Evaluating the impacts of climate change on the hydrology and water resource availability in the 3S river basin of Cambodia, Laos, and Vietnam

Nguyen Thi Thuy Trang[1*], Sangam Shrestha[2], Hiroshi Ishidaira[3], Pham Thi Thao Nhi [1, 4]

[1]*Faculty of Environment, University of Science, Vietnam National University, Ho Chi Minh city, Vietnam*
[2]*Water Engineering and Management, School of Engineering and Technology, Asian Institute of Technology, Thailand*
[3]*Interdisciplinary Centre for River Basin Environment, Graduate Faculty of Interdisciplinary Research, University of Yamanashi, Japan*
[4]*Institute for Computational Science and Technology (ICST), Ho Chi Minh city, Vietnam*

Received 12 August 2020; accepted 10 November 2020

Abstract:

The goal of this study is to examine the responses of hydrology and water resource availability to future climate change in the 3S (Sekong, Sesan, and Srepok) river basin located in the tropical countries of Laos, Vietnam, and Cambodia. The calibrated the Soil and Water Assessment Tool (SWAT) model was used to investigate changes to the hydrological regime and water resources under various climate change scenarios. The climate change scenarios were designed based on an ensemble of 5 GCM simulations (HadGEM2-AO, CanESM2, ISPL-CM5A-LR, CNRM-CM5, and MPI-ESM-MR) for medium emission (RCP4.5) and high emission (RCP8.5) scenarios. The climate of the basin was prognosticated to be warmer and wetter with increased temperature and precipitation in the future. Future climate change causes an increase in stream flow from 29.0 to 45.0%, 2.0 to 8.3%, and 1.2 to 10.6% for the Srepok, Sekong, and Sesan rivers, respectively. Although the discharge is projected to increase in the future, the per capita water availability is projected to decrease to 48.5, 55.1, and 80.2% in the 2090s compared to 2010 for the Srepok, Sekong, and Sesan rivers, respectively, due to population growth. The Sekong and Srepok basins will experience the most serious decline in trend and absolute value of water availability, respectively. The results of this study will be helpful to water resource development, planning, and management under climate change scenarios in the 3S river basin (3SRB).

Keywords: **climate change, SWAT model, transboundary river basin, water resources, 3S (Sekong, Sesan, Srepok) river basin.**

Classification number: **5.1**

Introduction

As emphasised in the IPCC Fifth Assessment Report (AR5), climate change is occurring across nearly all the regions of the world [1]. Climate change can considerably affect the regional hydrology and water resources through changes in hydrological processes, especially in evapotranspiration, soil water, and surface runoff. Furthermore, climate change may include an increased frequency and magnitude of hydro-meteorological extremes, namely droughts and floods [2]. Such hydrological changes will lead to the redistribution of water resources that impact water supply, hydropower, and irrigation on multiple scales. Therefore, discovering ways that water resource systems can be impacted and their respond to climate change scenarios has been the research topic of interest of the IPCC and many other international organizations and research institutions.

Many studies have been conducted to evaluate climate change impacts on regional hydrology and water resources [3-7]. In these studies, the modelling approach is preferred because it is the most suitable for hydrology simulation. The hydrological model is first calibrated against the observed data and then run with future climate scenarios using calibrated hydrological parameters. There are numerous hydrological models that have been developed such as HEC-HMS (Hydrologic Engineering Center - Hydrologic Modelling System), HSPF (Hydrological Simulation Program - FORTRAN), the NAM (Nedbor-Afstromings Model) rainfall and runoff model, and SWAT (Soil and Water Assessment Tool). Among these models, SWAT has been proven to be effective for simulating hydrology in several types of watersheds with various agro-climate conditions around the world (see SWAT database: https://www.card.iastate.edu/ swat_articles/). However, the climate change impact on hydrology and water resources are spatially different depending on the geographic location of the study area. For this reason, it is necessary to quantify the hydrological impact of climate change in specific basins.

[*]*Corresponding author: Email: ngtttrang@hcmus.edu.vn*

The Sesan, Sekong, and Srepok rivers form the transboundary 3SRB in the Mekong river, which is shared by three tropical countries namely Cambodia (33%), Laos PDR (29%), and Vietnam (38%), which contribute between 16 and 26% of the Mekong's total annual flow [8]. The 3SRB plays an important role in economic growth and ecosystem services. The biggest paddy field in the Vietnamese Mekong delta is located downstream of the 3SRB, which means that the outflow from the outlet of the 3SRB will impact the water use in the Mekong delta for irrigation or rice growth. This will undoubtedly affect national food security and the export industry. In recent years, the continuous trend of population increases, urbanisation, and industrial development in the upstream of the Sesan and Srepok basins has caused a higher water demand for multiple purposes such as the domestic, agricultural, industrial, and fishery as well as environmental [8-10]. Moreover, as more hydropower dams are constructed in the basin, the streamflow regime and water availability downstream will change accordingly. There is also a problem with the three countries in the trans-boundary basin sharing water benefits and responsibility for water pollution.

Additionally, the 3SRB has been identified as one of the three most vulnerable areas impacted by climate change in the lower Mekong basin [11]. There could be an increase of 3 to 5°C in annual temperature and a 35 to 365 mm increase in annual rainfall, which may result in sudden changes to the habitat of certain livestock, aquatic life, and crops. In economic development and climate change scenarios, the water resource management task becomes more challenging, especially in the transboundary basin, which is associated with the issue of sharing benefits and responsibility. Therefore, a reliable and comprehensive assessment of changes in hydrological characteristics and water resources for the whole basin and each sub-basin under the future climate change perspectives is important for supporting decision-makers and managers in sustainable water resource management and planning. There have been some studies conducted on the 3S basin considering the fish assemblage dynamics affected by a dam [12], the change of riverine nitrate in the periods of 2005-2008 [13], sediment trapped in reservoir alternating by the flow and hydropower regime management [14], and the hydropower production and impact by the seven large proposed dams on water flows [15]. The projection of 3S river discharge change under the impact of future climate has been done using SWAT model by various researches [6, 16-18]. These studies assessed and analysed the change of streamflow for the whole 3S basin but did not consider an analysis of each of the three sub-basins. Meanwhile, each basin has its own socio-economic characteristics that required unique management measures and policies. Therefore, to ensure the demand of each sub-basin, but also to not compromise the development of others, we decided to conduct a study on streamflow change and water availability across the whole 3S basin considering the assessment from each sub-basin.

The main goal of this study is to investigate changes in the hydrology and water resource availability over the whole 3SRB and each sub-basin under various climate change scenarios to support managers in obtaining further wisdom into climate change impacts on water resources and adaptation.

