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Climate Change Impact on the Streamflow for the Nam Ou Catchment, North Laos in the Mekong Basin

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ABSTRACT

Southeast Asia, in general, and the Mekong Basin (MB), in particular, with its typically warm and wet climate, face water resource challenges. A deep understanding of the future streamflow is needed to manage water resource successfully. Data scarcity and topographical differences have made it difficult to accurately reproduce the streamflow regime in the sub-catchment of the MB. The main goal of this study was to provide the first assessments of streamflow impacts due to climate change for the Nam Ou Basin, a primary Lao sub-catchment of the MB, employing the most updated Couple Model Intercomparison Project Phase 6 (CMIP6) climate scenarios. The MIKE-NAM (Nedbor Affstromnings Model), the observed hydro-meteorological data, and the Moderate Resolution Imaging Spectroradiometer (MODIS) evaporation were employed. The climate change scenarios showed increases in seasonal and annual river discharges with different magnitudes in the future. The annual streamflow was expected to rise by 0.31%, 16.75%, and 38.31% in the 2040s as well as 23.35%, 32.80%, and 74.82% in the 2080s under three scenarios, respectively. The wet season in the Nam Ou Basin occurs one month earlier. The wet season flows increased by 5.6–76.9%, and the dry season flow showed a contrasting directional change, decreased by 8.4%. The annual peak discharge also exhibited an increase of 3.2–14.6% for the SSP1-1.9 scenario in the mid-century (the 2040s), and end-century (2080s). Those figures are 8.9–19.7% for the SSP2-4.5, and 23.3–48.9% for the SSP5-8.5 scenario, respectively. The study revealed the streamflow variation under the effect of climate change in the Nam Ou Basin, a sub-catchment of the MB, highlighting the need for special consideration in disaster risk mitigation, especially under climate change.

Keywords: streamflow, CMIP6, climate change, Nam Ou, Mekong Basin.

INTRODUCTION

It is projected that evapotranspiration and the pattern of precipitation will change due to global warming. Therefore, they will affect the streamflow regime and increase the challenge for sustainable water resources management (Hu et al., 2013, Lu, 2005). Many studies found that under global warming, the severe weather like drought, heavy precipitation, and the streamflow will change significantly (Varouchakis et al. 2018, Lehner et al. 2017; Wang et al. 2013). Various studies have revealed that climate change will have a severe effect on the streamflow in the Mekong and its sub-basins (Lauri et al. 2012; Try et al. 2020), including the Prek Thnot Basin in Cambodia (Ich et al. 2022), Nam Ou in Laos (Shrestha et al. 2013, 2016), Sesan, Sekong, and Srepok Basins in Vietnam (Oeurng et al. 2016). River flow is anticipated to increase in the wet and reduce in the dry season.

In order to evaluate streamflow variation under climate scenarios, the main variables, namely temperature and precipitation, are used as input for hydrology modeling. This approach is the most common and reliable for climate change impact assessments on hydrology (Li et al. 2021, Tan et al. 2017, Lauri et al. 2012). Using the soil and water assessment tool (SWAT) and the CMIP Phase 5 (CMIP5) Representative Concentration Pathway RCP8.5, Ma et al. (2021) examined the streamflow variation for upstream MB from

2071 to 2100. The study projected an increase of 1.0–72.7% in streamflow when mean annual precipitation increases by 3.4–55.8%. Try et al. (2020) used the inundation and high-resolution atmospheric general circulation models to evaluate flood inundation in the Mekong Delta. The results revealed an increase in inundation area of 19–43% and inundation volume of 24–55% in the Lower Mekong Basin (LMB) under climate change without a change in peak flood timing. Duong et al. (2018) used the MIKE 11 model to investigate the effect of rainfall change on seasonal flows in the Vietnamese MB. Shrestha et al. (2018) evaluates the effects of climate change and reservoir construction on sediment load in the Nam Ou Basin, a sub-catchment of the MB in Northern Laos. Shrestha et al. (2018) found that the sediment discharge in the basin increases under climate change and consequently decreases the reservoir's capacity. However, construction of reservoirs will reverse that shift and lowering the sediment outflow by 44 to 89%. These findings suggested that extreme occurrences (floods) are more frequent and intense. These projections provide insight into the hydrological changes caused by climate change, significantly affecting socioeconomic and ecological development.

