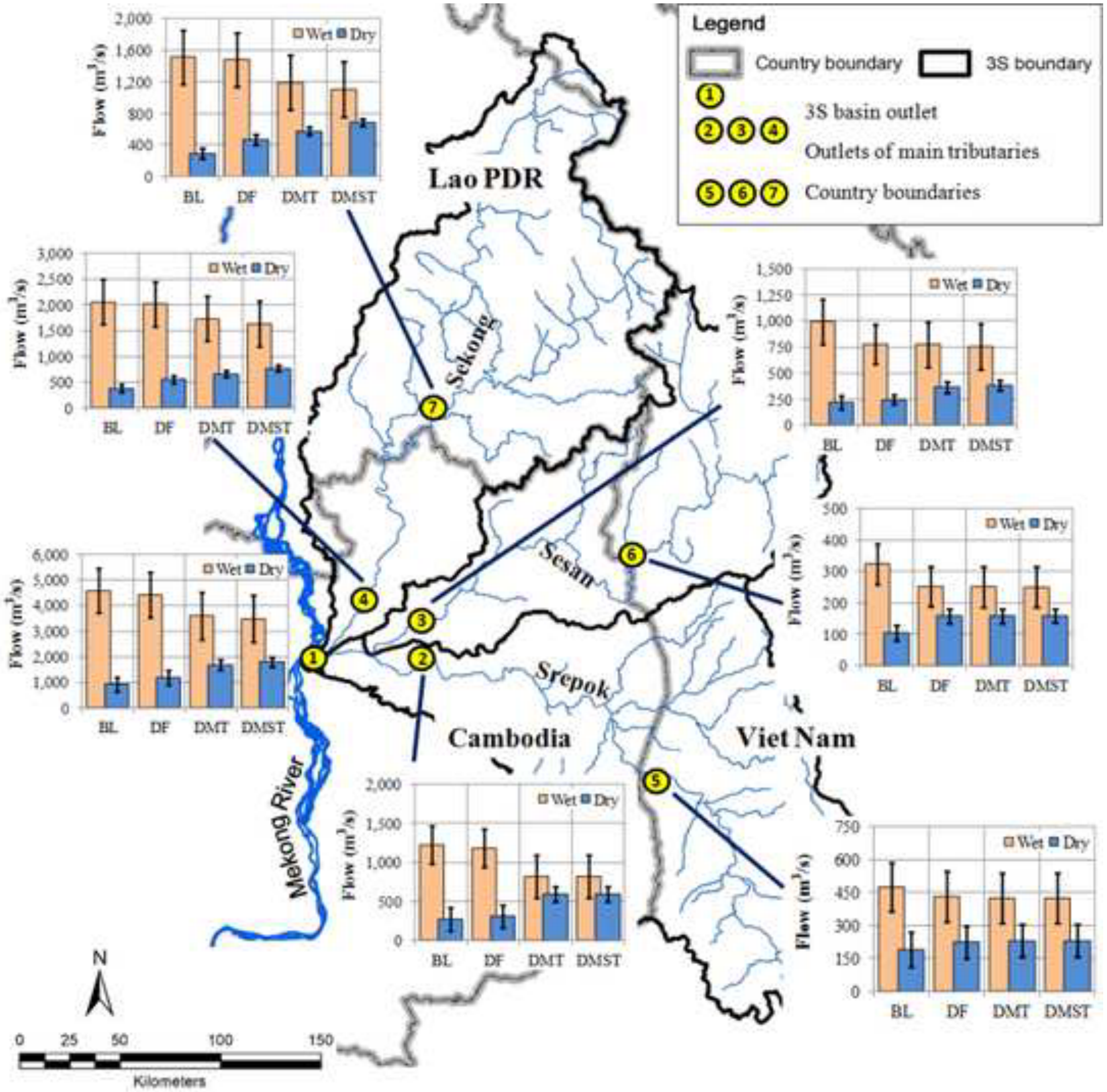
Legend
Country boundary
3S boundary
① 3S basin outlet
②③④ Outlets of main tributaries
⑤⑥⑦ Country boundaries
Lao PDR