Materials and methods

Study area description (Fig. 1)

Located in the south eastern part of the Mekong basin, the 3SRB comprises an area of 78529 km^2 accounting for 10% of the Mekong basin and contributing to 16-26% of the Mekong's river total flow [8]. The Sekong river originates in the

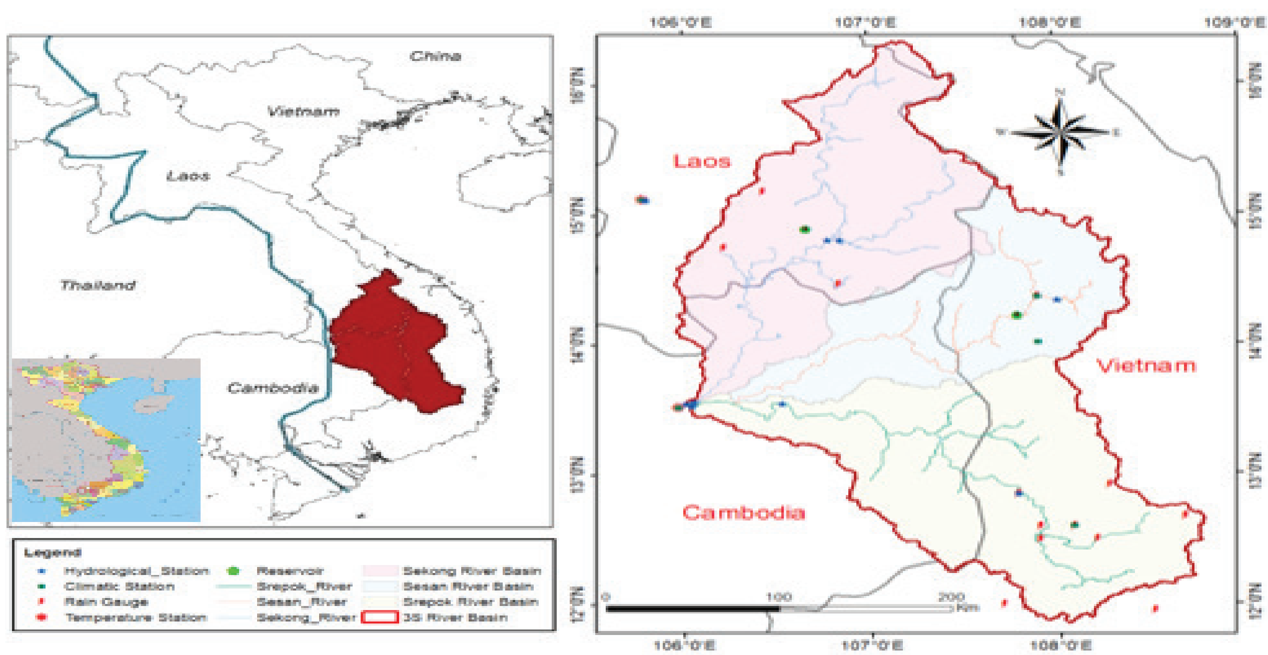

Fig. 1. The locations of 3SRB and hydro-meteorological stations.

Annamite Range in Laos PDR, while the Sesan and Srepok rivers originate in the Central Highlands of Vietnam. The elevation of this region ranges from 80 to 2040 m and runs from south to north and east to west. The area of the basin in Cambodia is flatter than those located in Laos and Vietnam. In the 3SRB, the climate is divided into two distinct seasons of wet (May to October) and dry (November to April). The annual precipitation and temperature over the basin, recorded in the period 1981-2008, were 2080 mm and 22-23°C, respectively. The heavier rainfall intensities occurred in the Highlands of Laos PDR and Vietnam. The annual discharge generated from the whole basin was observed at 2970 m^3/s from 1999 to 2008.

Hydrological simulation

Data requirements and model setup for hydrological simulation: the SWAT model is a semi-distributed, time-continuous, and process-based hydrological model that is widely used for investigating the impacts of climate change on hydrology and water resources at the regional scale, especially southeast Asia [19]. In this work, the authors used SWAT version 2012 that was integrated into an ArcGIS 10.3 interface.

SWAT requires spatial and temporal data as shown in Table 1 to simulate the hydrological processes of the 3SRB. The spatial data, which includes the topography, soil properties, and land use/land cover, were collected from the Mekong River Commission (MRC). Daily discharge data over the period 1994-2008 at nine hydrological stations, the operation data of two reservoirs, and meteorological data over the period 1981-2008 that includes precipitation, temperature, relative humidity, wind speed, and solar radiation were obtained from the MRC and Vietnam's National Hydro-Meteorological Service (NHMF) (see Fig. 1). In addition, population data was collected from the MRC.

Table 1. Required input data for the hydrological simulation in the 3SRB.

Data type	Spatial resolution	Temporal coverage	Sources
Soil map	250x250 m	-	
Land use map	250x250 m	2003	
Digital elevation model (DEM)	250x 50 m	-	MRC
Population	-	2007, 2030, 2060, 2090	
Weather data (precipitation, max and min temperature, relative humidity, solar radiation, and wind speed)		1981-2008	NHMF
Streamflow	-	1994-2008	NHMF
Reservoir	-	1999-2008	MRC

The 3SRB was separated into several sub-basins using the DEM to present the topological characteristics. The DEM at a spatial resolution of 250x250 m provided by the MRC was used in the study. The Hydrologic Response Unit (HRU) represents the smallest geographical area for processing the transport of flow and substances [20], which was generated by the land use/land cover, soil, and slope maps of 250x250 m resolution (Fig. 2). As a result, 133 sub-basins and 1011 HRU determined by the Arc SWAT model represent homogeneity and heterogeneity, respectively.

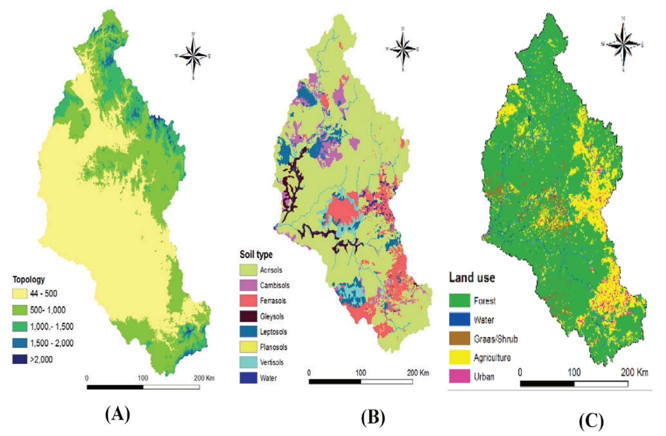

Fig. 2. (A) Topology characteristic, (B) Soil type, and (C) Land use maps of the 3S basin [18].

Calibration, validation, and sensitivity analysis: the daily flow data was observed over nine stations between 1994 and 2008. Since the observation periods of streamflow at eight of the stations were not well distributed across the basin, the calibration and validation of the data may not be conducted at the same station. The flow calibration was processed not only at the basin outlet station, but also the 5 stations that distribute to the 3 sub-basins of Sekong, Sesan, and Srepok. The SWAT-CUP was used to calibrate streamflow for the period between 2005 and 2008 and was validated over 3 time periods: 1994-1999, 2001-2005, and 2006-2008. The calibration and validation periods are presented in Table 2. The SWAT-CUP model built by the "Neprash Corporation and Texas A&M University" was employed to calibrate the model due to its high efficiency and popularity [21] in large-scale watersheds [16] while still considering the uncertainty of input data. There are four procedures of calibration, validation, and uncertainty analysis that are integrated in SWAT-CUP.