All the existing studies used the future climate conditions of previous scenarios. CMIP Phase 6 or CMIP6, which is the most current climate change scenario, showing essential updates to the horizontal resolution and the emission mechanism in the scenarios (Peng et al., 2023, O'Neil et al., 2020), has not yet been used to investigate streamflow impacts due to climate change for the Mekong or it sub-basins. Therefore, this study used an ensemble mean of CMIP6 scenarios to provide critical hydrological knowledge for the Nam Ou sub-catchment of the MB.

One of the most basic and reliable tools to address the streamflow response under various climate change scenarios of the above-mentioned hydrologic models is the rainfall-runoff model, MIKE-NAM (Golmohammadi et al., 2014; DHI 2009). Its key advantage is the ability to model quickly with minimal input requirements. This advantage makes it a good option for developing countries with inadequate observations for hydrologic modeling, such as the Nam Ou River basin.

The Mekong River in Southeast Asia's tropical region is especially vulnerable to the consequences of climate change (Shrestha et al. 2016). Undeveloped nations, such as Laos, are even more vulnerable to droughts and floods due to the dramatic climate change in Southeast Asia. The Nam Ou basin is one of the essential Mekong sub-catchments, and is Laos's largest catchment. It supplies approximately 12.2 × 109 m^3 of water to the MB annually, making it the sixth largest river regarding streamflow (Peter-John Meynell 2016). Therefore, variations in the Nam Ou River's flows may cause adverse effects downstream of the Mekong River. Even though recent studies have started investigating these concerns (Shrestha et al., 2016; Mouche et al., 2014; Kinouchi, 2010; Lacombe et al., 2010), the river discharge impact due to climate change of the Nam Ou basin is mainly unidentified. Since the severity of severe weather is expected to grow, an updated evaluation of streamflow impacts due to climate is crucial for water resources management in the Nam Ou catchment and the broader MB (Lauri et al. 2012).

This study aimed to provide the first assessment of streamflow impact due to climate change on annual and seasonal scales for the Nam Ou Basin to mitigate the water-related challenges in the research study.

METHODOLOGY

Study area

The Nam Ou River runs over 448 km. It is an essential Mekong River tributary (Fig. 1). It begins near the Lao-Chinese border in Muang Ou Nua and crosses the northern Laos mountains until the Mekong River in Ban Pak Ou (MRC 2011). The Nam Ou Basin area is 20087 km^2, with an altitude range of 129–1946 m. The Nam Ou Basin experiences average annual precipitation from 1650 mm to 1950 mm. The monthly average temperature is 27.3°C (between 24°C and 29°C). This area is dominated by the dry season, which lasts from November to April, and the wet (rainy) season, which lasts from May to October, with 90% of precipitation occurring (MRC 2011).

MIKE NAM model

The MIKE-NAM is a lumped-parameter rainfall-runoff model and requires a little input data. The MIKE-NAM model illustrates the runoff generation process by simplifying the catchment to four separate connected reservoirs with representing parameters. Nine default parameters representing surface-root zone and groundwater were calibrated and validated. The initial conditions used to depict the condition of the basin at the start of the rainfall event include the initial value of overland flow, water contents in surface and root zone storage, and baseflow and interflow. It is usually best to run the model when the dry season ends with the initial conditions set to zero, excluding root zone storage and baseflow value. Water content in the root zone storage usually occupies 10–30% of the capacity, and the baseflow value is close to the observed one (DHI 2017). This study did not consider irrigation and snowmelt parameters due to the climate features and unavailable irrigation information.

