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Assessment of climate change impact on river flow regimes in The Red River Delta, Vietnam – A case study of the Nhue-Day River Basin

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Abstract

Global warming has caused dramatic changes in regional climate variability, particularly regarding fluctuations in temperature and rainfall. Thus, it is predicted that river flow regimes will be altered accordingly. The purpose of this paper is to present the results of modeling such changes by simulating discharge using the HEC-HMS model. The precipitation was projected using super-high resolution multiple climate models (20 km resolution) with newly updated emission scenarios as the input for the HEC-HMS model for flow analysis at the Red River Basin in the northern area of Vietnam. The findings showed that climate change impact on the river flow regimes tend towards a decrease in the dry season and a longer duration of flood flow. A slight runoff reduction is simulated for November while a considerable runoff increase is modeled for July and August amounting to 30% and 25%, respectively. The discharge scenarios serve as a basis for water managers to develop suitable adaptation methods and responses on the river basin scale.

1. Introduction

Climate change is believed to be one of the predominant challenges for mankind in the 21st century. It has resulted in immense adverse effects on human and natural systems around the world. Many fields are also being impacted by climate change. For example, a decline of agriculture production and heightening risk of animal and plant extinction are created by rising temperatures; severe flood events are leading to the destruction of infrastructure and loss of lives; and severe droughts occurring in dry seasons will likely lead to water conflict. A regional assessment of climate change on mankind was to some extent addressed in the Fifth Assessment Report by the Intergovernmental Panel on Climate Change **[1]**.

The key factors of climate change are the increases in temperature and variability of precipitation. According to observed data, the last decade has been recorded as the warmest in the last hundred years. The global average surface temperature calculated by a linear trend shows a warming of 0.85°C over the period 1880 to 2012 **[1]**. The global mean surface temperature change for the period 2016-2035 relative to 1986-2005 will likely be in the range of 0.3 to 0.7°C, which is based on the simulation of the new Representative Concentration Pathway scenarios. The new Representative Concentration Pathway of radiation by the end of this century include 2.6 W/m^2 (CPR 2.6/CS1), 4.5 W/m^2 (CPR 4.5/CS2), 6.5 W/m^2 (CPR 6.5/CS3), 8.5 W/m^2 (CPR 8.5/CS4) **[1]**. Increases in temperature are likely to lead to change in hydrological cycles, particularly the growth of spatiotemporal variation in rainfall. It is expected that river flow regimes will fluctuate. Flow in most tropical areas is predicted to rise because of the higher frequency of extreme precipitation. At the same time, more serious drought events during dry seasons may lead to water shortage and further inland salinity intrusion.

The assessment of climate change impacts on hydrology has been addressed for several years. It has been constantly revised thanks to the improvement of climate model outputs regarding spatiotemporal resolution and projection capability. Most estimations are based chiefly upon the coupling method between global atmospheric general circulation models (GCMs), which are set up to simulate the past and current climate and then used to project the future state of the global climate with specific greenhouse gas emission scenarios and hydrological models. Although climate models can be expected to project trends correctly, different climate models can give different outputs. In other words, application of various climate model outputs often results in discrepancies in runoff simulations. Assessment of climate change impacts with multi-climate models has been exhibited as a cost-effective method to determine the scope of the project in the Coupled Model Inter-comparison Project (CMIP).

To date, a large number of impact assessments on flow regimes and water resources have been conducted on river basin scales as a result of changes in rainfall, temperature, and evapotranspiration **[2]**. Typical studies are, for example, the fourth assessment report on climate change **[1]**, **[3]**, impact assessments on river basin scales in Canada **[4]**, **[5]**, America **[6]**, **[7]**, Germany **[8]**, **[9]**, Japan **[10]**, Australia **[11]**, **[12]**, the Mekong River basin **[13]**, **[14]**, **[15]**, the Srepok River **[16]**, and the Thu Bon River **[2]**, etc. These studies mostly focus on the analysis of inter-annual or inter-seasonal variation in streamflow. Studies into changes in frequency and intensity of rainfall have been conducted insufficiently due to the limited capability of climate models for intense rainfall projections. These climate models were developed with very coarse spatial resolution (approx. 300 km grid distance), thus, they are unable to diagnose extreme phenomena occurring on scales much smaller than the computational grid distance.

The variation of river flow regimes in some large river basins was estimated in the latest evaluation. The Fifth Assessment Report conducted by the IPCC **[1]** is an example, employing advanced climate models developed by leading modeling organizations around the world (CMIP4). The report showed that a significant decline in river flow is expected during dry seasons. Increasing temperature and rapid population growth in most of these river basins will lead to severe water shortages by the middle of this century. Other research shows that flood flow during wet periods is forecast to increase in frequency under most climate change scenarios **[17]**. However, it is expected that hydrological responses are dissimilar in each particular river basin because of the distinction in topography and weather patterns. Vietnam is one of the nations most influenced by climate change and the country has grown to consider it as a primary challenge in recent decades. With regard to adaptation strategies to climate change, valuations of river flow change on a river basin scale can provide decision-makers and exposed communities with essential information for improved development of water resource management. This study presents a projection of short-term runoff change in the Nhue-Day river basin as a case study. The precipitation prediction during the period of 2026-2035 under different scenarios simulated by multi-climate models is used as input for a distributed hydrological model to estimate flow fluctuation.

