Integrated modeling to assess flow changes due to future dam development and operation in Stung Sen River of Tonle Sap Lake Basin, Cambodia

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ABSTRACT

In response to rapid development and high demand for electricity, Cambodia has planned to build more hydropower dams. As a result, there are significant concerns for the changes in seasonal flow regimes which will result in degrading fisheries and biodiversity downstream. In this paper, we assess how a multipurpose dam affects downstream flows. To predict the magnitude of flow changes, flows which were simulated using SWAT (Soil and Water Assessment Tool) and other necessary data were computed into HEC-ResSim (Reservoir Simulation) models to simulate regulated flow from the dam. Downstream flows under three different operation scenarios (full-level, low-level, and seasonal variation) were modeled to compare with the baseline flows. For low-level and seasonal variation operation scenarios of Stung Sen dam, daily and seasonal flows saw a significant change. There would be an average increase of 42% in dry season flow and an average decrease of 46% in wet season flow, with the corresponding standard deviation of 22% and 19%, respectively, at the outlet of Stung Sen Basin, resulting from an operation to maximize energy production.
The natural river flow in this river would be significantly changed due to this dam construction.

Key words | dam development, flow change, HEC-ResSim, integrated modeling, SWAT, Tonle Sap Basin

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INTRODUCTION

Investments in water resources infrastructure, especially hydropower dams have been essential for economic development by generating electricity. However, when they are improperly planned, designed, or operated, they can cause problems for downstream ecosystems and communities because of their impact on the volume, pattern, and quality of flow. For thousands of years, dams have been used to store water to ensure adequate water supply during dry periods and to regulate river flows (McCartney *et al.* 2000). More recently, they have been used to impound water in order to provide sources of energy, first by the use of waterwheels, and later by using hydro turbines (Gatte & Kadhim 2012). Currently, dams act as an alternative to non-renewable energy resources which produce the majority of the world's electricity. Dams also play a significant role in reducing the risk of natural disasters such as floods and droughts. Despite the social and economic benefits, dams also have negative impacts as they interfere with the ecological system (McCartney *et al.* 2000). Dams block fish migration routes and alter aquatic habitats both upstream and downstream which lead to the potential loss of fisheries (Barlow *et al.* 2008). Dams have major impacts on river hydrology, primarily through changes in the timing, magnitude, and frequency of low and high flows, producing a hydrologic regime differing significantly from the pre-impoundment natural flow regime (Magilligan & Nislow 2005). Dammed rivers reduce flood magnitude, and this has negative consequences on the floodplains downstream that depend on seasonal

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waters for survival (Lin 2011). Dams are built to modify the timing and distribution of water. Flow variation should be guaranteed by flow regulation.

The acceleration in plans for hydropower development in the Mekong mainstem and its major tributaries has led to growing concerns over the potential environmental, economic, and social costs, and the basin's fisheries (Dugan *et al.* 2010). A recent study by Intralawan *et al.* (2017) suggests that the net economic impact of planned hydropower projects on the Mekong River and its tributaries is negative based on updated data for project economics, fisheries, and social and environmental mitigation costs. Regarding the development of hydropower dams in Cambodia, there are about 60 possible sites of small to large hydropower projects in the whole country which have the total potential of around 10,000 MW; 50% is in the Mekong main river, 40% in its tributaries, and the remaining 10% in the south-western coastal area outside the Mekong River Basin (CNMC 2003). The proposed Stung Sen dam is a medium-scale dam with a capacity of 40 MW. This dam is to be constructed on the Stung Sen River which is a major tributary of the Tonle Sap Lake Basin. The change of flow regime from the dam will influence the wildlife sanctuary and wetlands which are the habitats for numerous key species. The presence of this dam will affect the people, hydrology, ecology system, and aquatic lives both upstream and downstream. Thus, it is very important to study the variation of flow after the dam construction to predict potential socio-economic and environmental impacts which could then be used to minimize these impacts.

Several studies have been done to investigate flow changes due to dam development and operation by integrating hydrological and reservoir modeling. For example, Cochrane *et al.* (2010) applied HEC-HMS (Hydrological Modeling System) with HEC-ResSim (Reservoir Simulation) to assess potential impact of dam development and operations on water flows from Se San and Sre Pok tributaries. Piman *et al.* (2012) used SWAT and HEC-ResSim to assess flow change from hydropower development and operations in Sekong, Sesan, and Srepok rivers under various scenarios.

In this study, we use SWAT and HEC-ResSim model to predict the changes of flows in the downstream part of Stung Sen River due to dam development by applying three different operation rules. These three different rules limit the target water level for the reservoir and are known as (1) seasonal variation, (2) full-level, and (3) low-level.