There are many parameters related to flow simulation, each with different magnitudes of effect on runoff calculations. Significant changes to non-sensitive factors do not result in a pronounced change in hydrology. Additionally, the calibration of all parameters is very time consuming but it does not generate a remarkably better model for simulation purposes. Therefore, sensitivity analysis was first performed in the SWAT-CUP (SUFI2) to ascertain the parameters that strongly affect the hydrological simulation. The parameter values were determined by sensitivity analysis simulation.

Sensitivity analysis was conducted to determine the influence a set of parameters has on predicting streamflow. Sensitivity was approximated using the relative sensitivity (S):

$$S = \left(\frac{p}{y}\right)\left(\frac{y_2 - y_1}{p_2 - p_1}\right)$$

where p is the particular parameter and y is the simulated value, p_1, p_2 and y_1, y_2 correspond to ±10% of the initial parameter and corresponding simulated flows, respectively [22]. The greater the S value, the more sensitive the simulated flow was to that particular parameter.

The Nash-Sutcliffe efficiency coefficient (NSE), percentage bias (PBIAS), and correlation coefficient (R^2) [18, 19, 21] was applied to examine the model's performance. In general, simulation results can be accepted with NSE ≥0.5.

The R^2 parameter (i.e. correlation coefficient) considers the pattern of the observed and simulated data. Therefore, a high R^2 value may be obtained despite any underestimates or overestimates of the model. The correlation coefficient (R^2) considers the model's ability to explain the dispersion showing in the observed data. Therefore, only the pattern of observed and simulated data is concerned. Thus, underestimation or overestimation of the model in maintaining the hydrograph's pattern will still result in good R^2.

The NSE is used to determine the relative magnitude of the residual variance ("noise") compared to the measured data variance ("importance"). PBIAS measures the consistency of the observed and simulated value. PBIAS measures the average tendency of the model's predicted values to be larger or smaller than their corresponding measured values. The optimal value of PBIAS is 0.0 and low magnitude values indicate accurate model simulations. Positive or negative values indicate model underestimation or overestimation bias, respectively [23].

$$R^2 = \frac{\sum_{k=1}^{m}\left(\left(X_k - \bar{X}\right)\times\left(Y_k - \bar{Y}\right)\right)}{\sqrt{\left(\sum_{k=1}^{m}\left(X_k - \bar{X}\right)^2 \times \sum_{k=1}^{m}\left(Y_k - \bar{Y}\right)^2\right)}} \quad (1)$$

$$E_{NS} = 1 - \left|\frac{\sum_{k=1}^{m}\left(X_k - Y_k\right)^2}{\sum_{k=1}^{m}\left(X_k - \bar{X}\right)}\right| \quad (2)$$

$$PBIAS = \frac{\sum_{k=1}^{m}\left(X_k - Y_k\right)}{\sum_{k=1}^{m}\left(X_k\right)} \times 100 \quad (3)$$

where X_k is observed data at time i, $\bar{X}$ is average value of observed data, Y_k is simulated data at time i, $\bar{Y}$ is average value of simulated data, and m is number of data points.

Table 2. Selected stations and time periods used for streamflow calibration and validation in 3 sub-basins.

Sub-basin	Station	Calibration	Validation
Sekong	Chantangoy, Attopeu, Ban Veunkhene	2000-2005	1994-1999/2001-2005
Sesan	Ban Kamphun, Kontum	2000-2005	1994-1999
Srepok	Lumphat, Ban Don	2000-2005	2006-2008/1994-1999
3S	Outlet	2000-2005	2006-2008

Climate change scenarios

The perturbation method was applied to correct the discrepancy between the measured and ensembles of data for 5 GCM simulations (HadGEN2-AO, CanESM2, ISPL-CM5A-LR, CNRM-CM5, and MP-ESM-MR) (Table 3). Perturbation facilitates the production of huge reasonable climate scenarios in a number of GCMs quickly leading to the popularity of its use in numerous hydrological studies [22-25]. The principles generate a future climate dataset to specify the factors and difference between the observed and simulated value in the GCM variables. Consequently, different factors will be assigned to the regional historical data such as daily precipitation and maximum and minimum temperatures to generate the future data set. The basic assumptions of the perturbation method are: (1) the baseline and simulated periods have same GCM biases; and (2) the similar values of temporal change (daily to inter-annual) for the observed climate variables are applied to both the baseline and projected periods.

$$\text{Temperature: } CF_m = T'^{GCMfut}_m - T'^{GCMref}_m, \quad T'^{fut}_{k,m} = T^{obs}_{m,k} + CF_m \quad (4)$$

$$\text{Precipitation: } CF_k = \frac{P'^{GCMfut}_k}{P'^{GCMref}_k}, \quad P'^{fut}_{k,m} = P^{obs}_{m,k} * CF_m \quad (5)$$

where CF_m is the monthly mean change factor at month *m;* T'^{GCMfut}_m and T'^{GCMref}_m are the GCM-simulated temperature for the future period and the reference period, respectively, at month *m*; $T'^{fut}_{m,k}$ and $T^{obs}_{k,m}$ are the future and observed temperature, respectively, at day *k* and month *m*; P'^{GCMfut}_m and P'^{GCMref}_m are the GCM-simulated precipitation for future and reference period, respectively, at month *m*; $P'^{fut}_{k,m}$ and $P^{obs}_{k,m}$ are the future and observed precipitation, respectively, at day *k* and month *m*.

Table 3. 5 GCMs used in this study.

Model name	Scenarios	Resolution (long. x lat.)	Institution	Country used GCMs
CanES2	RCP4.5 RCP8.5	2.8°x2.8°	Canadian Centre for Climate Modelling and Analysis, Canada (http://www.cccma.ec.gc.ca/data/cgcm4/CanESM2/index.shtml)	Malaysia
CNRM-CM5	RCP4.5 RCP8.5	1.4°x1.4°	Centre national de Recherches Meteorologiques, France (http://www.cnrm-game-meteo.fr/?lang=fr)	Vietnam
HadGEM2-AO	RCP2.6 RCP4.5 RCP6.0 RCP8.5	1.9°x1.25°	Hadley Centre, UKMO (http://www.metoffice.gov.uk)	South Korea
IPSL-CM5A-LR	RCP2.6 RCP4.5 RCP6.0 RCP8.5	3.75°x1.9°	Institute Pierre-Simon Laplace, France (https://www.ipsl.fr/en/)	Malaysia
MPI-ESM-MR	RCP2.6 RCP4.5 RCP8.5	1.9°x1.9°	Max Planck Institute for Meteorology (http://www.mpimet.mpg.de/en/science/models/mpi-esm.html)	Thailand

Results and discussion

Performance of the SWAT model

The key parameters controlling the basin's hydrology were found to be CN2, SOL_K, soil depth SOL_Z, CANMX, ALPHA_BF, GW_DELAY, CH_K2, SOL_ALB, CH_N2, and SLSUBBSN which were the results from the parameter sensitivity analysis of a previous study [18].