Cambodia
Viet Nam
Sekong
Sesan
Srepok
Mekong River
Flow (m³/s)
Wet
Dry
BL
DF
DMT
DMST
N
0
25
50
100
150
Kilometers

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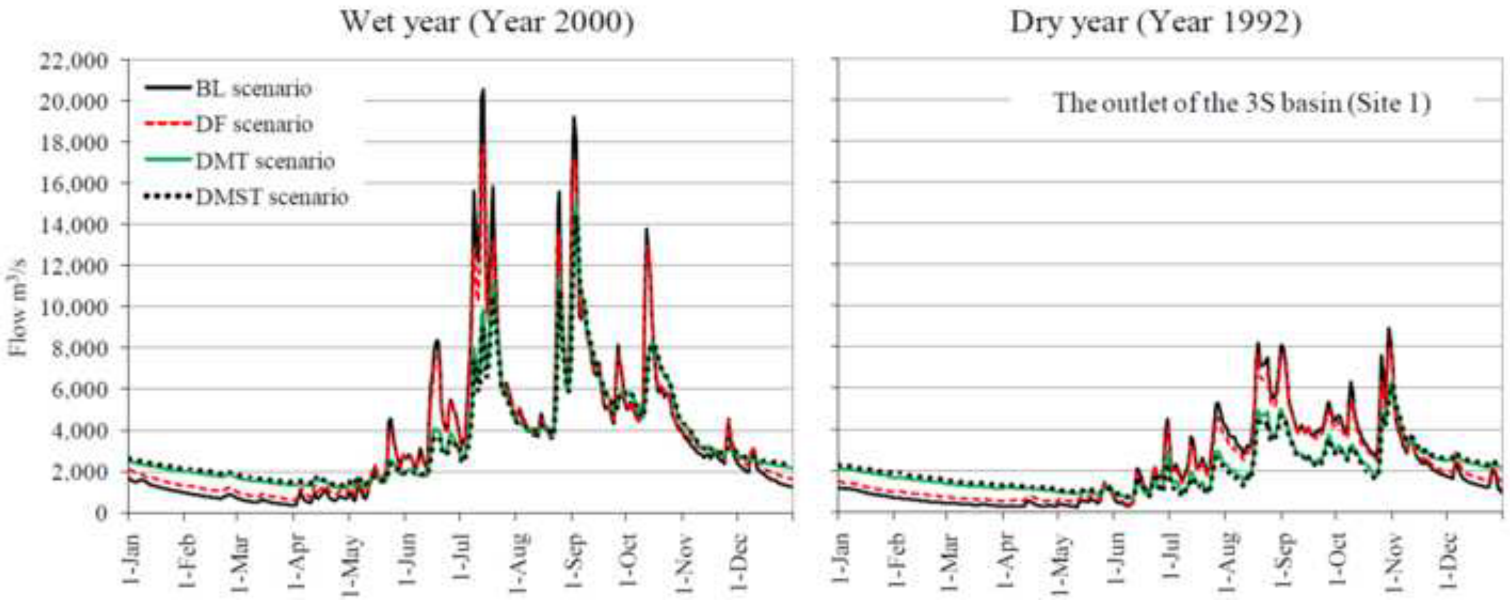

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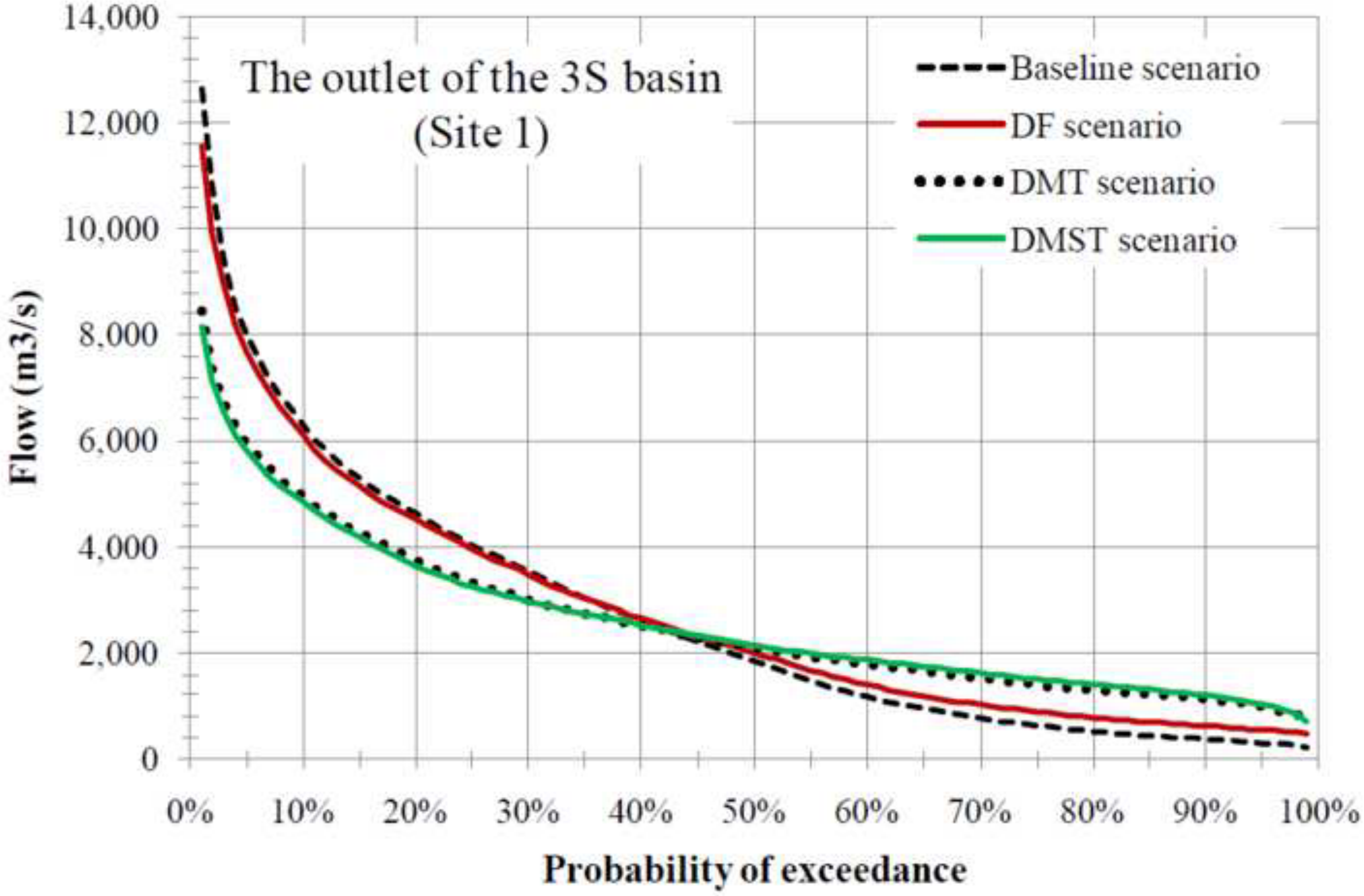