Model parameters are calibrated against discharge observations using automatic procedures. The correlation coefficient (), and the water balance error () given by the below formulas are used to evaluate the performance of the model:

$$R = \frac{\sum_{i=1}^{N}\left(Q_{o,i} - \overline{Q_o}\right)\left(Q_{s,i} - \overline{Q_s}\right)}{\sqrt{\sum_{i=1}^{N}\left(Q_{o,i} - \overline{Q_o}\right)^2}\sqrt{\sum_{i=1}^{N}\left(Q_{s,i} - \overline{Q_s}\right)^2}} \quad (1)$$

$$WB_{er} = \left|1 - \left(\sum_{i=1}^{N} Q_{s,i} \Big/ \sum_{i=1}^{N} Q_{o,i}\right)\right| \quad (2)$$

where: N – indicates the sample size; $\overline{Q_s}$, $\overline{Q_o}$ – the mean discharge of simulated and observed one, respectively; $Q_{s,i}$, $Q_{o,i}$ – the samples i of simulated and observed discharge. The model works well when the R reaches unity and WB_{er} approaches zero.

After the model's calibration and validation have been implemented, the model with the calibrated parameters is applied to evaluate streamflow response based on climate change scenarios.

Data requirements

Precipitation

There are three rain gauges in the Nam Ou Basin: Phongsaly, Oudomxay, and Muong Ngoy. The monthly precipitation (mm) time series of these three gauges are collected from the Mekong River Commission (MRC) (Fig. 1). The periods from 1998–2000 and 2002–2003 were applied for calibration and validation, respectively. A Thiessen polygon method integrated into Arc GIS 10.5 software generates the weighted rainfall average for a catchment. The resulting percentage weights of those rain gauges are displayed in Table 1.

Evaporation

The MOD16A2GF Version 6 product acquired monthly evaporation data at 500 m resolution. The MOD16 data product is based on daily meteorological reanalysis data, the Penman-Monteith equation, and Moderate Resolution Imaging Spectroradiometer (MODIS) data (i.e., vegetation property dynamics, albedo, and land cover) (USGS 2022). Monthly evaporation (mm) data for 1998–2000 and 2002–2003 were utilized for calibration and validation.

Discharge

Daily discharge at the Muong Ngoy outlet from 1998–2000 and 2002–2003 (2001 missing) obtained from the MRC was applied for calibration and validation (Fig. 1).

Climate change scenarios

The future precipitation generated by the precipitation percent change for mid (the 2040s) and far future (2080s) according to three SSPs (1–1.9, 2–4.5, and 5–8.5). The observed precipitation of the baseline 1999–2008 (the 2000s) multiplied with the proportions (i.e., the precipitation percent change) to generate the precipitation for each rain gauge. The mean of the multi-model CMIP6 ensemble for sub-national aggregations was employed (WB 2022). The precipitation percent change using average level is a simple but widely used technique. It is worth noting that selecting a baseline period representing the current climate conditions plays a particular role in researching the impact of climate change. The longer the rainfall time series is, the more representing the climate are. However, based on the maximum data that can be collected for the study

Table 1. Areal percentage weights of rain gauge stations in the Nam Ou river basin

Catchment (km^2)	Rain gauge		
	Muong Ngoy (171)	Oudomxay (172)	Phongsaly (175)
Nam Ou (20087)	0.5	0.23	0.27

