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Flow regime alteration analysis under climate change in Tonle Sap Subbasin

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Abstract. Climate change is considered as a major driving factor to intensify the challenges to the ecosystem. Critical flow condition which is occurred under climate change could lead issues to ecosystem and biodiversity. In contributing to this concern, Soil and Water Assessment Tool (SWAT) and Indicators of Hydrologic Alteration (IHA) were integrated to define the impact of climate change relevant to ecosystem. SWAT model presented a good performance on simulating daily streamflow in this research. As the result, model calibration was evaluated with statistical indicators of NSE=0.63, RSR=0.61, and PBIAS=-5.42%, while model validation obtained better performance of NSE=0.71, RSR=0.54, and PBIAS=-5.04%. The developed model was used to simulation streamflow under climate change scenarios. Three projected climate change models (GFDL-CM3, GISS-E2-R-CC, IPSL-CM5A-MR) with different two Representative Concentration Pathways (RCP2.6 and RCP8.5) in the 2030s, 2060s, and 2090s were selected. Results indicate that timing, frequency, magnitude, and variability are more likely to have great changes for GISS-E2-R-CC with both emissions, while result indicates small changes with GFDL-CM3 and IPSL-CM5A-MR models.

1. Introduction

Aquatic ecosystems have been challenging current global concerns due to climate change. Climate change is predicted to intensify the challenges to the ecosystem. Many valuable species and mitigation of vulnerability from hydrological hazards are gaining benefits from aquatic ecosystems [1]. A variety of streamflow conditions is considered as a significant driving factor in ecosystem and biodiversity production [2]. Flow regime alteration has been causing by variation under climate change conditions [3]. However, climate change is considered a big concern in Cambodia, especially in the Tonle Sap Basin. Several studies were conducted on climate change issues in the Tonle Sap Basin [4], [5], [6], &[7]. Significantly, this study was done by using different climate change scenarios and difference methods to analysis the impacts of climate change compared to previous studies. Flow alteration in river systems has been changed due to climate change by creating shifts in timing and magnitude of peak flow or baseflow and magnitude of seasonal flow [8]. Influenced components of flow alteration such as magnitude, frequency, duration, timing, and rate of change indirectly and directly impact on river ecosystems [8].

In the assessment of hydrological variables and their impacts on the ecosystem, there are numerous eco-hydrological approaches were already developed. In a comparison of numerous hydrological indicators, IHA has been recommended as it completely determines hydrological alteration relating to ecological impacts [9]. IHA application was developed according to flow regime components such as magnitude, timing, duration, frequency, and change rates [10]. IHA indicators have 33 parameters which categorize into 5 groups as monthly magnitude (1), extreme event magnitude and duration (2), the timing of extreme event happened (3), frequency of flood and drought event (4), and rate changes of flow. Due to the strong correlation of IHA indicators with eco-flow metrics, the application is commonly used to study hydrological impacts on the ecosystem. Literally, IHA indicators are usually used to assess the flow regime for pre-event and post-event of dam construction or under climate change conditions.

Predicted flow in the future is commonly projected by using a hydrological model to simulate flow under climate change scenarios. Many assessments of climate change impacts on streamflow have done by using a different hydrological model. In particular, SWAT is an efficient hydrologic model that is broadly used to determine freshwater streamflow, water quality, sediment transport, nutrient loss, climate change, and land use change impacts [11]. Especially, SWAT has been recommended as a powerful hydrologic model to study climate change effects [12]. Therefore, SWAT was used in this study to simulate daily streamflow for baseline periods (1997 to 2013) and projected flow under climate change scenarios in the future. Then IHA tool is used to determine the impacts on ecologic relevant of hydrologic parameters.

2. Methodology

2.1. Study Area

Flow regime analysis is conducted in the Sreng River Basin, which is a subbasin of Tonle Sap Lake in Figure 1. Sreng River Basin covers a total area of 9933 km^2 and has numerous natural resources. The basin has 11.7% of the protected areas stated by the government's conservation strategy. The basin overlay four provinces of Cambodia, such as Oudor Meanchey, Siem Reap, Banteay Meanchey, and Battambang. The catchment outlet is 5 meters above the mean sea level and the highest point at 670 meters above the mean sea level. Forests and shrubs cover 71 % of the land, and 29% of the rest is used for agriculture or grassland. This basin has a total population of 348,000 since 2003 amount of 284 villages [13].