For the feasibility of using simulated values for future flow projections, the statistical coefficients of R^2 and PBIAS were calculated as in a previous study [18]. Almost all values of R^2 and NSE were greater than 0.6 and the range of PBIAS was ±25%. The model performs flow simulation at the 3SRB outlet determined by the highest value of R^2 and NSE and the lowest PBIAS values. As elaborated in Table 4 [26], the calibrated SWAT model would be acceptable for discharge simulation in 3S.

Table 4. The statistic for the observed and simulated daily flow calibration and validation periods.

Sub-basin		Sekong	Sesan	Srepok	3S
Calibration	R^2	0.56	0.6	0.5-0.74	0.72
	NSE	0.49	0.36	0.54-0.65	0.72
	PBIAS	-9.36	-9.56	-8.3- -6.9	8.21
Validation	R^2	0.59-0.80	0.58-0.68	0.58-0.77	0.68
	NSE	0.65-0.80	0.60-0.73	0.57-0.8	0.68
	PBIAS	1.61-8.01	-0.82-24.11	-3.52- -0.83	-2.86

The streamflow peak occurring in the months of August and September did not fit well and was mostly underestimated at 5 stations despite of the good fit between observed and expected data (Fig. 3). Missing and undistributed rainfall gauges, unpresented local rainfall storms, or the curve number (CN2) employed to simulate surface runoff may have caused the mismatch. The CN2 method assumes a unique relationship between cumulative rainfall and runoff for the same antecedent moisture conditions generated from the study conducted at a basin located in the US [27-29]. Nonetheless, this study aimed to assess the water resources but not predicting flood. Therefore, the peak flow mismatch was not significantly more important than the total flow or mean annual water balance shown in Table 5. The difference between the average annual observed value and simulated value was less than 10% for 5 monitoring stations in the calibration period, which indicated a good match between the historical and the model's simulated flow.

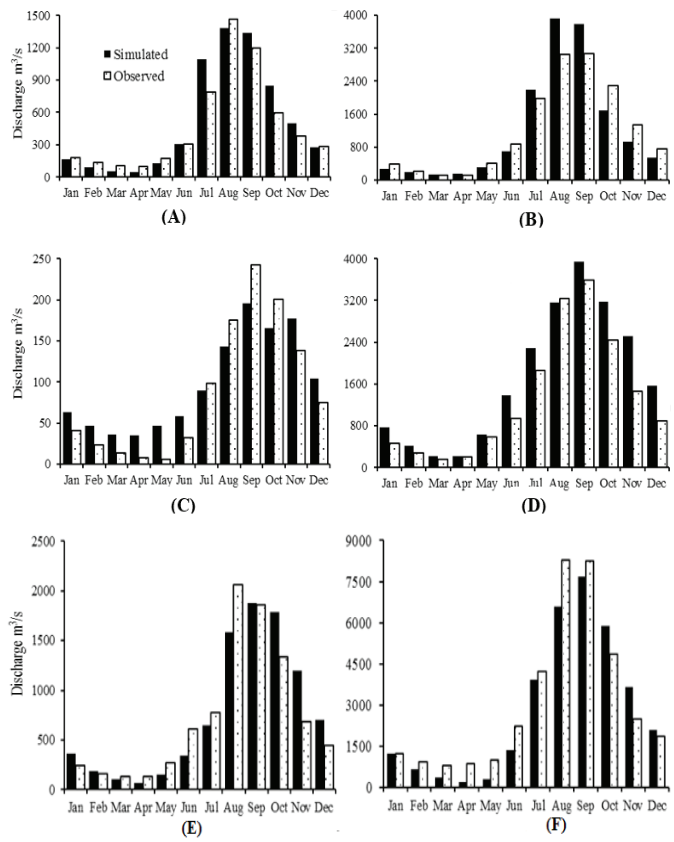

Fig. 3. Comparison of the observed and expected discharge for calibration and validation in the 3S basin and 3 sub-basins at (A) Attapeu (Sekong basin); (B) Chantangoy (Sekong basin outlet); (C) Kontum (Sesan basin); (D) B. Kamphun (Sesan basin outlet); (E) Lumphat (Srepok basin outlet); and (F) 3S basin outlet.

Table 5. The average annual water balance in the calibration and validation periods.

Station	Annual mean flow(m^3/s)					
	Calibration			*Validation*		
	Observed	*Expected*	*Difference (%)*	*Observed*	*Expected*	*Difference (%)*
Attapeu	477.02	521.65	9.36			
Kontum	91	98	7.69	102.36	77.4	-24.38
Bandon	267.50	289.70	8.30	308.02	333.67	8.33
Lumphat	733.67	758.9	3.44	722.92	743.54	2.85
Outlet	3014	2850	-5.44	2737	2688	-1.79

Future climate of temperature and rainfall

Temperature and precipitation indicate climate change magnitude, which directly affects the focal water resources. These prognostic variables changed for different periods along with radiative forcing [18]. The change in average monthly temperature over the 2030s, 2060s, and 2090s decades under the RCP4.5 and RCP8.5 scenarios is provided in Fig. 4. The temperature was found to continually increase under both RCPs, which spanned 3 periods every month. An increase in temperature was indicated from 0.4 to 0.99°C, 1.22 to 1.72°C, and 1.51 to 2.05°C in RCP4.5 and from 0.67 to 1.25°C for the 2030s, 2.04 to 2.59°C for the 2060s, and 3.26 to 4.01°C for the 2090s. The temperature increases in RCP8.5 was approximately 1.2 to 2 times greater than RCP4.5 across the 3 time periods. The highest change occurred in January for the 2030s and 2060s and in April for the 2090s in both RCP4.5 and RCP8.5. The magnitude of the change in temperature is associated with time and radiative forcing. The most substantial increase will occur in the RCP8.5 scenarios in the late twentieth century.

There is an obviously fluctuation in the average monthly precipitation for the 2030s, 2060s, and 2090s in the 3S basin for both the RCP4.5 and RCP8.5 scenarios related to the base years illustrated in Fig. 5. The changes in monthly rainfall fluctuated according to time and radiative forcing scenarios. Compared to the baseline, the average monthly precipitation changed from -7.1 to 18.9%, -2 to 10.8%, and -14.5 to 15.9% under RCP4.5 for the 2030s, 2060s, and 2090s, respectively, and from -18.4 to 21.9%, -16.3 to 17.2%, and -33.9 to 15.8% under RCP8.5 for the 2030s, 2060s, and 2090s, respectively. However, the most substantial decrease occurred in March in all cases. Generally, monthly rainfall is expected to increase during the 3 periods for the RCP 4.5 scenario in the wet season months (May to October) with fluctuations during the dry season months. Meanwhile, a major decline occurred in the period of February to April and at the beginning of the wet season (May) for the RCP 8.5 scenario (Fig. 5B). The precipitation had higher fluctuations under RCP8.5 due to the most severe increases and decreases occurring in the 2060s and 2090s.