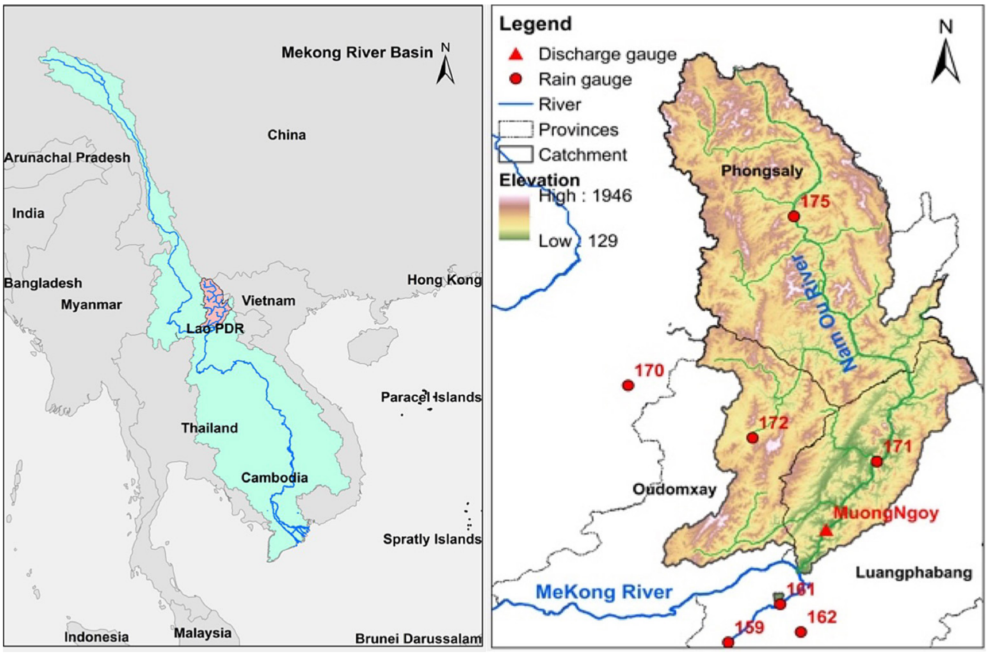

Fig. 1. Location of study area and river monitoring network

basin, 1998–2008 is determined as the baseline condition for the Nam Ou basin, which somewhat depicts the basin's climates partly compared with the 1995–2014 reference period in the CMIP6. The evaporation series is assumed not to change significantly, although this assumption may increase the uncertainty of climate change impact.

RESULTS

MIKE-NAM performance

A computer-based automatic calibration procedure was used to calibrate the model's parameter using the daily data from 1/1/1999 to 31/12/2000. The validation period was from 1/1/2002 to 31/12/2003. The ten parameters of MIKE-NAM were determined through observed discharge of the Muong Ngoy station (Table 2).

The model's performance has been evaluated both visually and quantitatively. Figure 2 compares simulated and observed discharge at the Muong Ngoy station for verification. Both calibrated and validated results show that the simulation at the Muong Ngoy station highly resembles its observation. The mathematical equation of evaluation criteria is provided in Table 3. The values were 12.4% (calibration) and 1.6% (validation), indicating that the simulated discharge was typically underestimated compared with the observation. The calibrated and validated were also 0.77 and 0.87, respectively. Regarding calibration (1999–2000) and validation (2002–2003), the MIKE-NAM model can generate the discharge with a high matching between the observation and simulation for the entire Nam Ou basin.

Projected precipitation

Under all three Shared Socioeconomic Pathways scenarios (SSPs), the monthly precipitation during the rainy season (from July to October) is predicted to rise consistently in the 2040s and 2080s across all provinces (Fig. 3). Moreover, it is expected that precipitation will decline mainly in January, February, May, June, November, and December in both time frames. The precipitation in February in SSP2-4.5 and SSP5-8.5 will drop during the 2040s and 2080s but increase in all remaining time slices under the three SSPs. The