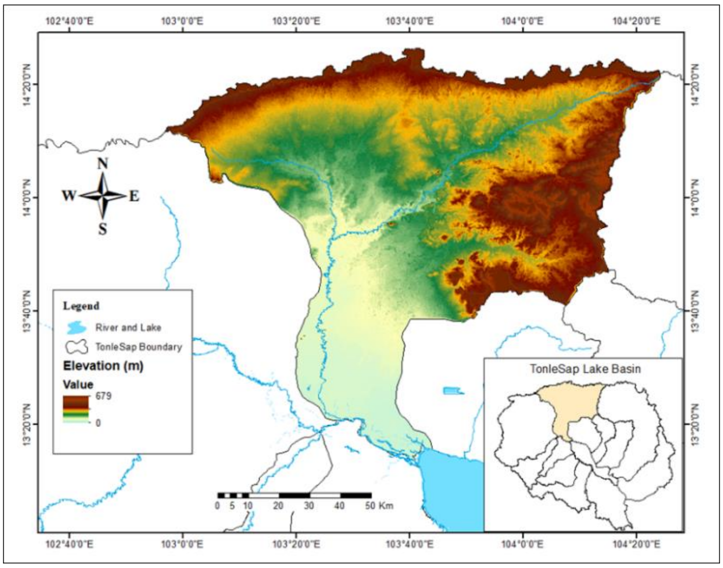

Figure 1. Sreng River Basin located in Tonle Sap Basin

2.2. Study Design

Daily streamflow was simulated from year 1997 to 2013 and predicted streamflow under climate change scenarios in future by using the SWAT model. The empirical basin was built in SWAT model by inputting the data from Table 1. To make the model reliable and capable of streamflow simulation in the Sreng River Basin, model calibration and validation was recommended by determining the best parameters for model performance [14]. Nineteen parameters, which are related to runoff, groundwater, infiltration, and flow movement, are primarily selected in the basin. Among selected parameters were reduced by applying the sensitivity analysis method [14]. In this point, SWAT Calibration Uncertainty Procedure (SWAT-CUP) tool is used for sensitivity analysis, auto-calibration, and validation [15]. The calibration period was chosen as sixty percent and validation periods was selected as forty percent of total available observed streamflow. Recommended statistical evaluation techniques for hydrological model simulation are also applied in this study such as Nash-Sutcliffe efficiency (NSE), Percent Bias (PBIAS), and Ratio of the Root Mean Square Error to the standard deviation of measured data (RSR) [16]. Then the completed model is used to simulate daily streamflow and predicted streamflow under climate change scenarios in the future. The baseline streamflow and predicted streamflow are analysed in IHA. The flow regime analysis was based on five group parameters in IHA.

2.3. Model Input

The digital elevation model (DEM) was used in this study with a resolution of 30 m from the National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM) (Figure1). The DEM was used to delineate watershed for basin boundary and sub-basin in the SWAT Model. Land use and soil type classification was obtained from the Mekong River Commission (MRC) are combined with DEM for generating Hydrologic Response Unit (HRU) in the model. The daily rainfall data from 1990 to 2013 were collected from rainfall stations located in Siem Reap province. A hydrological station at Kralanh was also provided 17 years of observed streamflow from year 1997 to 2013. All stations are situated downstream of the catchment and were received from the Ministry of Water Resources and Meteorology (MOWRAM). At the meantime, the climate data is not available in the basin; thus, it was downloaded from the Global Weather Data.

Table 1. Input data for SWAT model approach

Data Type	Description	Resolution	Period	Source
Topography Map	Digital Elevation Map (DEM)	30m	-	SRTM
Land-use Map	Land use classification	250m	2002	MRC
Soil Type Map	Soil classification	250m	2002	MRC
Weather Data	Daily rainfall	daily	1990-2013	MOWRAM
	Temperature, humidity, solar radiation and wind speed			Global Weather Data
Hydrological Data	Daily streamflow at Kralanh	daily	1997-2013	MOWRAM

2.4. Climate change scenarios

Climate change scenarios were selected based on time horizons and emission rates. Three climate models from general circulation models (GCMs) are reasonably applied in the monsoon climate area [17]. GFDL-CM3 was generated as wetter overall for climate conditions in the future, while GISS-E2-R-CC was recognized as drier overall climate condition. IPSL-CM5A-MR, was produced as the combination of drier overall and wetter overall varied on seasonal climate conditions, known as increased seasonality. The low emission rate RCP2.6 and high emission rate RCP8.5 were combined with time horizon early-century 2021-2040, mid-century 2051-2070, late-century 2081-2100. The selected GCMs were obtained as monthly change factor for rainfall, temperature, solar radiation, wind speed, and humidity in the future.