STUDY SITE

Stung Sen River was chosen for this study because it is a major tributary and key contributor to the Tonle Sap Lake. The floodplain of this river extends along the lower reaches between about 50 and 230 km upstream from Lake Tonle Sap (NAGUMO *et al.* 2015). Monsoonal rains cause regular seasonal floods on the floodplain of the basin (Nagumo *et al.* 2013). The change of flow regime caused by dam operation would affect the wildlife sanctuary and wetland habitats which many key species depend upon.

The Stung Sen River source is located in the mountainous Cambodia–Thailand border in Preah Vihear province at the elevation of approximately 790 m. It flows through Kampong Thom Province to Lake Tonle Sap with a total length of 508 km and the average slope of the river is around 1%. In the lower reaches, the 7 m deep meandering river channel has a rectangular cross section and a very small gradient of 0.06/1,000 (Nagumo *et al.* 2013). The mean flow of Stung Sen River is 249 m^3/s with the standard deviation of 320 m^3/s (Oeurng *et al.* 2019). Despite the small headwaters, the abundant water resource from this river provides significant hydropower potential.

The water in this river comes from Stung Sen Basin which is the largest sub-catchment among 11 sub-basins around Tonle Sap Lake. Based on the data from the Ministry of Water Resources and Meteorology, the total catchment area of Stung Sen River Basin is 16,344 km^2. However, the actual drainage area in this study, which was delineated by SWAT model, covers only 14,138 km^2 and the drainage area of the reservoir is 10,437 km^2 (Figure 1). The basin encompasses 487 villages with a total population of 318,705 in 1998 and 359,084 in 2003, and the total agricultural land of the basin is 165,420 ha (ADB 2006).

The climate in Stung Sen Basin is dominated by tropical monsoon with two distinct seasons. The wet season is from May to October and the dry season from November to April. The average annual rainfall is around 1,500 mm. The

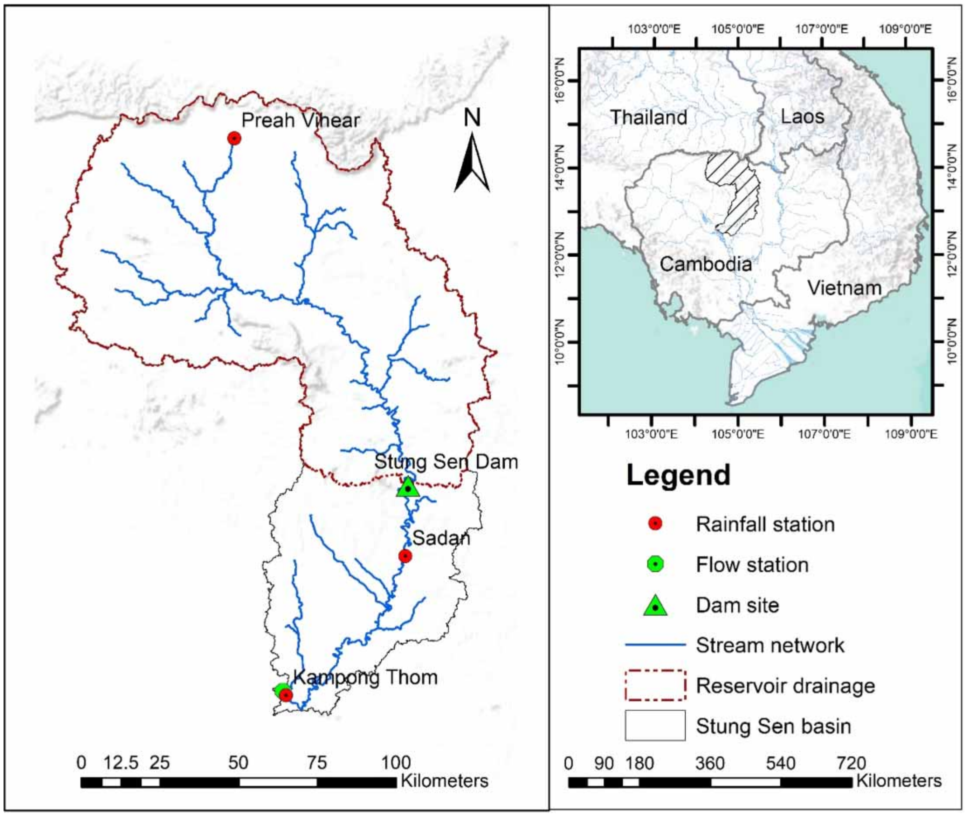

Figure 1 | Location map of Stung Sen Basin, Cambodia.

average temperature is about 27.5 °C with the maximum and minimum temperatures of 35° and 20 °C, respectively (ADB 2009).