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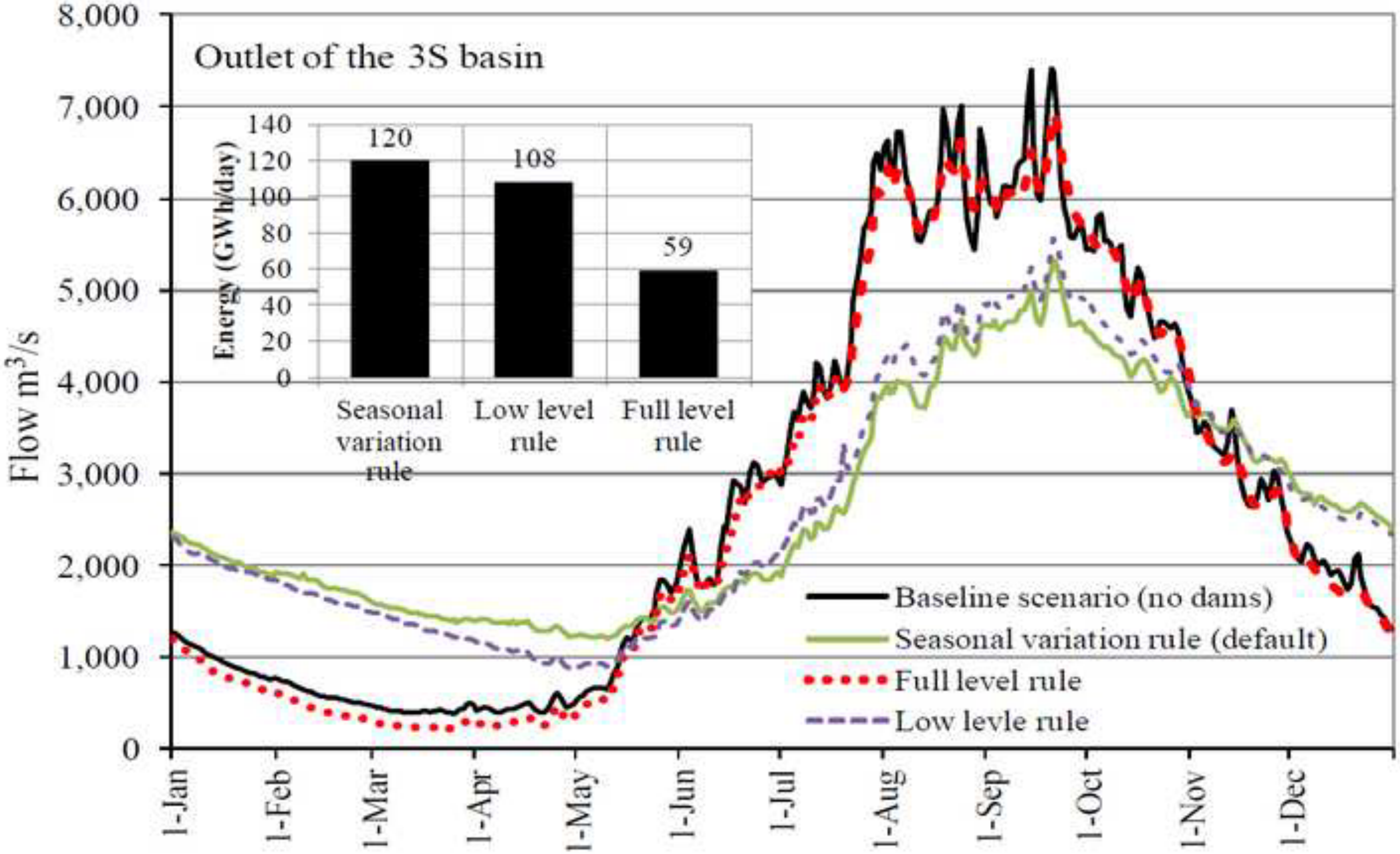

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