2. Data and Methods

2.1 Study Area

The Nhue-Day river basin, a sub-basin of the Red River Basin in Vietnam, has been chosen as a case study for assessing changes in flow regimes. This basin is approximately 114 kilometers in length, covering five northern provinces of Phu Tho, Vinh Phuc, Hoa Binh, Ha Nam and Hanoi, with a drainage area of 7665 km^2 (**Figure 1**). The basin is often adversely affected by tropical cyclones from the northwest Pacific Ocean to the South China Sea. As shown by observed data, flood and drought frequencies have increased dramatically in recent years.

2.2 Data

Changes in flow regime are governed by some factors, such as rainfall, evaporation, topography, geography, land cover and so on.

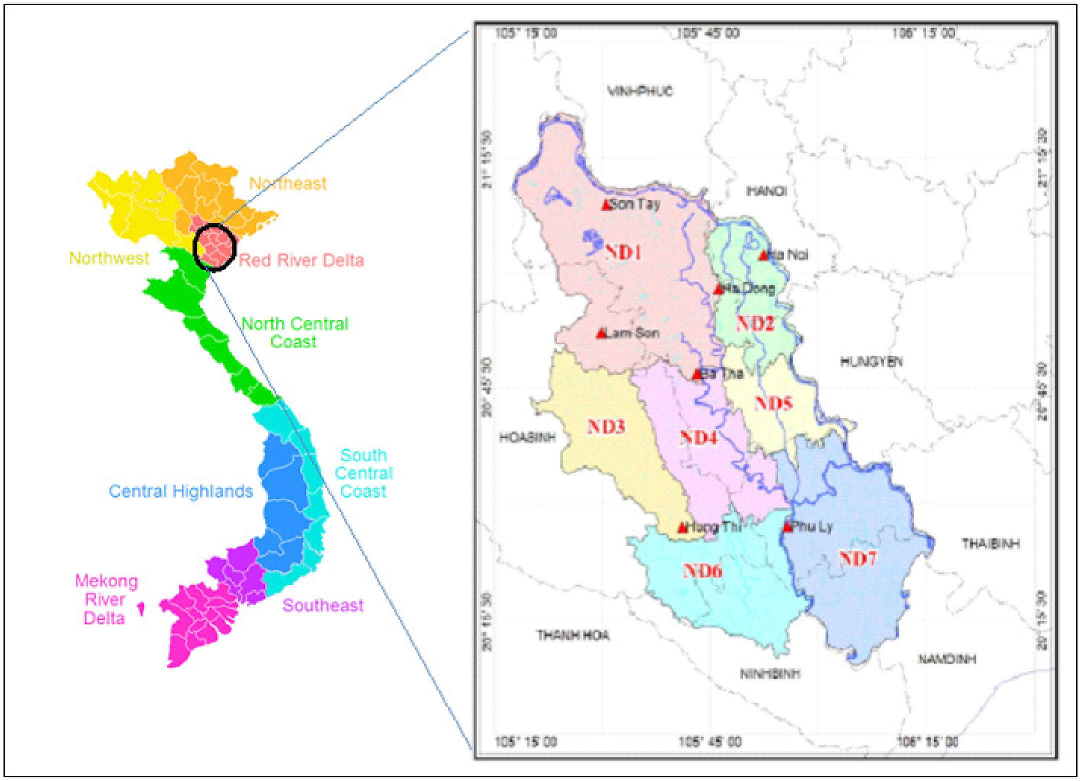

Figure 1: Map of the Nhue-Day river basin and locations of hydro-meteorological stations **[18]**

This study, however, considered certain significant points, namely rainfall, topography, geography, and land cover.

SRTM90 digital elevation data developed by The CGIAR Consortium of Spatial Information was used to extract topographic factors such as elevation and slope. These factors were used to assess hydrological variables such as flow direction and accumulation.

Regarding geographic parameters, the FAO-UNESCO Soil Map of the World 2003 was used. For the vegetation, global land cover classification collected by the University of Maryland Department of Geography was applied. Images from the AVHRR satellite acquired between 1981 and 1994 were analyzed to distinguish fourteen land cover classes. This product is available at three spatial scales: 1 degree, 8 kilometer, and 1 kilometer pixel resolutions (**Table 1**).

Table 1: Code Values for 1 km and 8 km data

Value	Label	RGB Red	RGB Green	RGB Blue
0	Water	68	79	137
1	Evergreen Needleleaf Forest	1	100	0
2	Evergreen Broadleaf Forest	1	130	0
3	Deciduous Needleleaf Forest	151	191	71
4	Deciduous Broadleaf Forest	2	220	0
5	Mixed Forest	0	255	0
6	Woodland	146	174	47
7	Wooded Grassland	220	206	0
8	Closed Shrubland	255	173	0
9	Open Shrubland	255	251	195
10	Grassland	140	72	9
11	Cropland	247	165	255
12	Bare Ground	255	199	174
13	Urban and Built	0	255	255

Meteorological data included mean daily rainfall, mean daily evaporation and mean daily discharge data. The mean daily rainfall was extracted from APHRODITE project (1970-2007) and nine gauges (1962-2010) from the National Center for Hydro-meteorological Forecasting, namely Son Tay, Lam Son, Ha Dong, Lang, Ha Noi, Ha Nam, Phu Ly, Hung Thi, and Ninh Binh. The data from the nine stations was used to verify the APHRODITE data. The APHRODITE data was the data collected from meteorological gauges and then downscaled to precipitation points with a resolution of 0.25 degree. The mean daily evaporation was collected from Lang station while the mean daily discharge data was gathered from three stations: Lam Son, Hung Thi and Ba Tha (1970-1978).