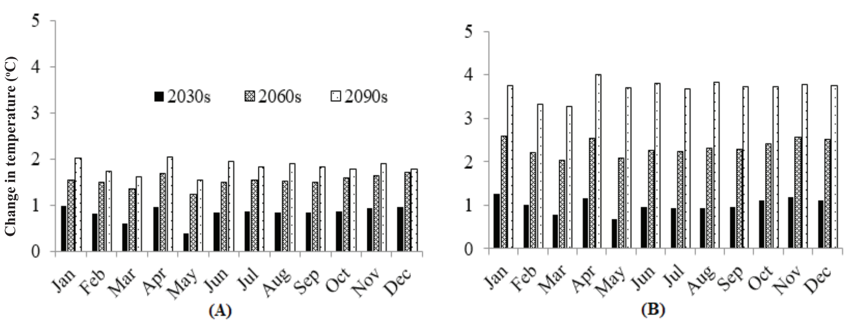

Fig. 4. Changes in monthly average temperature under (A) RCP4.5 and (B) RCP8.5 for the 2030s, 2060s, and 2090s compared to the baseline.

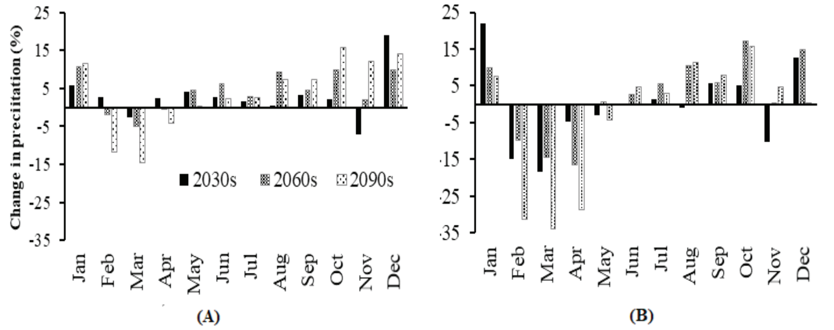

Fig. 5. Changes in monthly average precipitation under (A) RCP4.5 and (B) RCP8.5 for the 2030s, 2060s, and 2090s compared to the baseline.

Climate change impact on hydrology and water resources for the 3SRB

The relative change of average monthly streamflow under the climate change scenarios are presented in Fig. 6. The average monthly streamflow is projected to rise during the wet season and fall in dry season during all 3 decades for both RCP scenarios. Reductions in streamflow were detected from January to April for RCP4.5 and January to May for RCP8.5 for all 3 examined decades. The highest growth in streamflow occurred in June by 79% (2060s) for RCP4.5 and by 95% (2030s) for RCP8.5. The largest reductions in precipitation occurred in March at -66% (2030s) for RCP4.5 and in April at -79% (2090s) for RCP8.5. The increase in streamflow can be explained by increases in precipitation. The simulation results showed a reduction in runoff during the dry season under RCPs 4.5 despite the increase in precipitation. This may be explained by the combined impact of evaporation and precipitation on streamflow. The temperature during the dry season is predicted to increase more than in the wet season (Fig. 4), which leads to greater evaporation. In addition, the increase in precipitation during the dry season is not significant compared to that of the wet season. The river flow change is marginal in terms of absolute value but significant in term of relative value to the dry season.

Impact of climate change on hydrology and water resources for the 3SRB

The climatic, geographical, and social characteristics of the 3SRB are obviously different. Therefore, the assessment of climate change impact on each of the 3 sub-basins is essential to the launch of an appropriately tailored plan and mitigation measures for each sub-basin.

There was an average increase of flow by 6.1 and 3.2 % in Sekong, 5.9 and 2.7% in Sesan, and 35.9 and 32.1% for Srepok under RCP 4.5 and RCP 8.5 scenarios, respectively. However, the change in monthly flow of the 3 rivers varies as illustrated in Figs. 7-9. It can be seen that the pattern of monthly flow changes varies for all 3 sub-basins as well as over the different climate change scenarios. The projected simulated annual flow was analysed for the 3 sub-basins. Considering the monthly flow, a decrease was detected at the end of the dry season and in the middle of the wet season for the Sekong and Srepok basins (Figs. 7 and 9). Meanwhile, a decrease in monthly flow occurred from the end of the dry season to the beginning of the wet season in the Sesan river basin as shown in Fig. 8. The Sekong basin will experience the most severe decline and the highest increase in monthly flow during April and May, respectively. The extent of the change is more substantial for the Sekong and Srepok basins.

The relative monthly discharge increase was projected to be the highest in Srepok followed by the Sekong and Sesan river basins. The highest increase observed under RCP8.5 was 120% at the Srepok river basin in November (2060s). The highest increase observed under RCP4.5 was 125% at the Sekong river in May(2060s) and for 16.8% in March (2030s) at the Sesan river basin. The discharge in April increased under RCP4.5 and vice versa for the RCP8.5 at the Sekong river as shown in Fig. 7. The difference in flow between RCP4.5 and RCP8.5 is significant during the wet season for all 3 sub-basins.

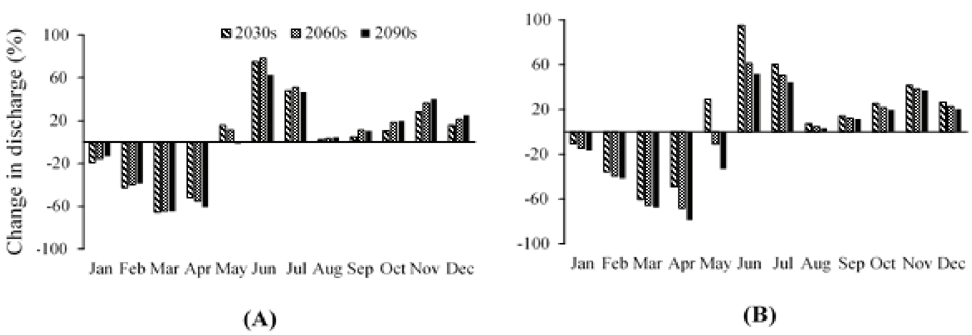

Fig. 6. Changes in monthly discharge in 3SRB under (A) RCP4.5 and (B) RCP8.5 for the 2030s, 2060s, and 2090s compared to the baseline.

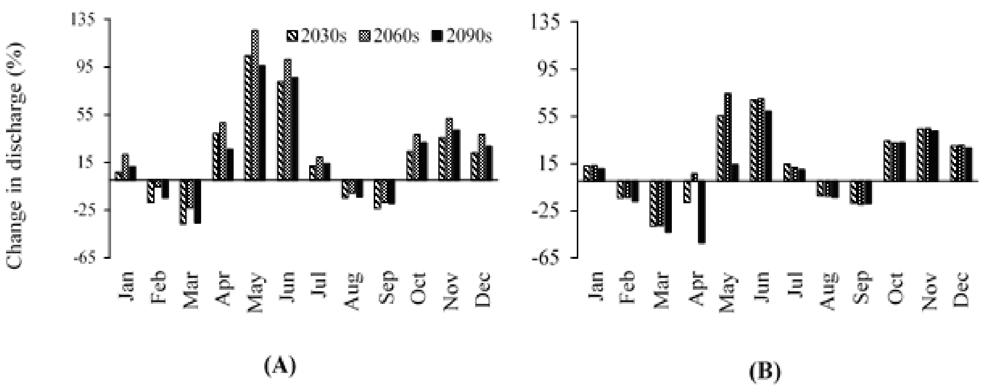

Fig. 7. Changes in monthly river discharge under (A) RCP4.5 and (B) RCP8.5 for the 2030s, 2060s, and 2090s relative to the baseline in the Sekong river basin.