Table 2. Optimized parameters for Nam Ou river basin

Umax	Lmax	CQOF	CKIF	CK1,2	TOF	TIF	TG	CKBF	BF
19.8	300	0.287	222	49.6	0.755	0.979	0.784	3978	70

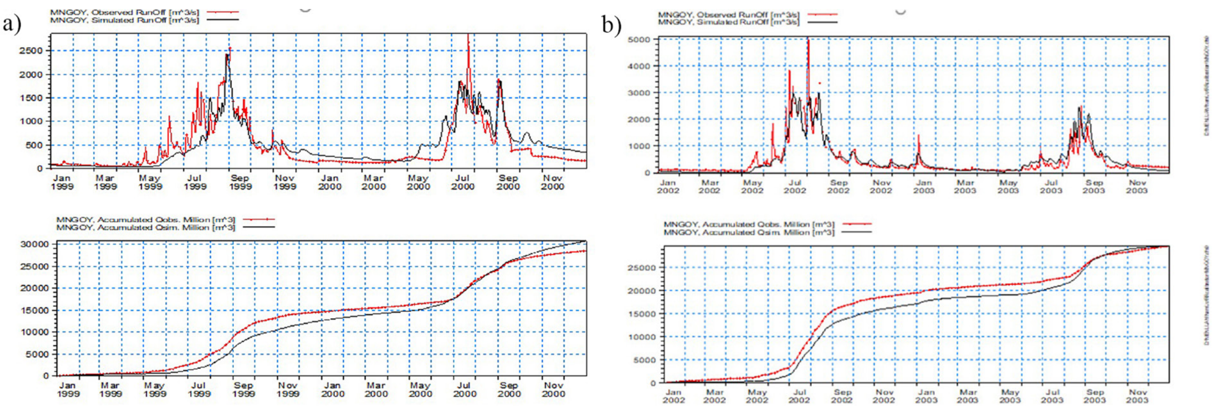

Fig. 2. Discharge and yearly accumulated water volume in Nam Ou River at the station Muong Ngoy for the (a) calibration period, and (b) validation period

Table 3. Evaluation of NAM model results at Muong Ngoy station of Nam Ou River

Statistical criteria	Calibration period	Validation period
WB_{er} (%)	-7.9 (obs 725 mm/y, sim = 783 mm/y)	0.0 (obs = 755 mm/y, sim = 755 mm/y)
R	0.77	0.866

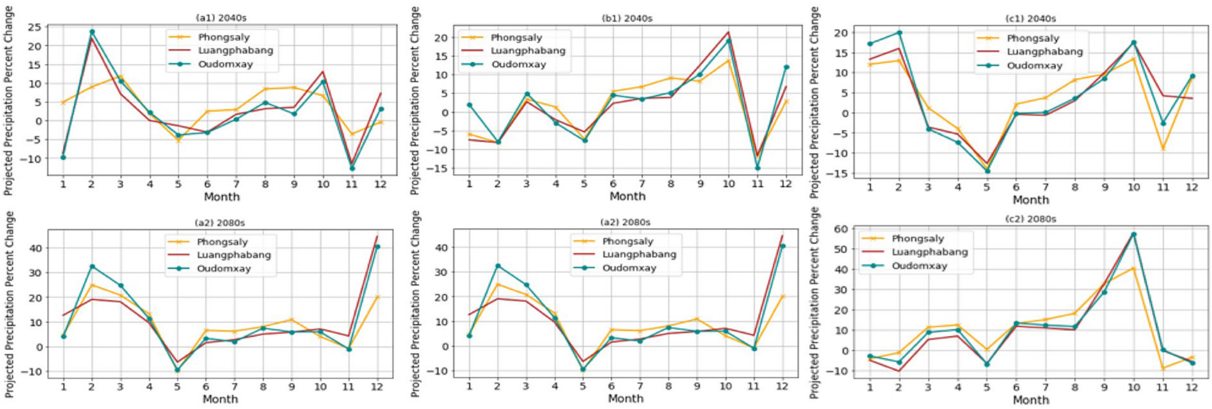

Fig. 3. Projected precipitation percent change for 2040s at Phongsali, Louangphabang, and Oudomxay SSP1-1.9 (a1-2), SSP2-4.5 (b1-2), and SSP5-8.5 (c1-2) with reference period 1995–2014

rainfall in June decreases only during the 2040s under the SSP1-1.9 and increases during the 2040s and 2080s under all three SSPs. December precipitation declines in the 2080s under SSP2-4.5 and SSP5-8.5 as well as grows during the 2040s in three SSPs and all-time slides in SSP1-1.9.