3. Results and Discussion

3.1. SWAT model calibration and validation

The sensitivity analysis defined the most nine sensitive parameters among fifteen parameters for model simulation in the basin. The most sensitive parameters were decreasing in order, according to their p-values less then 0.05. The most sensitive parameter for the flow simulations were the saturated hydraulic conductivity (SOL_K), the base flow alpha factor (ALPHA_BF), threshold d depth of water in the shallow aquifer (GWQMN), the soil evaporation compensation factor (ESCO), slope length for lateral subsurface flow (SLSOIL), and the groundwater evapotranspiration coefficient (GW_REVAP). Deep aquifer percolation fraction (RCHRG_DP), maximum canopy storage (CANMX), lateral flow travel time (LAT_TIME), and the curve number (CN2).

It was noted that the period of eleven years from 1997 to 2007 was used for this sensitivity analysis process. Hence, these sensitivity parameters were used to do a calibration process to reduce time and to conduct the best results. The calibration statistics showed an acceptable correlation between the daily simulated streamflow and observed streamflow with the NSE of 0.63, PBIAS of -5.42%, and RSR of 0.61. Therefore, the calibrated parameters from SWAT-CUP were substituted in SWAT model to do validation without any adjustment. For the reliable model simulation, the validation periods should be different from the calibration periods. Consequently, validation was performed for six years from 2008 to 2013 in Sreng River Basin. During the validating stage, the model performed well overall. The statistics for daily simulation are RSR value of 0.54, which gives the model performance rating of good, NSE value of 0.71 gives satisfactory model performance rating, and a PBIAS value of -5.04 % shows that the model is very good. The validating performance was better than calibration in the reason that the validating periods was less then calibrating periods and there were some gaps of missing rainfall for calibration. It is comparable to a previous study when their results of NSE for Calibration and Validation was 0.60 and 0.65, respectively [4]. Figure 2 shows the hydrograph between observed and simulated streamflow. There was an improved performance by the model in representing the true system during the validation stage from the initial simulation, reaching an acceptable performance level.

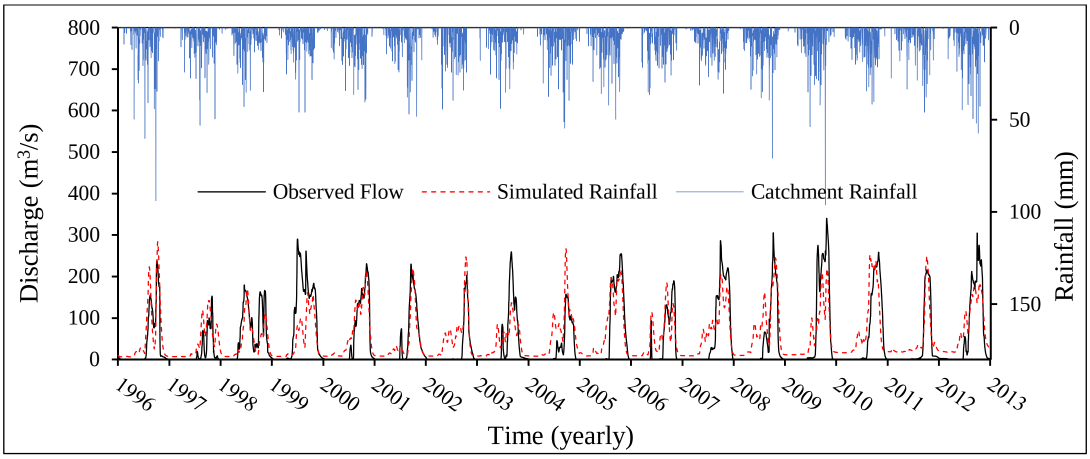

Figure 2. Hydrograph of observed streamflow and simulation streamflow.

3.2. Projected flow under climate change

Flow regimes such as peak flows and base flow or flood and drought are essential consequences of the nonlinear shift that can result in small climatic perturbations leading to more extreme impacts. This study shows that there will be shifts in the timing and duration of maximum and minimum streamflow in the future. In general, the changes in streamflow under climate change scenarios are both increased and decreased according to the model, RCPs, and periods. The analyses show that the magnitude and frequency of extreme flow are raised in the 2030s, 2060s, and 2090s for GFDL-CM3 and IPSL-CM5A-MR while they are decreased of model GISS-E2-R-CC for floods but become more drought. Figure 3 shows the flow duration curves of baseline flow and predicted flow in the future. The prediction shows that the streamflow is an increase between 2% to 42% in the future with GFDL-CM3 with a high and low emission rate for the probability of Q_5 (high flows exceeded only 5% of the time). At the same time, IPSL-CM5A-MR results between 1% to 63% of flow increasing in the future.