Regarding climate change scenarios, there are four representative concentration pathways (RCPs): RCP 2.6, 4.5, 6.5 and 8.5. This study, however, chose the first three scenarios. It was also assumed that the amount of emissions will reach their highest level in the near future. The precipitation was simulated by three climate models (AGCM3-2H, MIROC-4H, and GFDL-HIRAM-C360) corresponding to the three emission scenarios and was then applied to assess any changes in flow regimes. These data were extracted from the Coupled Model Intercomparison Project.

The Thiessen polygon method is used for interpolation of the rainfall data.

This is an area-based weighting scheme based on an assumption that the precipitation depth at any point within a watershed is the same as the precipitation depth at the nearest gauge in or near the watershed. Thus, it assigns a weight to each gauge in proportion to the watershed that is closest to that gauge.

The gauge nearest each point in the watershed may be found graphically by connecting the gauges and constructing perpendicular bisecting lines; these form the boundaries of polygons surrounding each gauge. The area within each polygon is nearest the enclosed gage, so the weight added to the gauge is the fraction or the total area covered by the polygon.

In this study, 15 rainfall points were used to develop regional meteorology data.

2.3 Methods

General Circulation Model and Climate Model Selection

With regard to the contribution of the Coupled Model Inter-comparison Project, some leading climate modeling centers in Europe, America and Asia have built a large quantity of GCMs. These models commonly give experimental simulations of the global climate with comparatively coarse spatiotemporal resolution; outputs are often on a monthly basis for a grid cell distance of 2 to 5 degrees. As the specific purpose of simulated output, each model generates its own simulation result depending on computational capability. The models thus may vary in terms of physical parameterization, time slice, and spatiotemporal resolution.

Climate modeling centers participating in CMIP5 have created approximately 40 climate models and more than 60 simulations. Most of these models, as the result of increases in computational capability, have much better spatial resolution than those in the past. These spatial resolutions vary from 20 to 500 km and some have even finer spatial resolutions. The fine spatial resolution of climate models can simulate extreme phenomena more accurately than models with coarse spatial resolution.

This study analyzes the predictions of rainfall, runoff and discharge from multiple climate models with the spatial resolution of 20 to 50 km experimented by leading climate modeling centers around the world. The climate models employed in this research include MRI-AGMC3.2H and MRI-AGMC3.2S models (Meteorological Research Institute of Japan), MIROC4h model (Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies), and GFDL-HIRAM-C360 (Geophysical Fluid Dynamics Laboratory - USA).

Hydrological Model

In order to assess climate change impacts on river flow regimes, it is suitable to use a less complex hydrological model which can accommodate the insufficient information of a future catchment **[19]**. In this research, HEC-HMS is applied to perform hydrological analysis of the river. This model is considered a valuable tool for climate change impact estimation because of the simplicity of the model structure and the nearly calibration-free feature of the model parameters. In actual applications, the HEC-HMS model has demonstrated great ability in precipitation-runoff analysis across a wide range of spatial scales **[20]**, **[21]**.

The HEC-HMS model is developed to simulate the rainfall-runoff processes of dendritic catchment systems. Hydrographs created by the program can be used directly or in conjunction with other software for studies of water availability, flow forecasting and so on. This program includes some model components which are used to simulate the hydrologic response in a watershed. The primary components are basin models, meteorological models, control specifications and input data components. A simulation calculates the rainfall-runoff response in the model when provided with input from the meteorological model, whereas the period and time step of the simulation run are defined by the control specifications.

With regard to the structure of the HEC-HMS model (**Figure 2**), the sub-basin storage consists of some components. River water is supplied from two sources, namely precipitation and base-flow. Precipitation falling on land is divided into three parts. Some parts are lost due to infiltration and evaporation, other parts infiltrate deep into the land to supply water for groundwater which then supplies a certain quantity to the river as base-flow, and the other generates direct runoff to pour into the river.

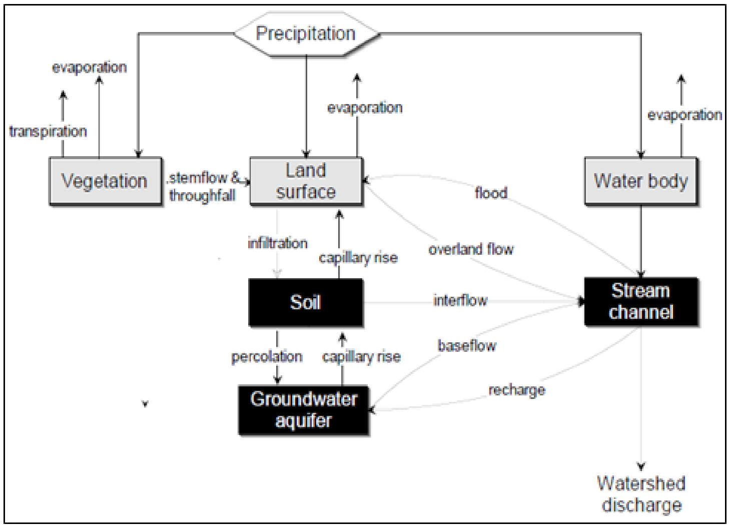

Figure 2: Schematic overview of the HEC-HMS model **[21]**

The estimation of runoff model performance is based on the Nash Sutcliffe Index (NSI), or so-called coefficient of model efficiency. This is detailed in Eq. 1.

$$NSI = 1 - \frac{\sum(Q_{obs} - Q_{cal})^2}{\sum(Q_{obs} - \bar{Q}_{obs})^2} \qquad (1)$$

Where, Q_{obs} = observed monthly streamflow; $\bar{Q}_{obs}$ = observed mean monthly streamflow; Q_{cal} = calculated monthly streamflow.