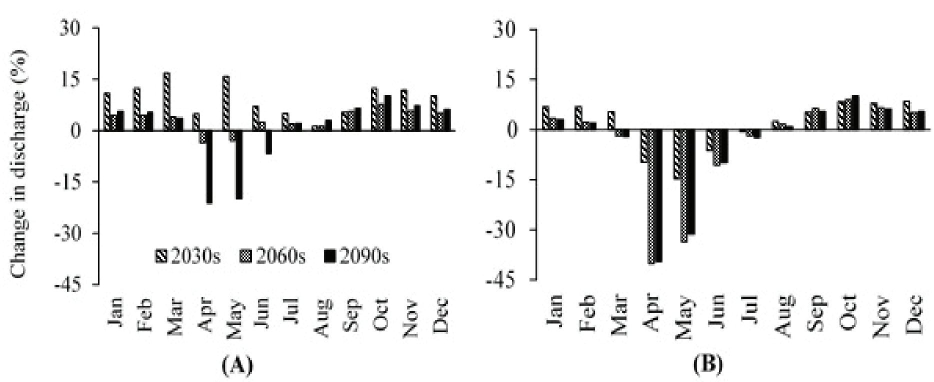

Fig. 8. Changes in monthly river discharge under (A) RCP4.5 and (B) RCP8.5 for the 2030s, 2060s, and 2090s relative to the baseline in the Sesan river basin.

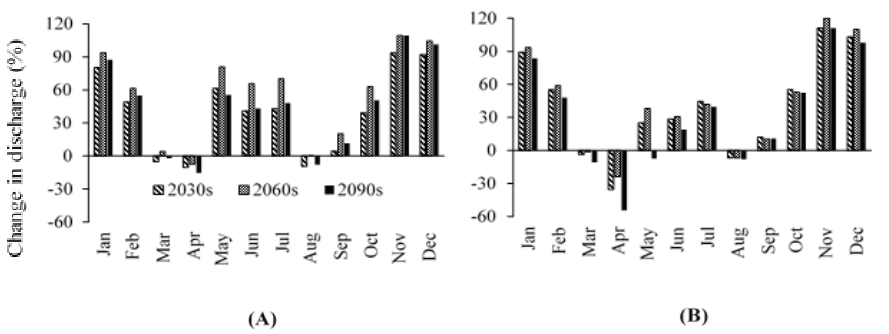

Fig. 9. Changes in monthly river discharge under (A) RCP4.5 and (B) RCP8.5 for the 2030s, 2060s, and 2090s relative to the baseline in the Srepok river basin.

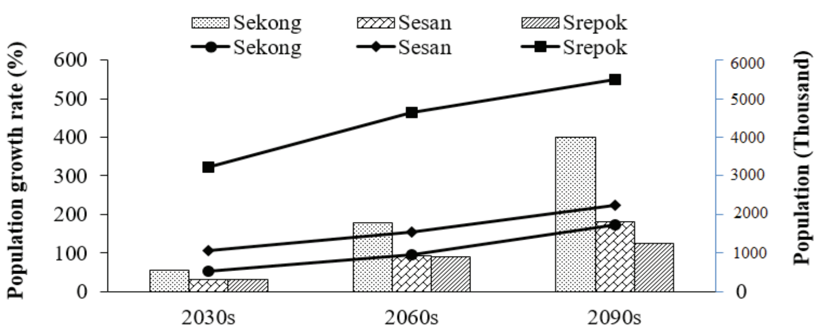

Fig. 10. Population growth rate (bar chart) and population (line) in the 3SRB over 3 decades: the 2030s, 2060s, and 2090s when compared to 2007.

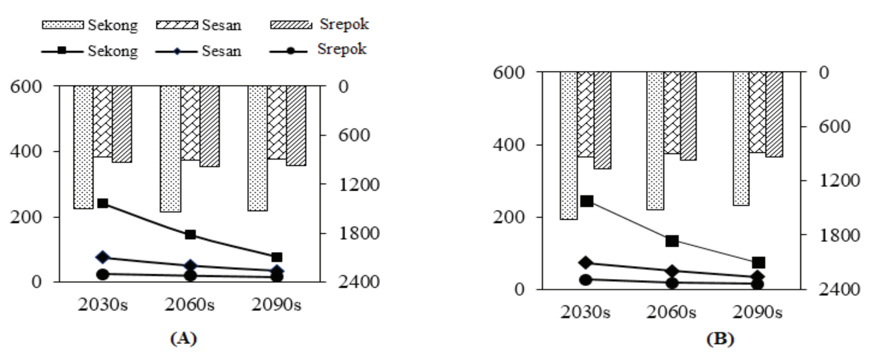

Fig. 11. Average annual flow (bar chart) and water availability (line) in the Sekong, Sesan, and Srepok sub-basins under climate change scenarios of (A) RCP4.5 and (B) RCP 8.5 with respect to the baseline.

Water availability response to climate scenarios and population growth

The population and growth rates of the 3 sub-basins were calculated based on the current and projected population density provided by MRC. These are depicted for 3 time periods, in both a line graph and bar chart, as shown in Fig. 10. In general, the population in the Srepok basin is higher than that of the Sekong and Sesan sub-basins by about 6 and 3 times, respectively, despite Srepok being the second largest in the 3S basin. The highest population is associated with the greatest urbanisation and industrialisation, which implies extended water consumption. The Srepok basin's population is predicted to increase from 2.4 million in 2007 to 3.2, 4.6, and 5.5 million people in the 2030s, 2060s, and 2090s, respectively. However, the increasing population rate in the Sekong basin is the highest at 55.8, 179.7, and 399% for the 2030s, 2060s, and 2090s, respectively. The population is projected to increase by 4, 1.8, and 1.25 times in the 2090s compared to that in 2007 at the Sekong, Sesan, and Srepok sub-basins, respectively. The rapid population increase in the Sekong basin will impose a burden on the water resources.

The annual flow and water availability at each of the 3 sub-basins is presented in Fig. 11 (A) and (B) by a bar chart and line chart, respectively. The results showed an increase in future discharge that underscores both emission scenarios across the 3 examined decades for all 3 sub-basins. In contrast, the sub-basin-specific water availability will have a decreasing trend throughout the century resulting from steady population growth whereas the Sekong river basin is expected to experience a dramatic decrease of 79.3%. The Sesan and Srepok basins may exhibit a consistent decline of 63.3% and 41.6%, respectively, at the end of this century. It can be seen that the declining trend is more severe in the Sekong basin compared to the two other basins. However, the absolute value of water availability in the Srepok basin is the lowest with 15.1 m^3/cap/day compared to 75.7 and 34.7 m^3/cap/day in the Sekong and Srepok, respectively, at the end of the twentieth century.