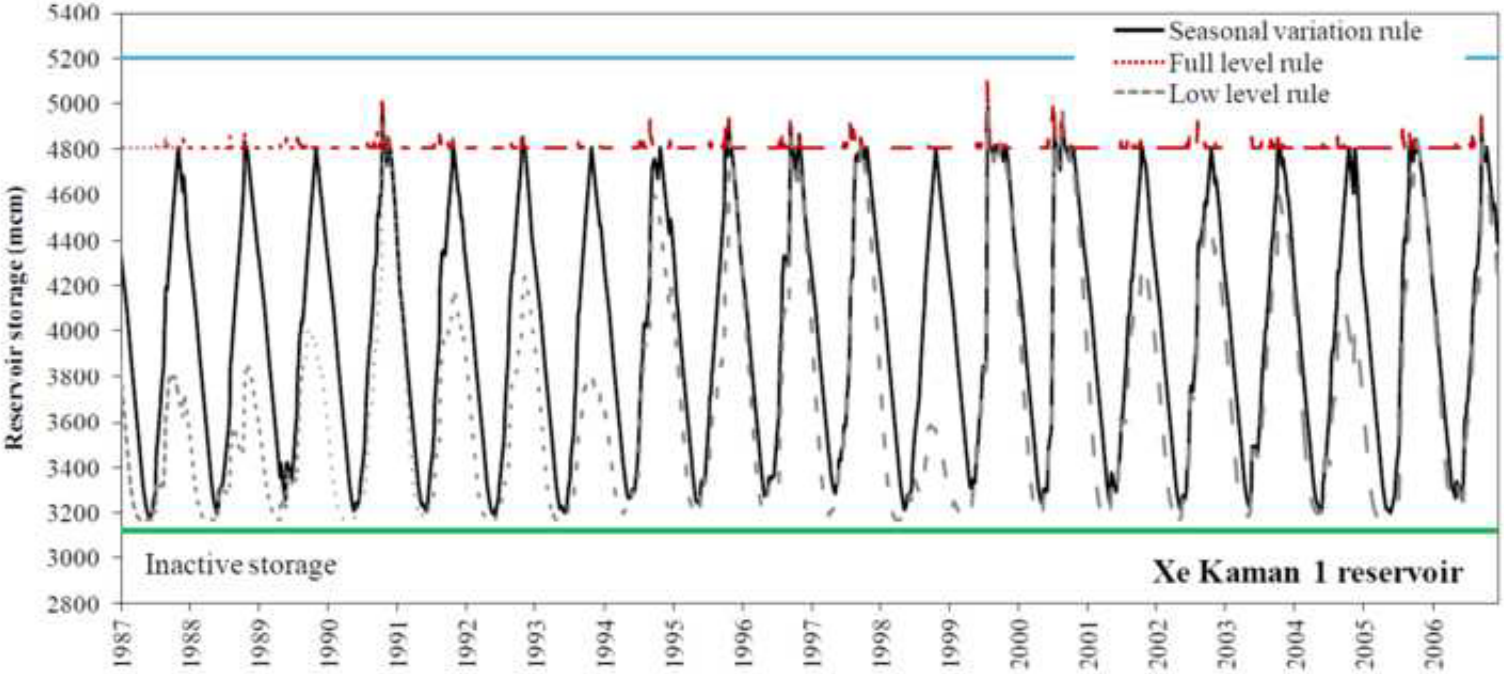

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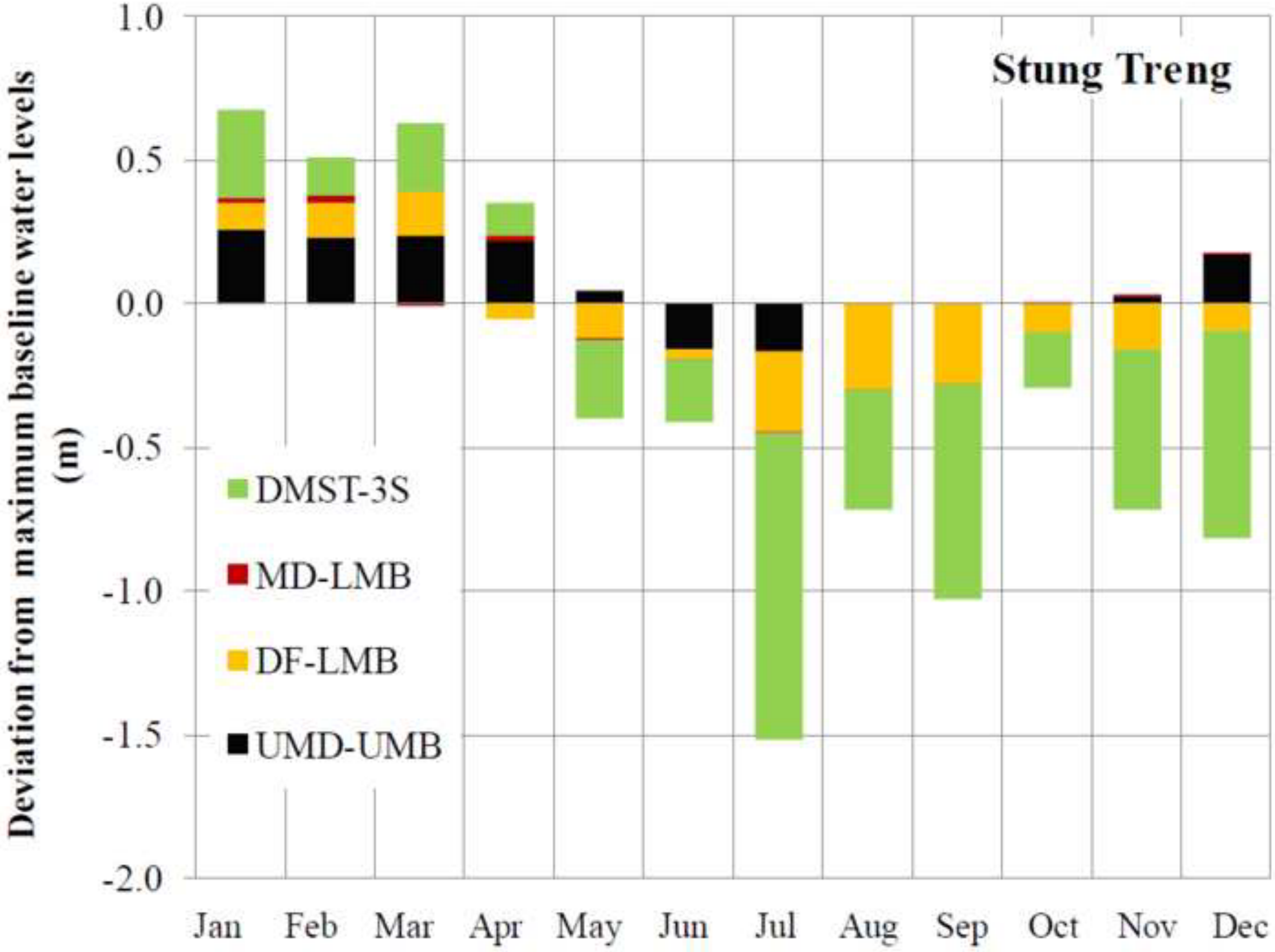

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Table 1. List of current and proposed 3S hydropower dams, their main characteristic, and their inclusion in modeling scenarios.