On the other hand, the percentage of flow changing shows the negative changes for GISS-E2-R-CC from 3% to 52%. By observing the probability of Q_{95}, the results show some significant changes. For IPSL-CM5A-MR for both low and high emission rates, the flow prediction shows the positive increase value for Q_5 probability. Meanwhile, it shows negative changes for Q_{95} (high flows exceeded only 95% of the time). It negatively changes from 1% to 3% on the IPSL-CM5A-MR model. A previous study was conducted using the same GCMs model but different emission rates (RCP6.0) [4]. Their results show that GFDL-CM3 and GISS-E2-R-CC decrease up to 26% and 47%, respectively, while in this study is increasing for GFDL-CM3 and decreasing for GISS-E2-R-CC for Q_5. IPSL-CM5A-MR increases from 18% to 23% comparable to this study. There are some significant changes in Q_{95} for RCP2.6 and RCP8.5, while there are no changes for RCP6.0 in the future compared the previous study [4].

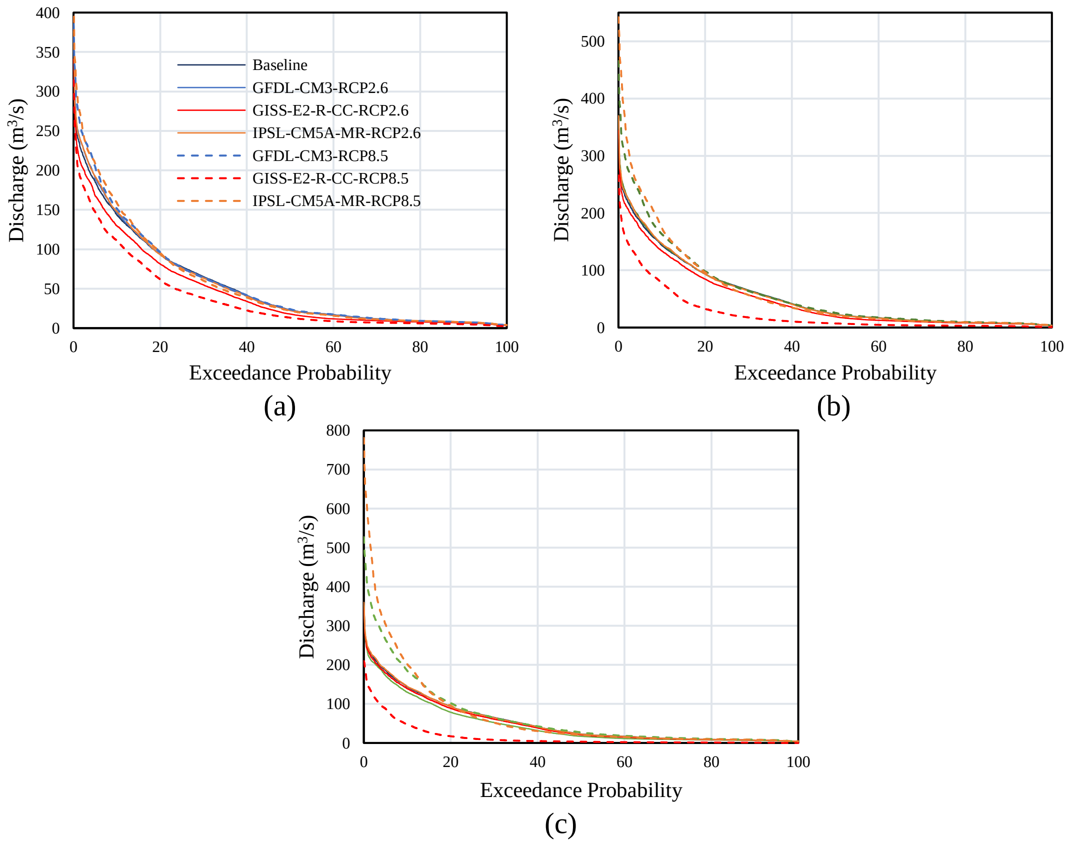

Figure 3. Flow duration curve of baseline and projected flow in the future (a) 2030s, (b) 2060s, and (c) 2090s.

3.3. Flow regime alteration in IHA

3.3.1.Alteration of selected months

The alteration analysis of monthly flow in the future is presented in Figure 4. The graph illustrates the average monthly flow of selected months (April, August, and October). A comparison of baseline flow and predicted flow adequately shows variability. By resulting in Figure 4, the GFPL-CM3 with high emission rate RCP8.5 are dramatically increased in early-century 2030s, mid-century 2060s, and late-century 2090s in April. The remaining models show slight increases. The GISS-E2-R-CC with high emission rate RCP8.5 results in the significant decreases in the range of flow in August. At the same time, GFDL-CM3 with high emission rate RCP8.5 shows a slight increase in October, meanwhile, it is significantly increasing in the IPSL-CM5A-MR model with high emission rate RCP8.5 for the same month in the future.