Discussion

Flood and drought induced from river discharge are the main natural water-related disasters that occur in the lower Mekong basin. Flood and drought is a primary disaster in terms of number of lives lost and number of people affected per disaster, respectively [30]. The risks resulting from these disasters, combined with socioeconomic development, leads to a serious water scarcity issue. Therefore, projecting alternative future hydrological regime scenarios is necessary to the advisement of the appropriate solutions for the adaptation and mitigation of water resources issues.

Under the two climate change scenarios employed in this work, the annual flow is predicted to increase for all the periods studied, namely, the 2030s, 2060s, and 2090s. This result is consistent with the finding from previous studies of 3S and the lower Mekong basin [31-33]. The results show a substantial decrease in flow during the dry season (January to April) under RCP 8.5, which would lead to a serious drought situation. Moreover, the dry season duration would extent to May over a long time period under the RCP 8.5 scenario.

The projected simulated annual flow was analysed for the 3 sub-basins, namely, Sekong, Sesan, and Srepok. The flow changes in the Sesan basin was examined and the projected annual flow was found to increase under all scenarios, especially in the peak month of September, which is similar to the results of [33]. The Srepok annual flow was projected to increase by about 33.9% under climate change impacts. A slight increase of about 3% over long periods was also found in a study by L.A. Ngo, et al. 2018 [34]. The different increasing amounts were explained by the uncertainty in using different climate change GCM models, a land use change map, and the period and station of the meteorological input data. However, our findings are totally different from the results of [30, 35]. In those works, the authors noticed that the annual flow decreased in the perspective of future climate change. This mismatch is explained by the different climate change scenarios used and water shed delineation. Furthermore, those two studies consider the Srepok basin, located in Vietnam only, to be half of the Srepok basin as defined in this study.

The remarkable finding here is the peak month of flow increase, September, and a decline in the trough month (April) for all 3 sub-basins, which exacerbates the severity of water shortages and floods. Together with the continuous increase of water demand induced by the growth of population, water scarcity during the dry month is much more serious. To mitigate the drought hazard, a water storage reservoir should be constructed and water should be reused and recycled.

Flood severity and related hazards increase as a result of the increase in streamflow during the peak month. The flood plain and damages could be mitigated by building embankments and levees to protect residential areas. Early and exact flood forecasting systems are very important and necessary to reduce damage. Effective hydropower dams and reservoir operations are measures considered to mitigate drought and flood magnitudes.

This study simulates and projects hydrology regimes in very large watersheds that lack meteorological data stations in regions like Laos and Cambodia. Therefore, hydrological monitoring systems can be improved by adding hydrological observation stations at borders between the two countries. Such observations could reveal inflow and outflow to respective downstream countries thereby showing the extent of the water resources used by each.

Conclusions

This study presents a quantitative evaluation of climate change and the future demographic impact on hydrological regimes and water resources along the transboundary basin of the 3SRB using the SWAT model integrated with ArcGIS, i.e. the SWAT-CUP.

The findings of this study show that the future climate is expected to be warmer with an increase in temperature and annual precipitation ranging between 10 and 21% over the entire 3SRB. As expected, the relative increase in river discharge reaches 20.9% for the 2060s under RCP8.5. However, the discharge is projected to decrease during the dry season. The important point here is that the streamflow increased in the peak flow month and decreased in the trough flow month for all scenarios leads to exacerbation of the severity of water shortages and floods.

The hydrological response to future climate perspectives varies between sub-basins in terms of magnitude and pattern. In general, the annual flow will increase for all 3 sub-basins under both climate scenarios and over 3 examined time periods. For most of the cases, the river discharge decreases at the end of dry season for the 3SRB, which exacerbates the severity of drought. The increase of flow in the 3SRB occurs in the peak flow month, which is a significant implication for the requisite flood management strategy.

The water availability, as determined by river flow and population characteristics, is anticipated to continuously decline throughout the century for all 3 sub-basins. The decreasing magnitude in the Srepok basin is the smallest among the 3 sub-basins. However, the Srepok river basin has the lowest water availability over all time periods and scenarios. If the decreasing trend continues for the Srepok river basin, water shortage is inevitable. Besides, water availability in the Sekong river basin will experience a dramatic decreasing trend. Therefore, these points should be taken into account in future basin planning for societal development and water supply.

The outcome of this study has significant implications that support policymakers in decision making in unique and appropriate water resource management for the entire 3SRB, and each separate sub-basin, in a sustainable and environmental manner.

ACKNOWLEDGEMENTS

The authors would like to thank the greater Mekong Sub-region for providing the funds required for this research. Similarly, the authors would also like to acknowledge the MRC for providing data and the Center of Water Management and Climate Change, Vietnam National University, and the scholarship of the Ministry of Education, Culture, Sports, Science, and Technology, Japan for facilitating this research.

COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

REFERENCES

[1] Intergovernmental Panel on Climate Change (2013), *Climate Change 2013, the Physical Science Basis*, Cambridge University Press, 1535pp.

[2] J.M. Kirby, M. Mainuddin, F. Mpelasoka, M.D. Ahmad, W. Palash, M.E. Quadir, S.M. Shah-Newaz, M.M. Hossain (2016), "The impact of climate change on regional water balances in Bangladesh", *Clim. Change*, **135(3-4)**, pp.481-491.

[3] J.M. Kirby, J. Connor, M.D. Ahmad, L. Gao, M. Mainuddin (2014), "Climate change and environmental water reallocation in the Murray-Darling basin: impacts on flows, diversions and economic returns to irrigation", *J. Hydrol.*, **518**, pp.120-129.

[4] A.R. Fonseca, J.A. Santos (2019), "Predicting hydrologic flows under climate change: The Tâmega basin as an analog for the Mediterranean region", *Sci. Total Environ.*, **668**, pp.1013-1024, DOI: 10.1016/j.scitotenv.2019.01.435.

[5] C. Luo, Z. Li, H. Liu, H. Li, R. Wan, J. Pan, X. Chen (2020), "Differences in the responses of flow and nutrient load to isolated and coupled future climate and land use changes", *J. Environ. Manage.*, **256**, p109918, DOI: 10.1016/j.jenvman.2019.109918.

[6] B. Shrestha, T.A. Cochrane, B.S. Caruso, M.E. Arias, T. Piman (2016), "Uncertainty in flow and sediment projections due to future climate scenarios for the 3S rivers in the Mekong basin", *J. Hydrol.*, **540**, pp.1088-1104, DOI: 10.1016/j.jhydrol.2016.07.019.

[7] J.L. Swirepik, I.C. Burns, F.J. Dyer, I.A. Neave, M.G. O'Brien, G.M. Pryde, R.M. Thompson (2016), "Establishing environmental water requirements for the Murray-Darling basin, Australia's largest developed river system", *River Res. Appl.*, **32(6)**, pp.1153-1165, DOI: 10.1002/rra.2975.

[8] D. Constable (2015), *The Sesan and Srepok River Basins*, IUCN Asia Regional Office, Thailand, 56pp.

[9] N.T.N. Quyen, N.D. Liem, N.K. Loi (2014), "Effect of land use change on water discharge in Srepok watershed, Central Highland, Vietnam", *Int. Soil Water Conserv. Res.*, **2(3)**, pp.74-86, DOI: 10.1016/S2095-6339(15)30025-3.