METHODOLOGY

The changes of downstream flows due to hydropower development and operation in Stung Sen River can be obtained by using simulated daily flows from the SWAT and the HEC-ResSim model. The 31 years outflow data (1985 to 2015) from SWAT at various points within the watershed along the Stung Sen main river and its tributaries, dam and reservoir characteristics, and evaporation were computed into the HEC-ResSim model to simulate regulated flows for three different operation rules. The changes of seasonal flow patterns from each operation rule at the outlet of the basin were compared with baseline flow where there is no hydropower project.

Input data source

Data used for hydrological modeling in SWAT include a topography digital elevation model (DEM), land use, soil type, observed streamflow, and weather data such as temperature, wind speed, humidity, and solar radiation. In this study, a DEM of 30-m resolution was extracted from the ASTER global digital elevation model (ASTER GDEM2) and was used to describe the topography of the study area. Soil type and land use data were obtained from the Mekong River Commission (MRC). Rainfall data were obtained from three stations distributed in the basins and measured flow was obtained from a flow monitoring station. Rainfall and flow data are available from 1985 to 2015 and from 2002 to 2011, respectively. Temperature, wind speed, humidity, and solar radiation data at a spatial resolution of 0.25° were extracted from global weather data for SWAT.

The physical characteristics of Stung Sen hydropower dam (dam height, length, width, installed capacity, discharge, spillway capacity, and tailwater levels) shown in Table 1 were obtained from the MRC. Relationships between storage, area, and elevation of the reservoir, shown in Figure 2, were calculated from 30-m DEM using spatial analyst tools in ArcGIS. The area of the reservoir is important for calculating water losses due to evaporation. Storage and elevation relationships for the reservoir were used to determine the variation of water level in the reservoir caused by inlet and the regulated flow from the reservoir.

Table 1 | Stung Sen dam physical characteristics

Parameter	Values
Coordinate N – Northing	13.3°
Coordinate E – Easting	105.25°
Dam length	2,700 m
Dam height	38 m
Capacity	40 MW
Head	19 m
Plant design Q	145 m^3/s
Full mamsl	43.5 mamsl
Tailwater level	24.5 m
Low mamsl	35 mamsl
Live storage	2,890 mcm

mamsl: meters above mean sea level.

Hydrologic and reservoir modeling

SWAT model

In this study, the SWAT model was used to simulate streamflow in Stung Sen River. This model is one of the widely used hydrologic models, which has been applied in different regions for solving a wide range of hydrological problems, especially potential changes to streamflow under various management scenarios. More than 1,000 peer-reviewed articles related to the use of the SWAT have been published (Gassman *et al.* 2010). SWAT was developed by the United States Department of Agriculture, Agricultural Research Service (USDA-ARS) during the early 1990s (Arnold *et al.* 1998). It is a semi-physically based model designed to simulate the impact of land management practices on the environmental–hydrological system in a watershed over long periods and allows a number of different physical processes to be simulated in a watershed, including water movement, sediment movement, crop growth, and nutrient cycling (Neitsch *et al.* 2011). SWAT separates watershed hydrology in two phases: land phase and routing phase. The land phase is composed of the watershed land areas that simulate the water transported to the channels together with sediment, nutrients, and pesticides. The routing phase comprises the behavior of the water in the channels from tributaries

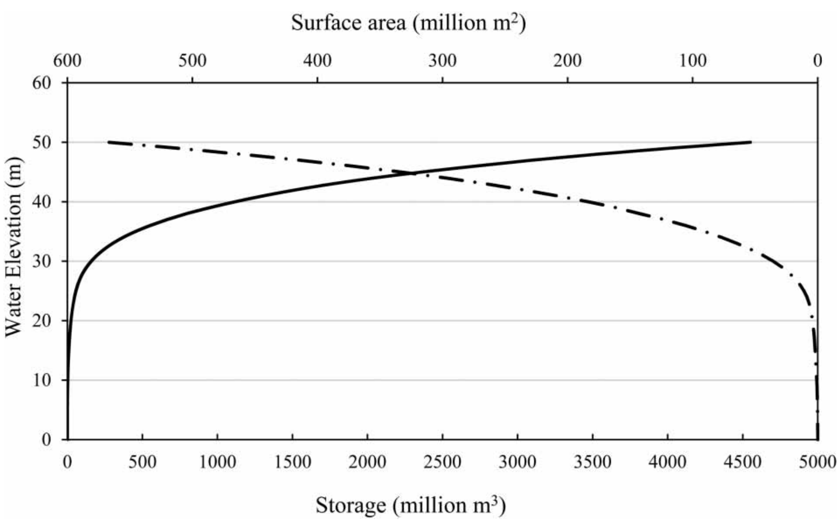

Figure 2 | Elevation–volume–area curve of Stung Sen dam reservoir.

to the watershed outlet. According to Glavan & Pintar (2012), the main weakness of the model in simulating streamflow is a non-spatial representation of the hydrologic response unit (HRU) inside each sub-catchment.