Streamflow change

Using the calibrated parameters, the discharge was projected in response to climate conditions under SSPs using the MIKE-NAM model. The annual flows increase during 2040–2099 under all three SSPs (Fig. 4). The SSP5-8.5 scenario's climate conditions resulted in the largest increase in streamflow (74.82%) from the 2020s to 2080s when compared to the baseline. The smallest increase was seen in the streamflow under the SSP1-1.9, which went from 472.44 m^3/s in the baseline to 473.89 m^3/s under the SSP1-1.9 (only 0.31% increase). Figure 5 displays annual, wet, and dry season flow changes under SSPs. The annual flow increased from 0.31% to 38.31% in the 2040s (Fig. 5a) and increased by 23.35%, 32.80%, and 74.82% in the 2080s under all SSPs. There was a significant difference in streamflow variation between seasons to climate change. Wet season flow increased (Fig. 5b) from 5.56% to 43.30% in the 2040s and from 24.75% to 76.89% in the 2080s in the future. The dry season flow decreased only in the 2040s under SSP1-1.9 scenarios (Fig. 5c).

Figure 5 displays the variation in monthly discharge for all SSPs over the two upcoming decades (the 2040s and 2080s). On the monthly scale, the different responses between scenarios were observed. For the upcoming decades, flow increased from April to July under all SSPs, with the most significant increase in June (Fig. 5). In contrast, the flow was expected to drop in January, February, August, September, October, November, and December in all future decades under SSP1-1.9 – with the largest decrease in September (Fig. 5). This was connected to the reduction in dry precipitation. Notably, the decreases in streamflow under SSP1-1.9 for the 2040s exceeded 20% in all dry months. Compared to the baseline period, streamflow increased in all months for all future decades under SSP5-8.5 and 2080s under SSP2-4.5, except for January projected to