Model Calibration

1) Theory of the rainfall-runoff model

One of the greatest benefits of the HEC-HMS model is its nearly calibration-free parameters. There are three components required for model calibration including computing runoff volumes, modeling direct runoff, and modeling baseflow. In this study, these parameters are selected as follows.

To compute runoff volumes (Eq. 2), a loss method of initial and constant was chosen. The initial and constant-rate model, in fact, includes one parameter (the constant rate) and initial condition (the initial loss). These respectively represent physical properties of the catchment soils and land use and the antecedent condition.

$$P_{et} = \begin{cases} 0 & if \sum pi < Ia \\ pt - fc & if \sum pi > Ia \; and \; pt > fc \\ 0 & if \sum pi > Ia \; and \; pt > fc \end{cases} \qquad (2)$$

Where, P_{et} is the runoff volume; *Ia* is the initial loss; *pt* is the MAP depth during a time interval t to t + Δt; fc is constant throughout an event.

In order to simulate direct runoff (Eq. 3), Snyder Unit Hydrograph Model is used. To apply this transform method, two parameters need to be defined, namely the lag tp and the peak coefficient C_p. While C_p ranges from 0.1 to 0.8 as suggested of Bedient and Huber (1992), the lag time tp is calculated with the following equation:

$$t_p = CC_t(LL_c)^{0.3} \qquad (3)$$

Where C_t = basin coefficient; L = length of the main stream from the outlet to the divide; L_c = length along the main stream from the outlet to a point nearest the watershed centroid; and C = a conversion constant (0.75 for SI and 1.00 for foot-pound system).

Baseflow is determined by an Exponential Recession Model. The recession model has been used many times to explain the drainage from natural storage in a watershed **[14]**. It defines the relationship of Q_t, the baseflow at any time t, to an initial value as:

$$Q_t = Q_0.k^t \qquad (4)$$

Where Q_0 = initial baseflow (at time zero); and k = an exponential decay constant.

2) Model calibration and validation

Based on input data on the physical properties of the catchment soils and land use, the previous conditions, observed precipitation and flow discharge, the above parameters are defined. However, since these model parameters are not measured parameters, they are best determined by calibration.

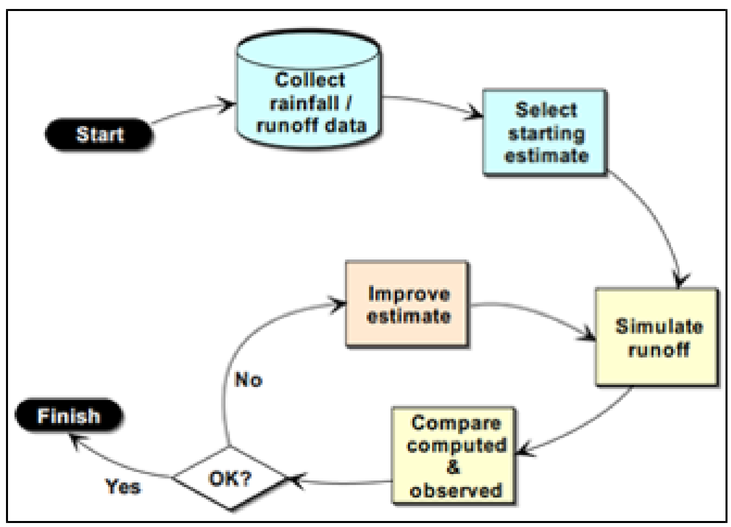

Figure 3: Schematic overview of calibration procedure **[21]**

The calibration procedure begins with data collection (**Figure 3**). For rainfall-runoff models, the required data are precipitation and discharge time series. The next step is to select initial estimates of the parameters. In this study, after the step of initial valuation of the parameters, historical rainfall and flow data for the period of 1972 to 1974 are used for calibration. Model validation is performed for the period 1976 to 1978.

3. Results

a) HEC-HMS Model Calibration

Through the calibration process, candidate predictor variables for model calibration are identified, as shown in **Table 2**. Results showed that the simulated hydrograph fits very well with the observed hydrograph (**Figure 4**); most high flow periods are caught by runoff model. It can be seen in **Figure 4** and **Figure 5** that the simulated discharge exhibits very good agreement with the observed discharge; it is comparable to those reproduced employing precipitation values from rain stations. The coefficient of model efficiency (NSI = 0.86) is attained for the overall model performance. Hence, validation of the runoff model demonstrates a high level of confidence for the application of this calibrated model in future climate and runoff analysis.