Within this study, the SWAT model was set up and run for streamflow simulation in Stung Sen River Basin from 1985 to 2015. This model was selected as it was constructed by a combination of many sub-models. Once the model is set up, it is not only able to simulate the streamflow, but also the other pesticide load in the studied river like sediment, phosphorus, and nitrate load which might be useful for further research concerning the assessment of water quality.

Sensitivity analysis, calibration, and validation

The output from the uncalibrated hydrological model is commonly poor due to the assumption of the initial value of parameters used. Thus, the process of sensitivity analysis, calibration, and validation must be conducted in order to evaluate the applicability of the model for the intended purpose (White & Chaubey 2005).

The first step in the calibration and validation processes in SWAT is the determination of the most sensitive parameters for a given watershed, either by expert judgment or sensitivity analysis (Arnold *et al.* 2012). In this study, sensitivity analysis was performed by using SWAT Calibration and Uncertainty Programs (SWAT-CUP) with sequential uncertainty fitting method (SUFI-2).

After identifying the most sensitive parameters to simulate flow, the calibration was then conducted to define the optimum value of these parameters. This is a process in which parameter adjustments are made so as to match the dynamic behavior of the rainfall–runoff model to the observed behavior of the catchment (Gupta *et al.* 2006). SWAT-CUP was used to automatically adjust the parameters for the SWAT model.

Finally, the calibrated model needs to be validated to ensure its applicability in predicting streamflow for another time period without making a further adjustment of parameters. In this study, the model was calibrated and validated using the available observed discharge from 2004 to 2011.

HEC-ResSim model

Results of flow simulation from SWAT were then used as the inputs to the HEC-ResSim model for reservoir simulation. The HEC-ResSim model, which was developed by the U.S. Army Corps of Engineers, is employed for water resources allocation and reservoir operations at one or more reservoirs for a variety of operational goals and constraints (Klipsch & Hurst 2013). The model consists of three sets of functions called modules: watershed setup, reservoir network, and simulation (Klipsch & Hurst 2013). These modules provide access to specific types of data within a watershed. The watershed setup module allows the creation of watershed which represents the study area. The reservoir module is used for inputting the physical and operational data of the reservoir. It is also used for editing element data and placing additional elements onto stream alignment. Finally, the simulation module is used to perform model simulation and view the results.

The HEC-ResSim model is capable of simulating reservoir operations for flood management, low flow regulation and hydropower production, detailed reservoir regulation plan investigations, and real-time decision support. Providing these special capabilities, this model is selected for this study to investigate the effect of hydropower reservoir under three operation rules which will be described in the following section.

Operation rules

The three operation rules (Figure 3) that were modeled to define the target water level for different purposes are explained based on Piman *et al.* (2012).

Seasonal variation rule (to maximize energy production): The rule fluctuates the target water level in the reservoir seasonally to maximize energy production. Another purpose of this operation rule is to minimize the risk of abundance spillage due to the reservoir being full before the end of the wet season and avoid running the reservoir dry before the end of the dry season. The water release decision of this operation is subject to the reservoir target level and the physical plant release capacities related

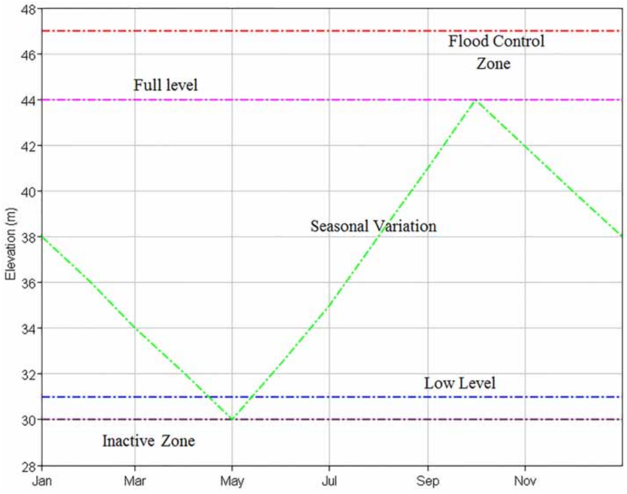

Figure 3 | Annual operation rules for Stung Sen dam.

to the reservoir levels. In the event that the water levels in the reservoir are lower than target levels, the dam operator will reduce or stop flows through the turbines to raise water levels in the reservoir.