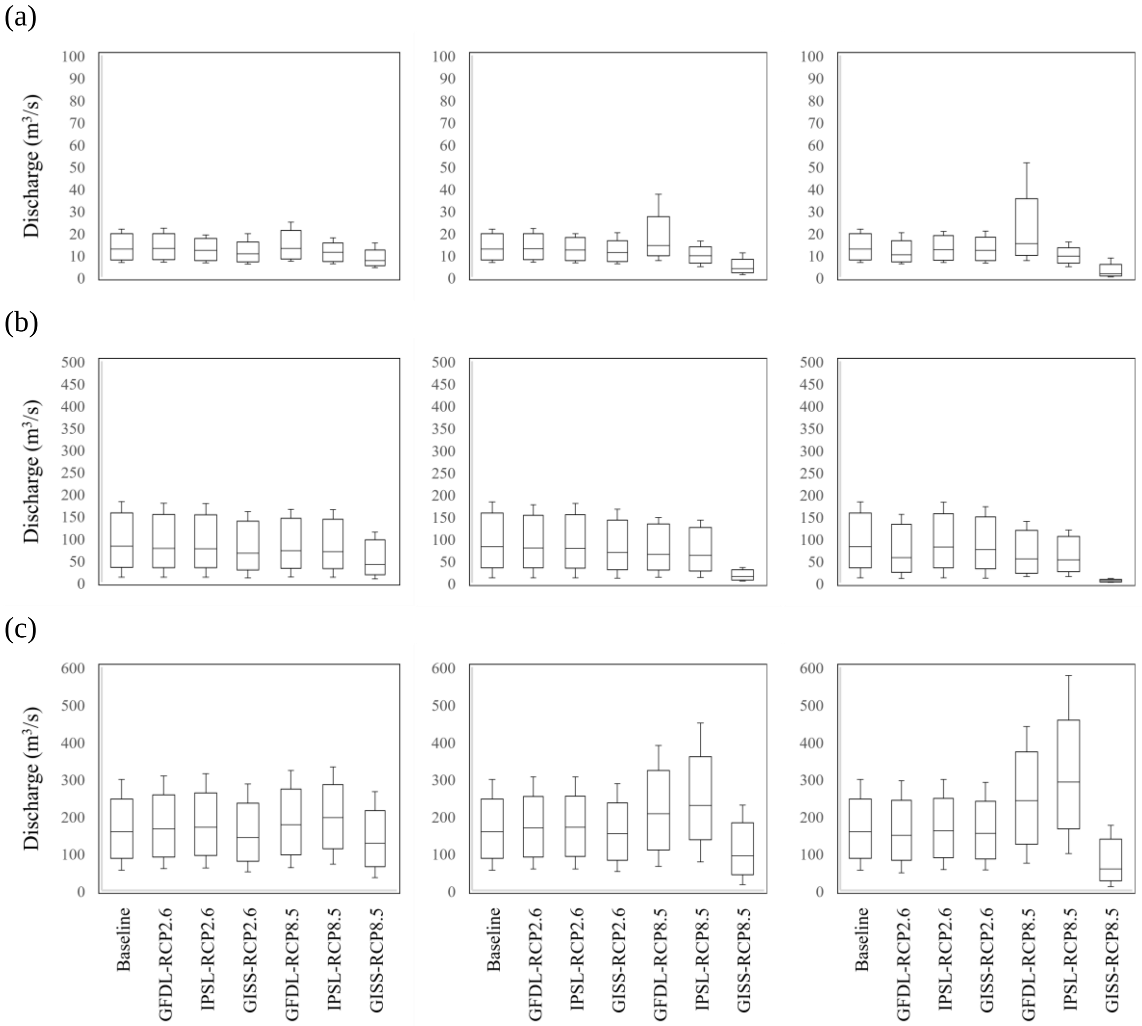

Figure 4. Projected changes of monthly streamflow on selected months (a) April, (b) August, (c) October in future 2030s, 2060s, and 2090s, respectively.

3.3.2.Alteration of magnitude of the extreme annual flow

Figure 5 displays the magnitude of extreme annual streamflow on the baseflow index. The prediction of the annual baseflow index results in a slight decrease and increases in a small percentage of flow frequency and magnitude in the future. Moreover, the baseflow of GISS-E2-R-CC with low emission rate RCP2.6 is remarkably increasing in frequency and magnitude. At the same time, frequency and magnitude slightly increase for GFDL-CM3 high emission rate RCP8.5. In observation, it is rising in the late century for GFDL-CM3. Comparison of baseflow between baseline and prediction, GISS in the 2030s for both RCP2.6 and RCP8.5 have a small range in baseflow index. Furthermore, there are no changes in the 2060s for GFDL and IPSL with RCP2.6, while there are some changes for other GCMs model. Baseflow in the 2090s for GFDL with RCP2.6 and RCP8.5 have dropped in frequency and magnitude, at the same time, GISS with RCP8.5 drops in frequency and magnitude.