Table 2: Candidate predictor variables for model calibration

Model	Parameter	Value
Initial and constant-rate loss	Initial loss	= 5.00 mm
	Constant loss rate	= 0.20 mm/hr
Snyder's Unit Hydrograph	Lag	= 20 hr
	C_p	= 0.15
Baseflow	Initial discharge	= 30 m^3/s
	Recession constant	= 0.96
	Flow	= 25 m^3/s
Muskingum routing	K	= 1.67
	X	= 0.15
	Number of steps	= 10 step

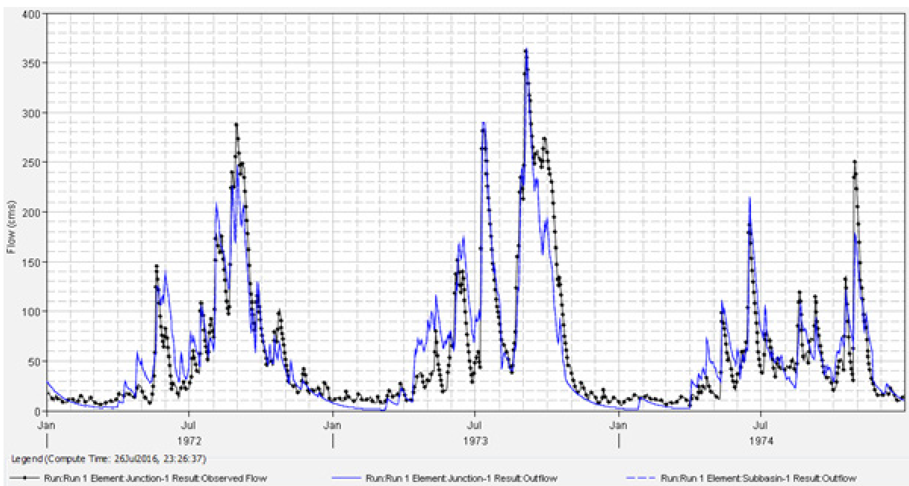

Figure 4: Time-series of observed and simulated discharge for model calibration (1972-1974).

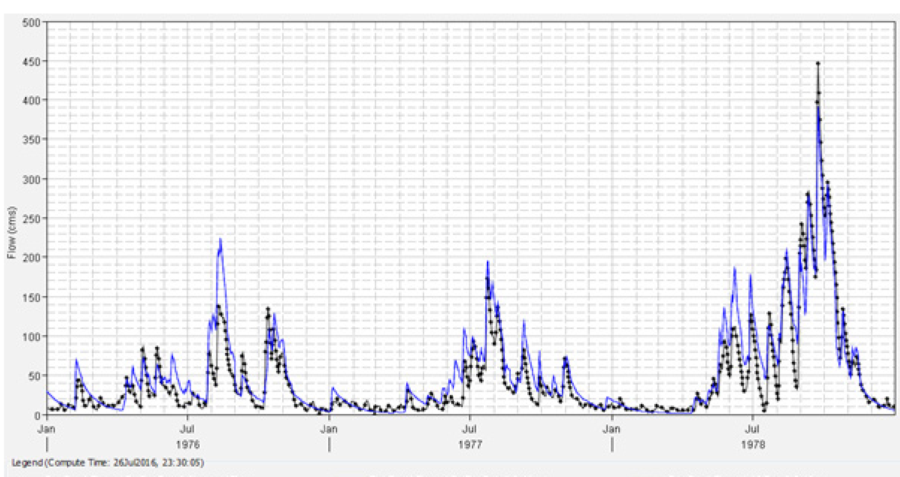

Figure 5: Time-series of observed and simulated discharge for model validation (1976-1978).

b) Evaluation of future variability in Climate change scenarios

The following section shows the short-term projections of variation in mean monthly precipitation relative to the baseline (1979-2003). The variation percentages of the predicted mean monthly precipitation are presented at **Figure 6**, **Figure 7** and **Figure 8**.

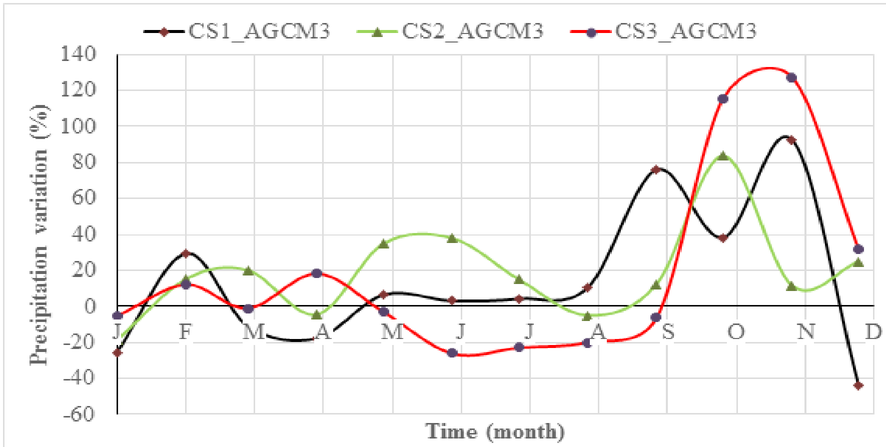

Figure 6: Short-term predictions of variations in mean monthly rainfall relative to the baseline, 1979-2003 (AGCM3 model).