Full-level rule (to conserve ecological flows): A full-level rule keeps the reservoir at the maximum active storage level throughout the year. The dam operator will reduce or stop releasing flow through the turbines if the water level in the reservoir is beneath the full level. At the point when the dam is full, it will be operated like a run-of-the-river dam where water outflows are close to inflows. The rule keeps the reservoir full and creates a similar outflow to the natural condition. This is comparable to a more sensitive environmental management of dams.

Low-level rule (to mitigate flood): Under this operation rule, the dam operator tries to keep the water levels in the reservoir below the target level throughout the year. To reserve water storage space for potential flood flows, water is released through the turbines as much as possible. As the water level is low, the release depends mainly on the power plant release capacity.

Simulated flows based on these operation rules were compared with baseline flow or natural flow, which is the flow that occurs without effect from hydraulic structures. The natural flow in this study was estimated by flow simulation using the SWAT model.

RESULTS AND DISCUSSION

Flow simulation

The identified sensitive parameters presented in Table 2 were calibrated using SWAT-CUP for a period of five years (2004 to 2008). The model was then validated based on observed data from 2009 to 2011. Before being used as inputs to the HEC-ResSim model, the results of simulated flow from SWAT were evaluated using three statistical indicators: Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), and the ratio of the root mean square error to the standard deviation of observed data (RSR). The predictive accuracy was judged as satisfactory in cases NSE >0.50, PBIAS $\pm 25\%$, and RSR ≤ 0.70 (Moriasi *et al.* 2007).

Table 3 shows the value of statistical indicators which were summarized for both the calibration and the validation period. Based on the model evaluation criteria recommended by Moriasi *et al.* (2007), calibration performance was rated as satisfactory. Figure 4 presents the time-series plot of measured and simulated daily streamflow at the basin outlet (flow gauge) from 2004 to 2011. In

Table 2 | The most sensitive parameters identified in the SWAT model (ranking from top to bottom)

Parameter	Description	Range Min	Range Max	Final fitted value
Cn2.mgt	Moisture condition II curve number	−25%	25%	−2.00%
Esco.hur	Soil evaporation compensation factor	0	1	0.12
Ch_N2.rte	Manning's value for the main channel	0	0.3	0.05
Sol_Awc.sol	Available water capacity of the soil layer	−25%	25%	−20.70%
Alpha_Bf.gw	Baseflow alpha factor	0	1	0.30
GW_Revap.gw	Groundwater evapotranspiration coefficient	0.02	0.2	0.03
Surlag.bsn	Surface runoff lag coefficient	0	24	4.11
Ch_K2.rte	Effective hydraulic conductivity of the main channel	0	500	164.52
GW_Delay.gw	Ground delay (days)	0	500	49.08

Table 3 | Statistical evaluation of the model

Statistical indicator	Calibration (2004–2008)	Validation (2009–2011)
NSE	0.70	0.68
PBIAS	5.01%	−18.83%
RSR	0.55	0.61

general, both observed and predicted hydrographs had a similar trend. The model seemed to capture the time to peak quite well in both periods, calibration and validation. However, it failed to simulate the accurate peak flows. The SWAT model tended to overestimate peak flows in some years during the calibration period and all years during the validation period. This was more evident at the end of the rainy season (October–November). These overestimates may be caused by the high monthly rainfall in those years. The parameters used in this model were calibrated to match simulated discharge with the observed data in the years with low monthly rainfall. However, it was observed that rainfall that occurred in some months during the validation period was very high (close to 400 mm). The difference between rainfall pattern between these two periods could cause the model to capture the peak flow incorrectly, especially in a flood year. It is also possible that the observed flow is not well measured during the flood period. The observed streamflow data might contain errors in the case that flow was observed before or after the time when peak flow occurred due to storm events.

Figures 5 and 6 present the daily and monthly hydrograph that were extracted from the SWAT model at both the proposed dam site and basin outlet for the whole simulation period (1985–2015).

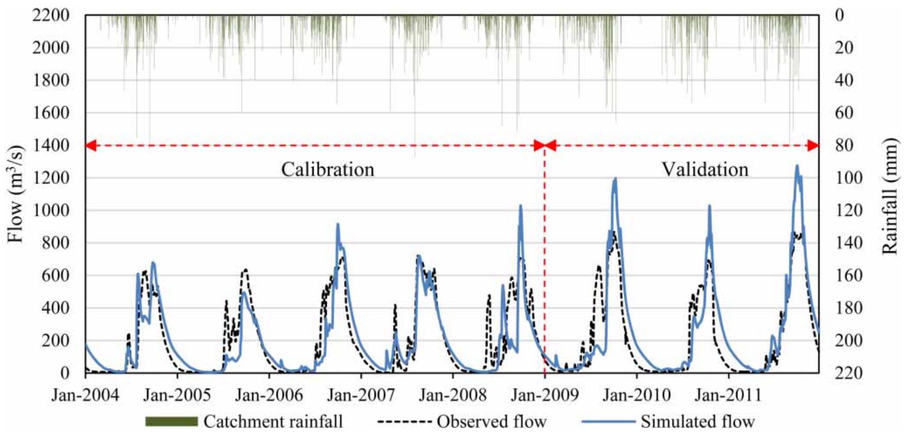

Figure 4 | Comparison of simulated and observed daily hydrograph at the outlet for both calibration and validation periods.