3.3.3.Alteration of the timing of annual extremes streamflow

Figure 6 presents the date of annual minimum and maximum streamflow in the predicted periods. The date of the annual minimum seems likely to shift backward for drier overall climate GISS and delay for wetter overall GFDL and seasonal climate IPSL. The timing is likely to shift backward and delay up to more than 30 days. At the same time, the date of the annual maximum is predicted to be more shifts in the 2060s and 2090s comparing to the 2030s. The timing of the annual maximum has no change in date for the 2030s. In contrast, high emission rate RCP8.5 of all chosen GCMs scenarios result in move backward and delay in mid-century and late-century.

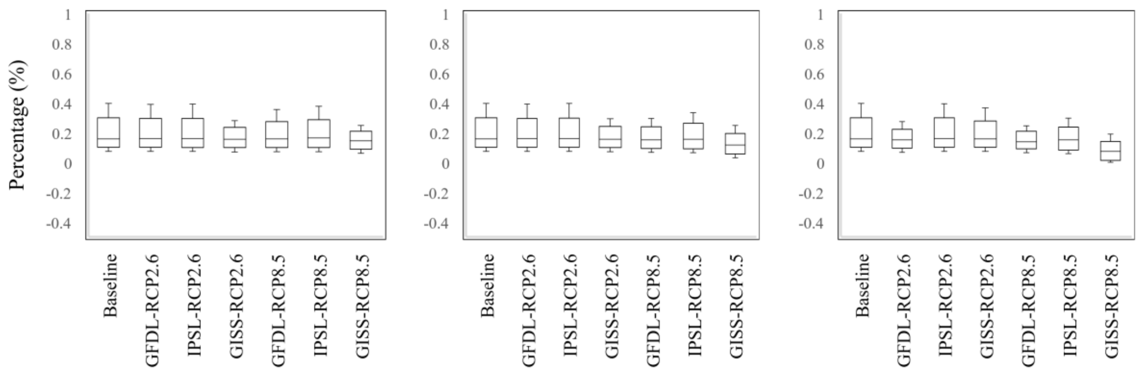

Figure 5. Projected changes in extreme annual flow (baseflow index) in future.

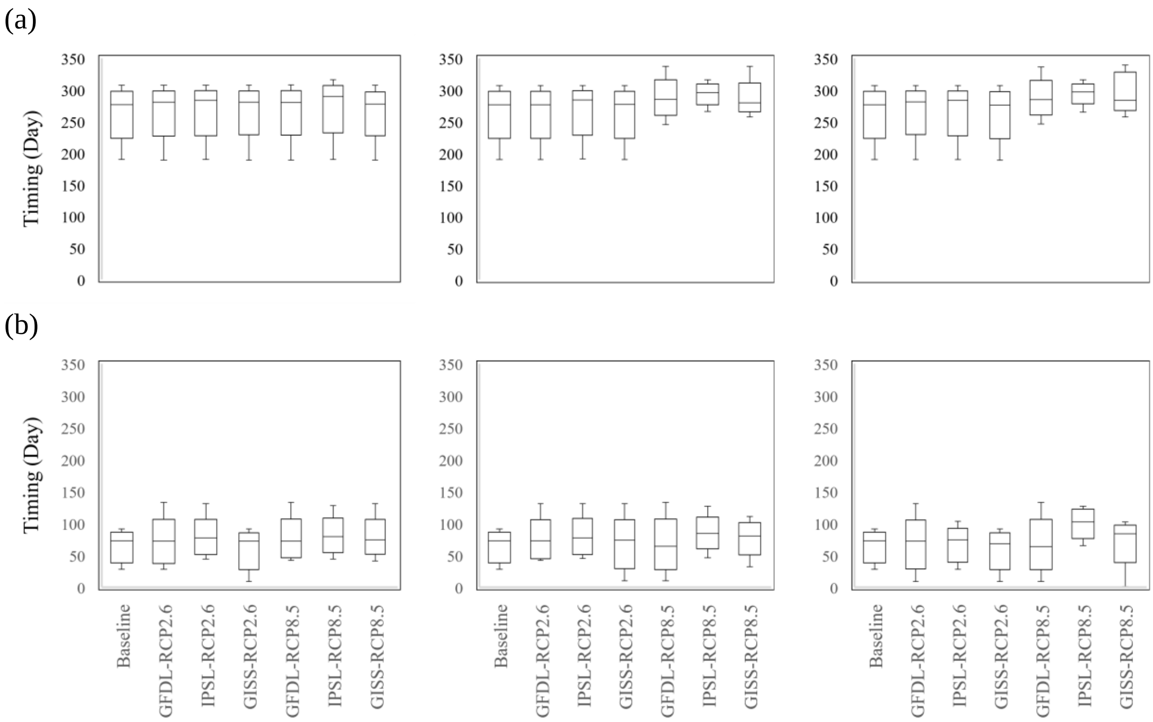

Figure 6. Projected changes in the timing of annual (a) maximum and (b) minimum in future