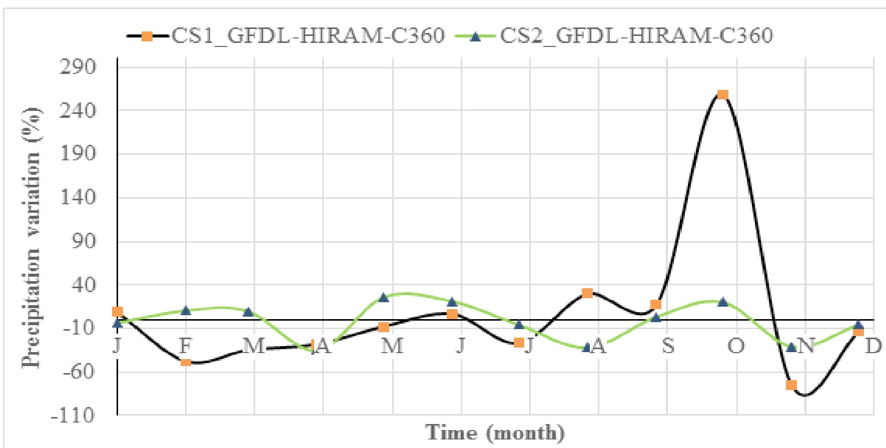

Figure 7: Short-term predictions of variations in mean monthly rainfall relative to the baseline, 1979-2003 (GFDL-HIRAM-C360 model).

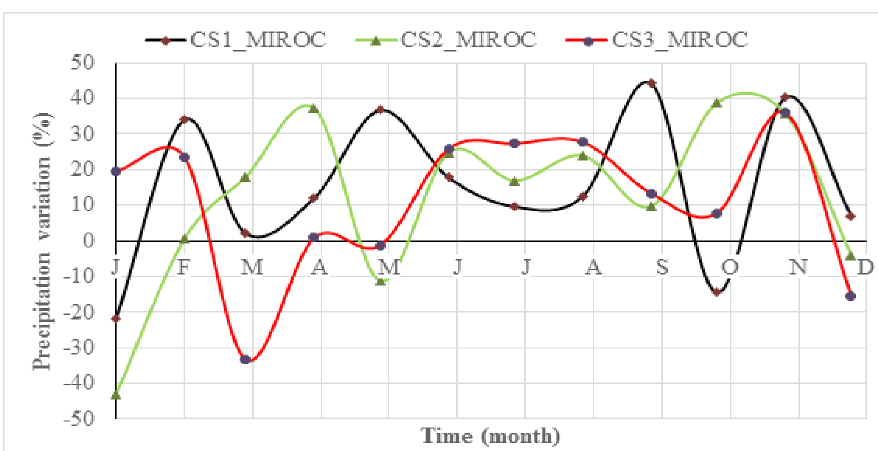

Figure 8: Short-term predictions of variations in mean monthly rainfall relative to the baseline, 1979-2003 (MIROC model).

The changes in projected mean monthly precipitation are described from **Figure 6** to **Figure 8**. The amount of projected mean monthly rainfall varies according to climate models, scenarios and the periods, but increasing trends are seen in most simulated results. The quantity of rainfall simulated by AGCM3 and GFDL-HIRAM-C360 models undergo slight fluctuations from -40% to 40% during most months of the year, except October and November (rainy season). In this period, the predicted mean monthly precipitation is expected to increase by more than 100 % relative to those of the baseline (1979-2003). Likewise, rising trends in future rainfall is forecast by the MIROC climate model and shown in **Figure 8**.

c) Projection of Runoff Variation

To estimate the potential runoff reactions to climatic change, the short-term predictions (2026 to 2035) of rainfall based on outputs of multiple climate models are used to simulate river regimes. Simulated discharges are then compared to those of the baseline during the period 1979 to 2003. Based on the input precipitation data, the model calculated the created discharge with a period of fifteen minutes through water loss transforming and baseflow. Water loss was computed by the method of initial and constant loss while the Snyder Unit Hydrograph method was used for calculating water transforming. The recession method was applied to identify baseflow. The mean discharge of fifteen minutes was used to calculate the mean daily discharge based on the weighting average method.

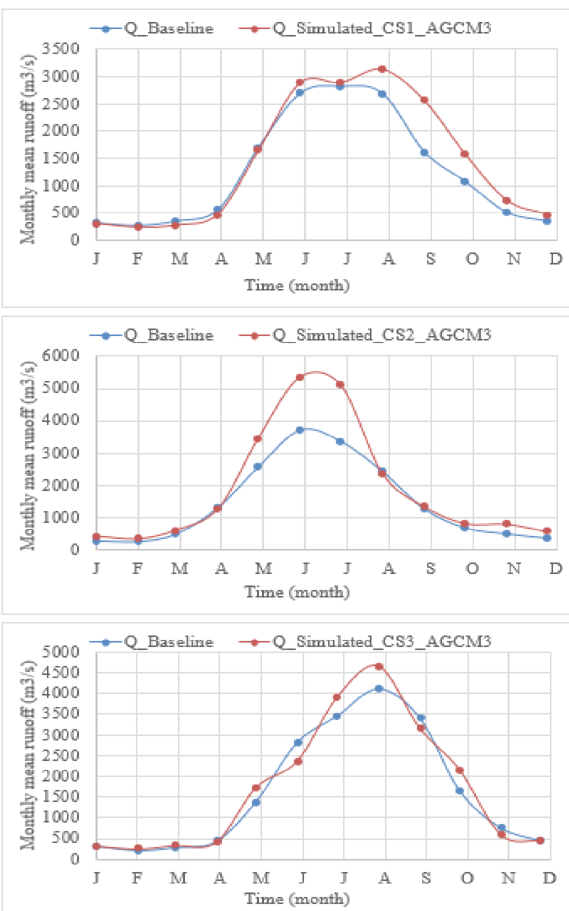

Figure 9: Hydrographs of observed and projected mean monthly discharge for the period 2026-2035 (Based on projected precipitation from the AGCM3 climate model with three scenarios, CS1, CS2 and CS3).