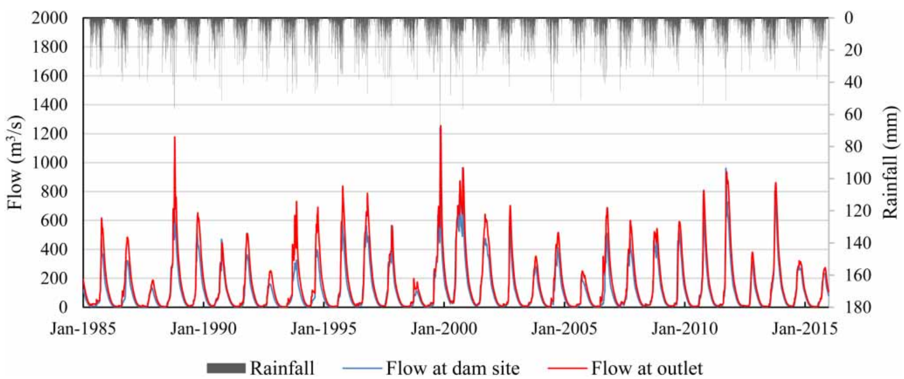

Figure 5 | Simulated daily hydrograph at both the outlet and proposed dam site (1985–2015).

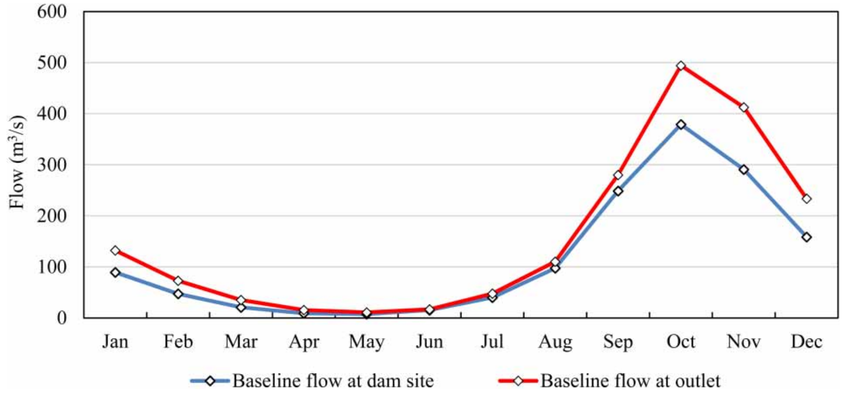

Figure 6 | Average simulated monthly hydrograph at both outlet and proposed dam site.

The average monthly flows at the dam site and outlet of Stung Sen Basin range from around 8 m^3/s and 11 m^3/s in May to 380 m^3/s and 495 m^3/s in October, respectively. The monthly flows at the basin outlet are normally higher than that at the dam site. However, the flow magnitudes are highly different in some months in the rainy season. This is because of the flow contributions from the sub-catchments downstream of the dam site which made the flow at the basin outlet higher. According to simulated daily flows between 1985 and 2015 (Figure 5), flow rate at the basin outlet increased up to around 1,200 m^3/s in 1988 and 1999 due to heavy rainfall which occurred for many consecutive days. Other large flood years were in 2000 and 2011 where the peak flows were more than 900 m^3/s. For the comparison between flow at the dam site and basin outlet, it was noticed that flows at the dam site are slightly larger than flows at the outlet in some periods which was probably because of the effect of flow routing. Streamflow depends mainly on rainfall data and in this basin there are three rain gauges. While there was continuous rain at the upstream station and no rain at the downstream, the discharge at the dam site would be larger than that at the outlet.

Assessment of flow changes

The results of regulated flows under three different operation rules from the HEC-ResSim model at the outlet of Stung Sen Basin, shown in Figure 7, are discussed in this section.