No.	Name	Status	Catchment area (km^2)	Full supply level (m.msl)	Low supply level (m.msl)	Live storage (mcm)	Designed discharge (m^3/s)	Designed head (m)	Installed capacity (MW)	Mean energy (GWh)	Scenario		
											DF	DMT	DMST
	Lao PDR												
1	Houayho	E	191.7	883.0	860.0	649.0	23.0	748.3	150.0	487.0	X	X	X
2	Xekaman 3	UC	712.0	960.0	925.0	108.5	62.5	477.7	250.0	982.8	X	X	X
3	Xekaman 1	UC	3,580.0	230.0	218.0	1,683.0	336.6	99.0	290.0	1,096.0	X	X	X
4	Xekaman-Sanxay	UC	3,740.0	123.0	122.0	7.1	378.0	12.2	32.0	123.0	X	X	X
5	Xepian-Xenamnoy	UC	522.0	786.5	760.0	885.0	70.0	642.0	390.0	1,748.0	X	X	X
6	Houay Lamphan	UC	140.0	840.0	800.0	128.2	18.5	536.4	60.0	264.4	X	X	X
7	Xe Kong 3up	PMT	5,882.0	160.0	155.0	95.1	460.0	33.7	144.6	598.7		X	X
8	Xe Kong 3d	PMT	9,700.0	117.0	111.0	168.4	568.0	17.2	91.1	375.7		X	X
9	Xekong 4	PMT	5,400.0	290.0	270.0	3,100.0	240.0	140.0	300.0	1,901.0		X	X
10	Xe Kong 5	PMT	2,615.0	500.0	470.0	1,355.5	146.0	188.1	248.0	1,201.0		X	X
11	Dak E Mule	PST	127.0	780.0	756.0	154.0	27.4	433.8	105.0	506.0			X
12	Xe Kaman 2A	PST	1,970.0	280.0	275.0	3.7	155.0	48.6	64.0	241.6			X
13	Xe Kaman 2B	PST	1,740.0	370.0	340.0	216.8	90.0	78.8	100.0	380.5			X
14	Xe Kaman 4A	PST	265.0	860.0	840.0	16.5	26.0	423.6	96.0	375.0			X
15	Xe Kaman 4B	PST	192.0	865.0	850.0	21.2	18.4	459.1	74.0	301.0			X
16	Xe Katam	PST	263.0	910.0	890.0	115.0	16.0	450.0	60.8	380.0			X
17	Xe Nam Noy 5	PST	60.2	800.0	780.0	8.8	3.9	572.3	20.0	124.0			X
18	Xe Xou	PST	1,273.0	180.0	160.0	1,714.0	131.3	51.8	63.4	286.2			X
19	Nam Kong 1	PST	1,250.0	320.0	287.0	505.0	44.5	186.0	75.0	469.0			X
20	Nam Kong 2	PST	860.0	460.0	437.0	139.6	76.5	106.5	74.0	309.5			X
21	Nam Kong 3	PST	650.0	540.0	520.0	298.6	37.6	80.0	25.0	113.0			X
	Cambodia												
22	O Chum 2	E	44.7	254.0	251.5	0.1	3.8	32.6	1.0	3.0	Not modelled (too small)		
23	Lower Se San2 + Lower Sre Pok 2	PMT	49,200.0	75.0	74.0	379.4	2,119.2	26.2	480.0	2,311.8		X	X
24	Lower Se San 3	PMT	15,600.0	150.0	147.0	3,120.0	500.0	58.5	243.0	1,977.0		X	X
25	Lower Sre Pok 3	PMT	26,200.0	125.0	118.0	5,310.0	775.0	31.5	204.0	1,101.6		X	X
26	Lower Sre Pok 4	PMT	13,00	190.0	185.0	2,700.0	327.0	52.2	143.0	772.2		X	X
27	Prek Liang 1	PST	883.0	330.0	310.0	110.0	27.2	153.0	35.0	189.0			X
28	Prek Liang 2	PST	595.0	515.0	496.0	180.0	17.7	168.0	25.0	186.4			X
	Viet Nam												
29	Plei Krong	E	3,216.0	570.0	537.0	948.0	367.6	31.0	100.0	417.2	X	X	X
30	Yali	E	7,455.0	515.0	490.0	779.0	424.0	190.0	720.0	3,658.6	X	X	X
31	Se San 3	E	7,788.0	304.5	303.2	3.8	486.0	60.5	260.0	1,224.6	X	X	X
32	Se San 3A	E	8,084.0	239.0	238.5	4.0	500.0	21.5	96.0	475.0	X	X	X
33	Dray Hlinh 1	E	8,880.0	302.0	299.0	1.5	94.9	15.0	12.0	94.0	X	X	X
34	Dray Hlinh 2	E	8,880.0	302.0	299.0	1.5	101.0	18.5	16.0	85.0	X	X	X
35	Se San 4A	E	9,368.0	155.2	150.0	7.5	Reregulating dam (no power plant installed)				X	X	X
36	Se San 4	UC	9,326.0	215.0	210.0	264.2	719.0	56.0	360.0	1,420.1	X	X	X
37	Upper Kontum	UC	350.0	1,170.0	1,146.0	122.7	30.5	904.1	250.0	1,056.4	X	X	X
38	Buon Tua Srah	UC	2,930.0	487.5	465.0	522.6	204.9	46.5	86.0	358.6	X	X	X
39	Buon Kuop	UC	7,980.0	412.0	409.0	14.7	316.0	98.5	280.0	1,455.2	X	X	X
40	Sre Pok 3	UC	9,410.0	272.0	268.0	62.6	412.8	60.0	220.0	1,060.2	X	X	X
41	Sre Pok 4	UC	9,568.0	207.0	204.0	10.1	468.9	17.1	70.0	329.3	X	X	X
42	Duc Xuyen	PMT	1,100.0	560.0	551.0	413.4	81.0	71.0	49.0	181.3		X	X

Note: E =Exisitng, UC = Under construction, PMT = Proposed on main tributaries, and PST = Proposed on sub tributaries

Table 2. Level of hydropower development in the 3S Basin for each country and simulation scenario.