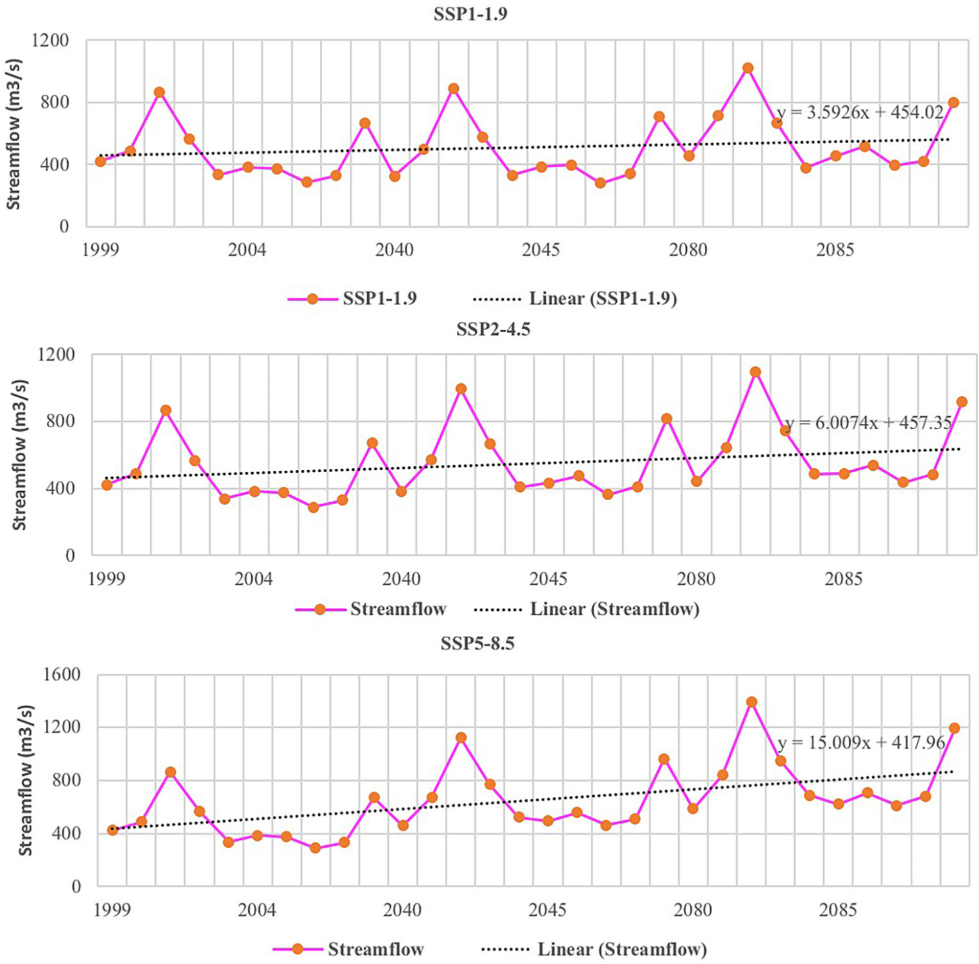

Fig. 4. The annual streamflow simulated by the calibrated MIKE-NAM model for 2020–2099 under the SSP1-1.9, SSP2-4.5, and SSP5-8.5 scenarios

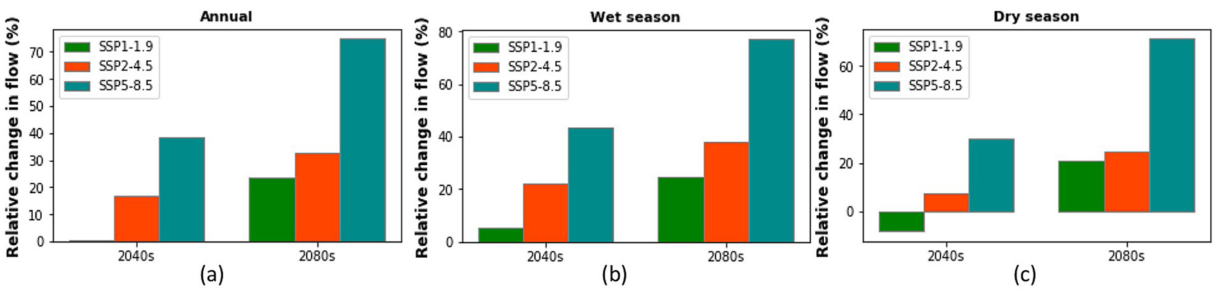

Fig. 5. Changes in mean annual (a), wet season (b), and dry season (c) streamflow for the 2040s, and 2080s

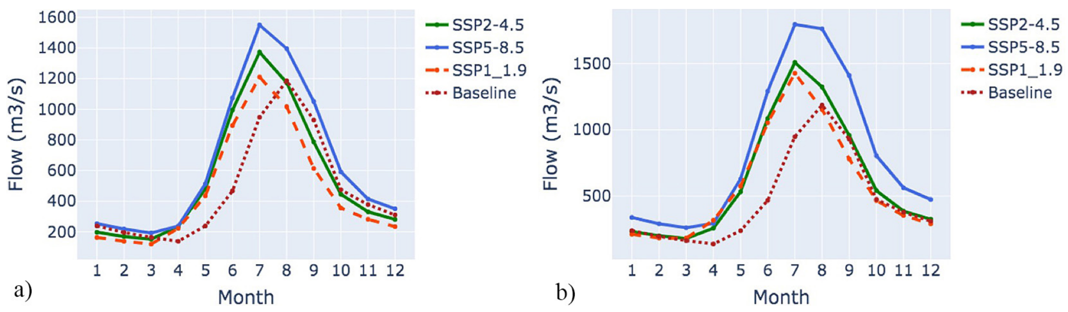

Fig. 6. Comparisons of the monthly mean streamflow between baseline and future projected period for the two future periods (a) 2040s, and (b) 2080s

decrease non-significantly. The flood season begins earlier and is more intense due to climate change (Fig. 6). The flood season in all subsequent decades will extend from June to September, as opposed to the flood season in the 2000s, which lasted from July to October. Flood peaks discharge of 1186 m^3/s appeared in August in the 2000s. Those figures occur in July with a value of 1210.3 m^3/s and 1550.1 m^3/s in the mid-2040s and late 2080s under SSP1-1.9, respectively.