[10] Asian Development Bank (2010), *Sesan, Srepok, and Sekong River Basins Development Study in Kingdom of Cambodia, Lao People's Democratic Republic, and Socialist Republic of Vietnam*, project number: 40082-012.

[11] P. Hartman, K. Carlucci (2014), *Climate Change Impact and Adaptation Study for the Lower Mekong Basin: Key Final Results*, USAID Mekong ARCC Climate Study, Bangkok, Thailand.

[12] P.B. Ngor, P. Legendre, T. Oberdorff, S. Lek (2018), "Flow alterations by dams shaped fish assemblage dynamics in the complex Mekong-3S river system", *Ecol. Indic.*, **88**, pp.103-114, DOI: 10.1016/j.ecolind.2018.01.023.

[13] C. Oeurng, T.A. Cochrane, M.E. Arias, B. Shrestha, T. Piman (2016), "Assessment of changes in riverine nitrate in the Sesan, Srepok and Sekong tributaries of the lower Mekong river basin", *J. Hydrol. Reg. Stud.*, **8**, pp.95-111.

[14] T.B. Wild, D.P. Loucks (2014), "Managing flow, sediment, and hydropower regimes in the Srepok, Sesan, and Sekong rivers of the Mekong basin", *Water Resour. Res.*, **50(6)**, pp.5141-5157.

[15] T. Piman, T.A. Cochrane, M.E. Arias, A. Green, N. Dat (2012), "Assessment of flow changes from hydropower development and operations in Sekong, Sesan, and Srepok rivers of the Mekong basin", *J. Water Resour. Plan. Manag.*, **139(6)**, pp.723-732.

[16] B. Shrestha, T.A. Cochrane, B.S. Caruso, M.E. Arias (2018), "Land use change uncertainty impacts on streamflow and sediment projections in areas undergoing rapid development: a case study in the Mekong basin", *L. Degrad. Dev.*, **29(3)**, pp.835-848.

[17] D.N. Khoi, L.V. Thang (2017), "Climate change impacts on streamflow and non-point source pollutant loads in the 3S rivers of the Mekong basin", *Water Environ. J.*, **31(3)**, pp.401-409.

[18] N.T.T. Trang, S. Shrestha, M. Shrestha, A. Datta, A. Kawasaki (2017), "Evaluating the impacts of climate and land-use change on the hydrology and nutrient yield in a transboundary river basin: a case study in the 3S river basin (Sekong, Sesan, and Srepok)", *Sci. Total Environ.*, **576**, pp.586-598.

[19] M.L. Tan, A.L. Ibrahim, Z. Yusop, Z. Duan, L. Ling (2015), "Impacts of land-use and climate variability on hydrological components in the Johor river basin, Malaysia", *Hydrol. Sci. J.*, **60(5)**, pp.873-889.

[20] K.C. Abbaspour (2012), *SWAT-CUP 2012: SWAT Calibration and Uncertainty Programs-A User Manual*, Swiss Federal Institute of Aquatic Science and Technology, Switzerland.

[21] C. Maringanti, I. Chaubey, M. Arabi, B. Engel (2011), "Application of a multi-objective optimization method to provide least cost alternatives for NPS pollution control", *Environ. Manage.*, **48(3)**, pp.448-461.

[22] L.D. James, S. Burges (1982), "Selection, calibration, and testing of hydrologic models", *Hydrologic Modeling of Small Watersheds, American Society of Agricultural Engineers, Hydrologic Modeling Monograph*, American Society of Agricultural Engineers.

[23] V.H. Gupta, S. Soroosh, Y.P. Ogou (1999), "Status of automatic calibration for hydrologic models: comparison with multilevel expert calibration", *J. Hydrol. Eng.*, **4(2)**, pp.135-143.

[24] S. Akhavan, J. Abedi-Koupai, S.-F. Mousavi, M. Afyuni, S.-S. Eslamian, K.C. Abbaspour (2010), "Application of SWAT model to investigate nitrate leaching in Hamadan-Bahar Watershed, Iran", *Agric. Ecosyst. Environ.*, **139(4)**, pp.675-688, DOI: 10.1016/j.agee.2010.10.015.

[25] M. Faramarzi, K.C. Abbaspour, R. Schulin, H. Yang (2009), "Modelling blue and green water resources availability in Iran", *Hydrol. Process.*, **23(3)**, pp.486-501, DOI: 10.1002/hyp.7160.

[26] D.N. Moriasi, J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmel, T.L. Veith (2007), "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations", *Trans. ASABE*, **50(3)**, pp.885-900, DOI: 10.13031/2013.23153.

[27] H.H. Nguyen, F. Recknagel, W. Meyer, J. Frizenschaf, H. Ying, M.S. Gibbs (2019), "Comparison of the alternative models SOURCE and SWAT for predicting catchment streamflow, sediment and nutrient loads under the effect of land use changes", *Sci. Total Environ.*, **662**, pp.254-265, DOI: 10.1016/j.scitotenv.2019.01.286.

[28] Q. Hong, Z. Sun, L. Chen, R. Liu, Z. Shen (2012), "Small-scale watershed extended method for non-point source pollution estimation in part of the 3 Gorges reservoir region", *Int. J. Environ. Sci. Technol.*, **9(4)**, pp.595-604.

[29] V.H. Gupta, H. Kling, K.K. Yilmaz, G.F. Martinez (2009), "Decomposition of the mean squared error and NSE performance criteria: implications for improving hydrological modelling", *J. Hydrol.*, **377(1)**, pp.80-91.

[30] Mekong River Commission (2012), *The Impact & Management of Floods & Droughts in the Lower Mekong Basin & the Implications of Possible Climate Change*, Working Paper (2011-2015), 112pp.

[31] T. Piman, T. Lennaerts, P. Southalack (2013), "Assessment of hydrological changes in the lower Mekong basin from basin-wide development scenarios", *Hydrol. Process.*, **27(15)**, pp.2115-2125.

[32] L.P. Hoang, et al. (2019), "The Mekong's future flows under multiple drivers: how climate change, hydropower developments and irrigation expansions drive hydrological changes", *Sci. Total Environ.*, **649**, pp.601-609, DOI: 10.1016/j.scitotenv.2018.08.160.

[33] S.V. Raghavan, M.T. Vu, S.-Y. Liong (2012), "Assessment of future stream flow over the Sesan catchment of the lower Mekong basin in Vietnam", *Hydrol. Process.*, **26(24)**, pp.3661-3668, DOI: 10.1002/hyp.8452.

[34] L.A. Ngo, I. Masih, Y. Jiang, W. Douven (2018), "Impact of reservoir operation and climate change on the hydrological regime of the Sesan and Srepok rivers in thelower Mekong basin", *Clim. Change*, **149(1)**, pp.107-119.

[35] L.P. Hoang, H. Lauri, M. Kummu, J. Koponen, M.T.H van Vliet, I. Supit, R. Leemans, P. Kabat, F. Ludwig (2016), "Mekong river flow and hydrological extremes under climate change", *Hydrol. Earth Syst. Sci.*, **20(7)**, pp.3027-3041.