Level of development		**Scenario**		
		DF	**DMT**	**DMST**
Number of projects	L	6	10	21
	C	0	4	6
	V	13	14	14
	Total	**19**	**28**	**41**
Installed capacity (MW)	L	1,172	1,956	2,713
	C	0	1,071	1,131
	V	2,470	2,519	2,519
	Total	**3,642**	**5,546**	**6,363**
Mean energy (GWh)	L	4,701	8,778	12,263
	C	0	6,166	6,541
	V	11,634	11,815	11,815
	Total	**16,335**	**26,759**	**30,620**
Avtive storage $(10^6\ m^3)$	L	3,461	8,180	11,373
	C	0	11,510	11,800
	V	2,742	3,156	3,156
	Total	**6,203**	**22,845**	**26,328**

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

Table 3. Seven -day mean annual low and high flows for development scenarios and statistical T-test comparisons.

Site	**Location**	**Flow**	**7-day mean annual (m^3/s)**				**T-Test value**		
			BL	**DF**	**DMT**	**DMST**	**DF-BL**	**DMT-BL**	**DMST-BL**
1	3S basin outlet	Low	296	541	936	1,002	*< 0.05*	*< 0.05*	*< 0.05*
		High	11,386	10,373	7,908	7,613	0.15	*< 0.05*	*< 0.05*
2	Srepok outlet	Low	83	124	259	258	*< 0.05*	*< 0.05*	*< 0.05*
		High	3,379	3,120	2,005	2,006	0.25	*< 0.05*	*< 0.05*
3	Sesan outlet	Low	68	90	151	162	*< 0.05*	*< 0.05*	*< 0.05*
		High	2,490	1,960	1,836	1,771	*< 0.05*	*< 0.05*	*< 0.05*
4	Sekong outlet	Low	102	249	388	447	*< 0.05*	*< 0.05*	*< 0.05*
		High	5,862	5,254	4,643	4,342	0.19	*< 0.05*	*< 0.05*
5	Cambodia-Viet Nam boundary, Srepok	Low	68	93	94	94	*< 0.05*	*< 0.05*	*< 0.05*
		High	1,264	1,145	1,136	1,136	0.19	0.17	0.17
6	Cambodia-Viet Nam boundary, Sesan	Low	39	54	54	54	*< 0.05*	*< 0.05*	*< 0.05*
		High	824	456	456	456	*< 0.05*	*< 0.05*	*< 0.05*
7	Cambodia-Lao PDR boundary, Sekong	Low	85	213	332	340	*< 0.05*	*< 0.05*	*< 0.05*
		High	4,567	3,978	3,415	3,134	0.16	*< 0.05*	*< 0.05*

Note: If the T-Test value is less than or equal 0.05, means of comparative scenarios are significantly different.