The changes of precipitation are regionally dependent on the increase in surface temperature which has been noted throughout the entire globe **[3]**. As a result of surface temperature increase, evapotranspiration is likely to rise, so that a higher evapotranspiration rate is expected in the future. This could directly affect flow creation routing. Thus, the variation of evapotranspiration rate plays an important role for flow estimation. However, the projected period of runoff in this research is short-term from 2026 to 2035 and thus surface temperature increase is insignificant, as it is projected to be about 0.4°C **[1]**. Meanwhile, the shift of simulated runoff is insignificantly impacted by the variability of evapotranspiration, meaning it may remain unchanged during the process of projection flow. Therefore, the procedure of flow response to climate change impacts is based mainly on the variability of projected precipitation from the output of three climate models with three scenarios, as mentioned above. The simulations of runoff response to the three climate scenarios are conducted using the HEC-HMS rainfall-runoff model. Simulated hydrographs during the period 2026 to 2035, which are illustrated in **Figure 9**, **Figure 10** and **Figure 11**, are compared to the observed discharge in the baseline period (1979-2003).

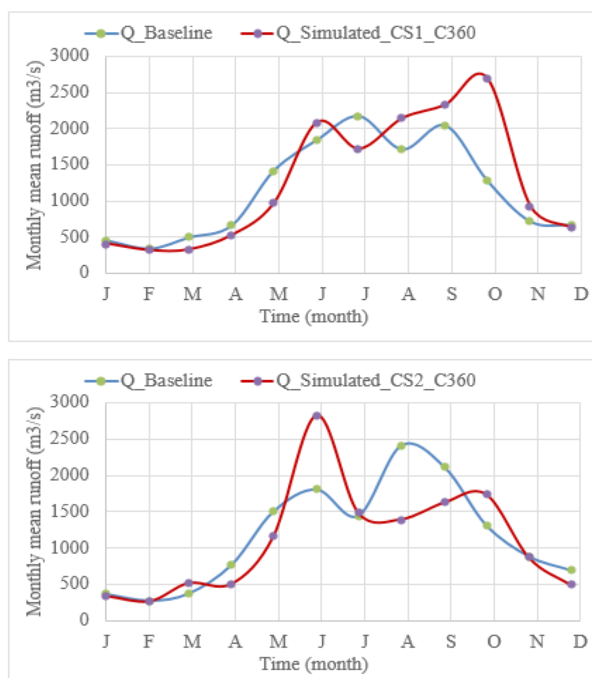

Figure 10: Hydrographs of observed and projected mean monthly discharge for the period 2026-2035 (Based on projected precipitation from the GFDC-HIRAM-C360 climate model with two scenarios, CS1and CS2).

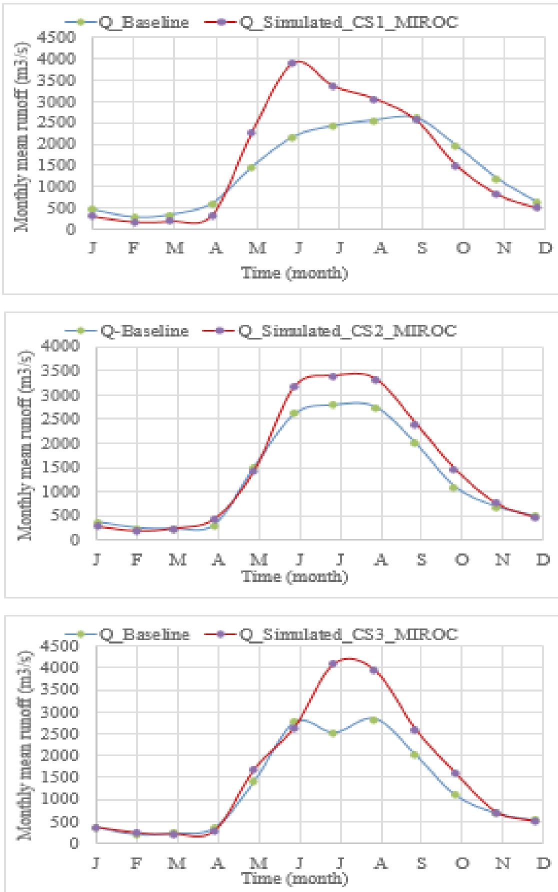

Figure 11: Hydrographs of observed and projected mean monthly discharge for the period 2026-2035 (Under scenarios CS1, SC2 and CS3, respectively).

4. Discussion

How are climate change tendencies projected for the Red River Delta by the different climate models?

Overall, although the computed mean monthly flow quantities differ considerably among the various scenarios used and the simulation period, the wet season discharges see more variation than the dry season discharges (**Figure 9** to **Figure 11**).

Under emission scenario CS1, the mean monthly discharge modeled by AGCM3 and GFDL-HIRAM-C360 greatly increase from September to November while the MIROC model shows a dramatic rise in simulated discharge during the period of May to August. The range of these changes is from 50 to 100% compared with the baseline. On the other hand, the simulated mean monthly discharge for the other months experiences an insignificant decrease, which accounts for approximately 10%.

Likewise, under emission scenario CS2, remarkable trends are indicated in the mean monthly discharge data projected by all climate models in the wet season. The range of these changes is from 20% to 40%. The discharge in the dry season is predicted to have a slight decline fluctuating between -30% and 10%.