3.3.4.Alteration of frequency and duration of high and low pules

Alteration of frequency and duration of extreme pules display in figure 7. The median of high pule duration generally presents a slightly increase and highly decrease trends. The projection of high pule in the future is hard to identify [9]. The high pules less occur in percentage changes for the 2030s.

Moreover. It shows the moderate change in the 2060s for GISS with a high emission rate and an extremely decrease in the 2090s. The prediction shows the opposite trend for low pule, in which there is a significant increase in the 2090s for the same climate scenario.

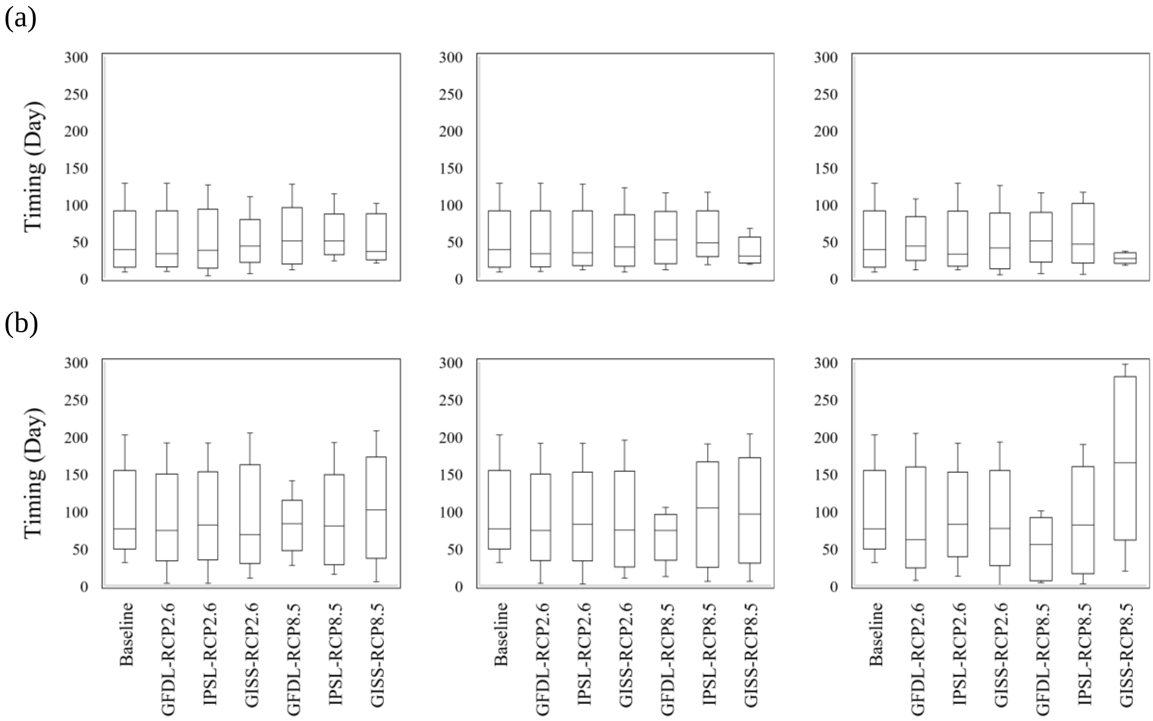

Figure 7. Projected count days and duration of the (a) high pules and (b) low pulse in the future.

3.3.5.Alteration of streamflow variability
The variability of the predicted flow has presented in figure 8. The trends of uncertainty for the rising rate across climate scenarios are small. Particularly, the value of the rising rate generates the trend, ranging nearly from 0% to 2.5%. As we can see in figure 8, the wetter overall climate model with high emission rate RCP8.5 is moderately increase every century from the 2030s to the 2090s. Meanwhile the other climate scenarios have a small percentage of changes. In contrast, the fall rate has a percentage of changes from 0% to -1.5%. At the same time, GFDL with RCP8.5 still shows a significate changes in fall rise while the other has small value changes.