A comparison of flow duration curves under the influence of different operation rules at the outlet of the Stung Sen Basin is illustrated in Figure 8. These curves show the percentage of time that the streamflow is likely to equal or exceed a flow value of interest and they are commonly used for studying flow characteristics of a stream, structure design, and determining flow recommendations for fish and aquatic ecosystem health. The curves were derived from simulated daily flows over a 30-year period (1985–2015). It can be seen that the flow duration curve of the baseline condition is similar to that of the full-level rule while the flow duration curve of the low-level rule is close to that of the seasonal variation rule. At a low exceedance probability (extreme events), the baseline condition has the highest flow magnitude followed by full-level, seasonal variation, and low-level. For instance, at the probability of 10%, flow under the baseline and full-level rule is 470 m^3/s and 441 m^3/s, respectively, while under the low-level and seasonal variation rule, flow is about 300 m^3/s. At high exceedance probability, the full-level rule flow has the smallest value followed by baseline condition, seasonal variation, and low-level rule.

The graph shown in Figure 9 represents the average daily flows of 31 years at the outlet of Stung Sen Basin. It can be clearly seen that the average regulated flows of each operation rule are highly different. The lowest flow rate is under the full-level rule which is under 10 m^3/s from the middle of April until late March. This could lead to water deficit. The highest flow rate is under natural flow condition, up to around 550 m^3/s in October. In the dry season, flows under the seasonal variation rule are similar to that of the low-level rule whereas flows under the full-level rule resemble the natural flows. In the rainy season, the flows under each operation rule saw a significant difference. If the dam is operated under the full-level rule, flows at

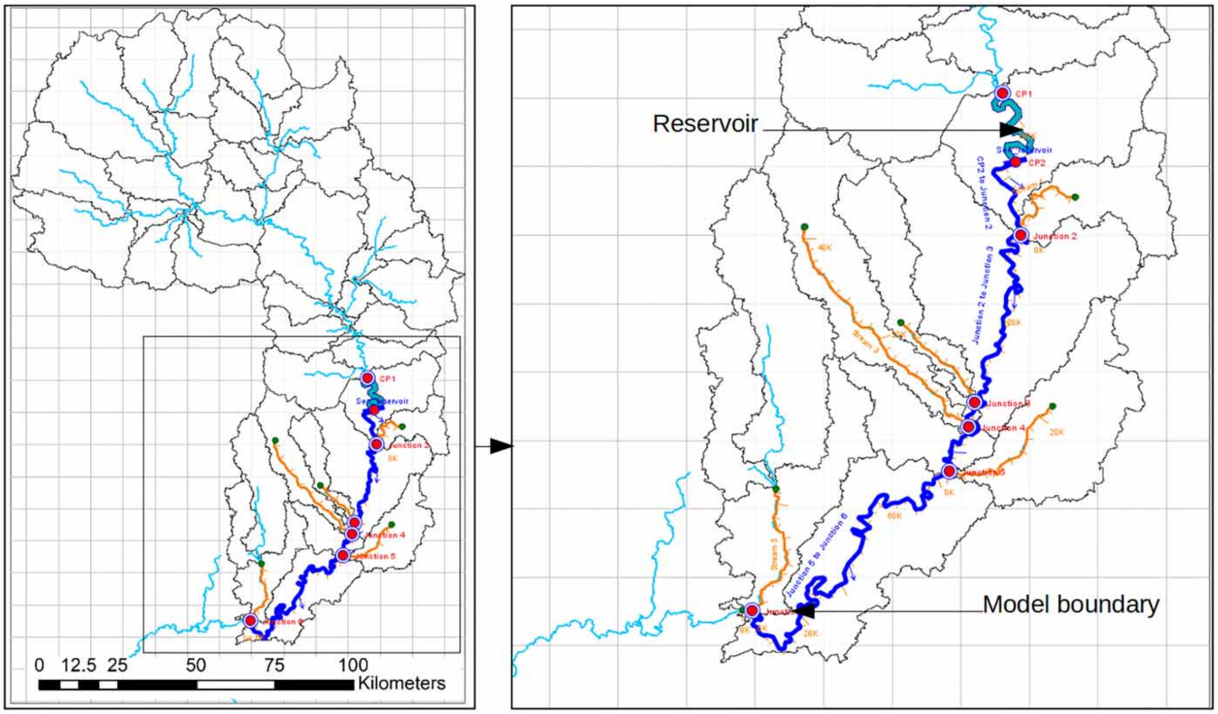

Figure 7 | Schematic of Stung Sen reservoir and outlet.