The decreased flows from November to March under the three SSPs during the 2040s may be caused by an expected decline in the dry month precipitation. This precipitation decline will probably result in an earlier wet season under climate change. A warmer climate (under the SSP5-8.5 scenario condition), with lower and higher rainfall at different places, results in higher streamflow in all-time slides (Fig. 5a and b). SP1-1.9 shows a slight decrease of 3.24% in the mid-future and an increase of 14.6% in the far future. In all evaluated periods, the peak discharge indicated a significant increase. Increases amounting to 8.9% and 19.7% are observed in the annual peak discharge at Muong Ngoy for SSP2-4.5, respectively, at the mid and end century. A sharply increased of 23.3% and 48.9% in the peak discharge is seen for the two future projection periods in the SSP5-8.5.

Since this study is the first evaluation of the streamflow variation using the CMIP6 and the MIKE-NAM model for the Nam Ou basin, its performance is assessed by contrasting its results to the previous related research for the MB. These results align with earlier research on the effects of climate change in the MB. An increase of 23%, 16%, and 36% in streamflow are observed in SSP1-1.9, 2-4.5, and 5-8.5, resulting from a 12%, 7%, and 16% increase in precipitation. In comparison, Li et al. (2020) found 10.5%, 20.1%, and 23.2% during 2020–2093 under RCP2.6, RCP4.5, and RCP8.5 scenarios. In 2049, the LMB's maximum annual flows under the A2 scenario (CMIP3) will increase by 3–14%, according to Vastila et al. (2010). Using the Coordinated Regional Climate Downscaling Experiment CORDEX datasets, Khoi et al. (2020) discovered that the annual river discharge of the MB increased by 3.35% to 9.13% in RCP4.5 and 8.5, respectively.

DISCUSSION

This study has presented the streamflow variations in the Nam Ou River basin based on an ensemble mean of CMIP6 scenarios. As such, these results provide critical updates to our understanding of how streamflow responds to climate change which is vital for adapting water resources under climate change. The streamflow response in the Nam Ou basin is generally consistent with the results of earlier research on climate change which observed increasing trends in monthly and wet season discharges. This analysis expects an increase of +0.31% – +75% in annual discharge at Nam Ou, compared to -17 – +66% by Shrestha et al. (2013). The wet season discharge and the yearly peak value will increase in all scenarios, but the low flow will reduce in the SSP1-1.9 scenario. These worsening trends can potentially increase water risks across the basin and affect the downstream area.

The approach used in this study has some drawbacks. The change factor method is used to project future climate conditions. Only scales of the mean of precipitation variables were used. The spatial pattern and the temporal sequence of wet days are assumed unchanged. However, this approach only requires information at a monthly time scale suitable for the data-scarce region as the Nam Ou Basin.

CONCLUSIONS

This study is the first climate change impact assessment on the streamflow for the Nam Ou river basin, a sub-catchment of MB in Lao PDR, based on an ensemble mean of CMIP6 scenarios. The results provide essential updates to understanding the streamflow variation under climate change for the data-scarce region, the Nam Ou basin. In most cases, precipitation increases by 7.7–15.8%, but certain areas and certain months show declining signals. As a result, all scenarios show an increase in annual river discharge, from 0.31 to 74.82%. Increases in both wet and dry seasons are also depicted under climate change impact. The discharge of the rainy season is more significantly impacted by climate change than the dry season. However, the discharge changes in different direction under the SSP1-1.9 and 2–4.5. The wet stream flow was expected to increase by 27.7–112.9% during 2040–2080. The dry season (from August to March) decreases by 1.06–31.53% in the mid-century under the SSP1-1.9. The wet season tends to occur one month earlier in the future. These changes imply significant consequences for controlling water risk in the downstream river delta.

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