Finally, the modeled results forecast by all climate models under emission scenario CS3 present some differences. Whereas a nearly unchanged trend is demonstrated in the mean monthly discharge simulated by the AGCM3 climate model during the predicted period, the discharge modeled under the MIROC model is expected to rise hugely in the wet period. Its discharge remains nearly unchanged in the dry season.

How does the discharge respond to climate change signals in the selected climate models?

The assessment of climate change impacts on flow regimes in the Nhue-Day river basin, as a case study of the Red River Basin, will deepen the understanding of the possible flow changes occurring in the Red River Basin and thus support the planning of water use and exploitation in this area. In the following sections, findings will be summarized, followed by discussion and comparison with those of the former similar assessments in the same field. Based on this discussion, a more general debate on the remaining challenges and future study themes will be specified.

In this analysis, the flood season happens from May to October, while the remaining months comprise the dry season. As can be seen in **Figure 12** and **Figure 13**, whereas flood flow is projected to increase significantly, the low flow regime is expected to decrease slightly. The high flow goes up from 20% to 60%, while the low flow insignificantly declines between about 10% and 20% according to scenarios and the output of the climate models. The results show better agreement with the estimates of Nguyen Nhu Y **[22]** on the direction and magnitude of the change (**Figure 12**). Nguyen Nhu Y projected an increase between approximately 15.9% and 69% for scenarios in the wet season, while the dry period saw decreases between around 20.58% and 27.51% depending on the scenario. This is perhaps because of the increased potential evapotranspiration rate over time, where a slight increment of precipitation is predicted.

It is obvious that the variability in river flow regimes will probably cause effects on ecosystems, the environment, and activity both within the watershed and downstream. Increased surface temperature and reduced water availability in dry seasons will tend to increase pressure on water resources. Moreover, the reduction of water availability in the dry period will lead to further inland salinity intrusion, which is a problem that lowers the amount of cultivable areas. Hence, agricultural production is predicted to fall. The level of water conflicts might also rise due to the increased water shortages. It is also expected that the risk of flood disaster will occur more frequently because of land-use change and rapid urbanization processes.

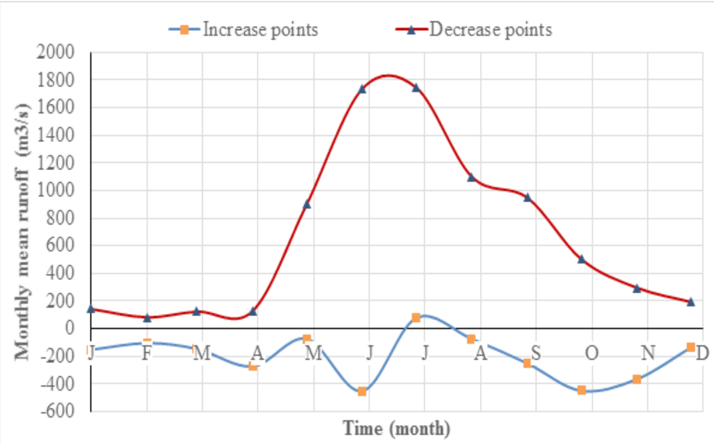

Figure 12: The range of variability in mean monthly discharge for the period 2026-2035 (Based on projected precipitation from multiple climate models).

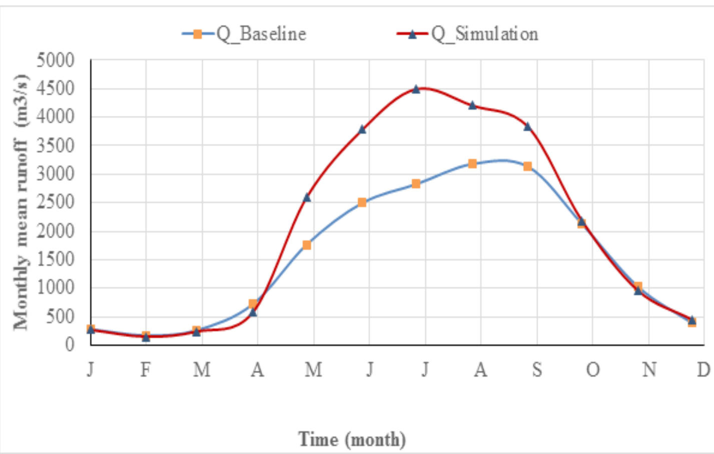

Figure 13: The absolute changes in mean monthly discharge for the period 2026-2035 (Based on projected precipitation from multiple climate models).

5. Conclusions

It is very likely that climate change impacts will be a primary concern for human beings, the environment, and ecosystems. It is very important to develop adaptation strategies in order to respond to climate change effects. This study presents how climate change might impact river flow regimes in the near future (2026-2035) in the Red River Delta with the Nhue-Day river basin being selected for a case study, using outputs from multiple state-of-the-art high resolution climate models (belonging to Coupled Model Inter-comparison Project – Phase 5, IPCC). The findings are summarized as follows:

• With different climate models predicting the outcome of different precipitation, the simulated flow results also differ. Hence, synthesized simulation results from different models give overall changes. This allows us to easily forecast the possibility of occurrence in the future.

• Aggregated results from all models showed that flow will significantly increase in the wet season while it will slightly decline in the dry period. This leads to more dangerous flooding during the rainy season to damage infrastructure while further water shortages will occur in the dry season.

• Along with population growth and rapid urbanization, these changes will further increase the pressure on sustainable water resource exploitation, use and management in the near future.

6. Acknowledgements

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