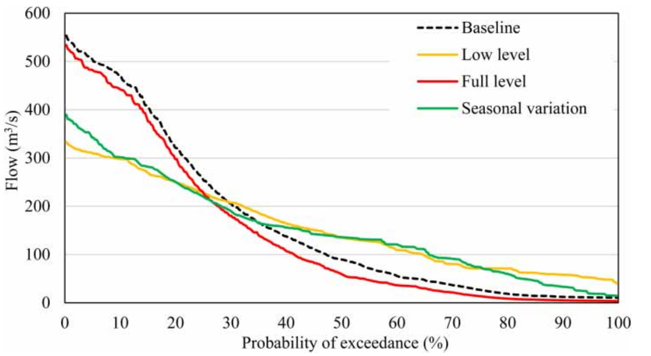

Figure 8 | Flow duration curves at the outlet of Stung Sen Basin under different operation rules.

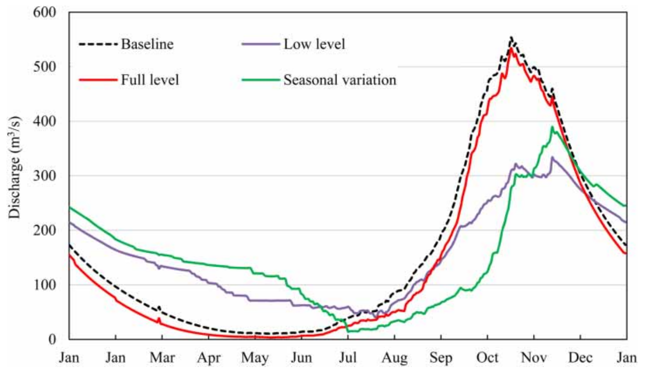

Figure 9 | Average flow at the outlet of Stung Sen Basin under different operation rules.

the outlet will be decreased by 12% and 14% in the dry season and wet season, respectively. Upstream of the dam will have abundant water whereas the downstream part will face the problem of water shortage in the dry season. The low-level and seasonal variation rules will increase flows by 22% and 42% in the dry season and decrease flows by 26% and 46% in the wet season, respectively. This proved that seasonal flow will be significantly changed comparing to the baseline flow if we maximize energy production (by using the seasonal variation rule). Under low-level and seasonal variation rules, flood in the wet season will be reduced. These predicted flow changes may be later used as the post-impact data series to assess the river regime alteration, especially the impacts of the dam on the ecosystem, by various methods such as using the indicator of hydrological alteration (IHA) (Richter *et al.* 1996) or river impact index (RI) developed by Haghighi *et al.* (2014).

Flow changes at the outlet of Stung Sen Basin based on these three operation rules follow the same trend as another study in the 3S River conducted by Piman *et al.* (2012). Both studies demonstrate the future changes of river flow in the Lower Mekong Basin as a result of dam developments. With the existing dams and those to be constructed in the future, flow in the main river is expected to change significantly due to the operation to maximize electricity production. These dam developments will definitely increase the economy by generating abundant electricity, increasing irrigation area, and by reducing flood and drought impact. However, they would also cause a considerable negative impact, especially to the people downstream who mainly depend on the ecosystem service and natural resource. The reduction in wetland area caused by low seasonal fluctuation of river flow, and the blocking of fish migration and sediment would adversely affect the productivity of Tonle Sap and the floodplains in Cambodia.

The integrated hydrologic and reservoir modeling approach presented in this study was just a comprehensive exercise, which entails more uncertainty analysis; this is, as such, beyond the scope of this paper, yet provides possible further research. For instance, land use patterns will generally change due to the impact of climate change and human activities for the periods that are longer than several years. When the time scale is long, the influence of land use change on the simulation of streamflow should be taken into account to reduce uncertainty in model output. However, in the simulation process of this study, a single period of land use was used without considering the variations in land use throughout the entire simulation period. Thus, future research work should consider dynamic land use inputs to improve model performance. On the other hand, the spatial variability of rainfall in this river basin might be not well represented by just interpolating data from three stations, and this can be considered as another source of uncertainty. Hence, satellite-based and reanalysis rainfall products should be used to represent the spatial distribution of rainfall, and this somehow improves the model performance.

CONCLUSIONS

Overall, the simulated flows at the outlet of Stung Sen Basin by HEC-ResSim differ significantly according to the operation rules adopted. The operation rules tested include full-level, low-level, and seasonal variation rule. By using SWAT and the HEC-ResSim model, we were able to discover how hydropower dam development and operation substantially affect the natural flow of the Stung Sen River. If the dam is constructed, dry season flow will be increased and wet season flow will be decreased. However, under the full-level rule flow will slightly decrease in both seasons. The magnitude of change is dependent on the operation of the dam. Thus, it is very important to make and agree a clear decision with stakeholders before operating. Moreover, the dam should be operated in consideration of disaster risk and environmental flow. This study has determined the downstream flow changes only. Further research, such as the impact of flow change on sediment flow, water quality, and ecology should be conducted to understand more about the impacts of dams in environmentally sensitive areas such as the Tonle Sap Biosphere Reserve.

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