4. Conclusion
The study was conducted in the Stung Sreng Basin which is one of the subbasins in Tonle Sap Basin. Two main objectives were proposed in this hydrological study. The first objective is to simulate daily streamflow for baseline and predict flow under different climate change scenarios by using SWAT. The second objective is analysing of flow regime alteration for river flows under climate change scenarios in the future. The climate change scenarios in the future were selected as the low emission rate RCP2.6 and high emission rate RCP8.5 were combined with time horizon early-century 2030s (2021-2040), mid-century 2060s (2051-2070), late-century 2090s (2081-2100).

Consequently, the SWAT model performance in this basin gave satisfying results in both calibration and validation. The model performance evaluation statistics during calibration period showed that NSE = 0.63, RSR = 0.61 and PBIAS = -5.42%. After that, the validation of the model was also done with independently measured streamflow data. During the validating period, the statistical indicators also illustrated good results of streamflow simulation with NSE = 0.71, RSR = 0.54 and PBIAS =-5.04%. In observation, the validation period performs better than calibration due to the length of year for each process and the observed flow pattern. It gives an indication of the possibility of SWAT model applicability to predict daily streamflow in the Stung Sen River Basin based upon the available input data.

The analysis of flow regime alteration, under climate change scenarios in the future, results in five different groups. Alteration of monthly flows results in the accelerations of GFDL-CM3 with high emission rate RCP8.5 has a large increase in the future. At the same time, GISS-E2-R-CC indicates the drop in predicted flows in monthly. The baseflow index presents small changes for all selected climate scenarios in the future. In particular, GFDL-CM3 with both RCP2.6 and RCP8.5 present less frequent and magnitude for predicted baseflows. The timing of annual minimum and maximum flows have been predicted to shift backward for drier overall climate model and shift toward for wetter overall and seasonal climate scenarios. High pules and low pules show less changes in the future. Moreover, the variable rates of flow have small percentage changes in the early-century but jump in high percentage changes in the late-century.

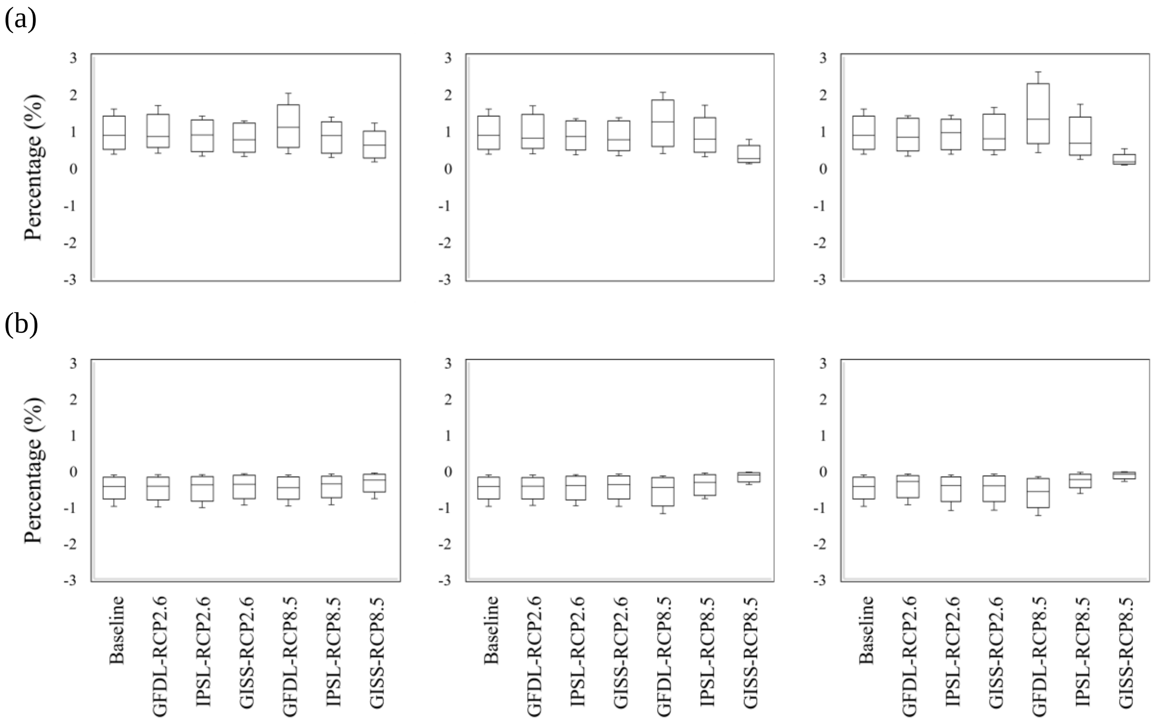

Figure 8. Projected (a) rise rate and (b) fall rate of streamflow in the future.

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