River Flow Estimation under Future Climate Conditions: The Case Study of the Nith River Basin Using SWAT Modeling Tools

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ABSTRACT

The impact of climate change may pose a threat to the magnitude and occurrence of river flow. Efficient watershed management requires a rational approach to predicting future climate change impacts. The Nith River in Ontario, Canada has experienced frequent flooding as a result of extreme storm events every year or sometimes multiple times per year. The purpose of this study is to provide guidance on building watershed resiliency through flooding condition assessments and the use of climate scenarios for the watershed. Three future climate scenarios are assessed, to identify the most suitable one. The North American Regional Climate Change Assessment Program (NARCCAP) provided a scenario using Canadian Regional Climate Model and Canadian Global Climate Model version 3 (CRCM-CGCM3); another scenario involved Regional Climate Model version 3 and CGCM3 (RCM3-CGCM3), while the Ministry of Natural Resources (MNR) provided an additional scenario. This statistical analysis represents the best match between the observed and projected data of MNR. According to future climatic data, precipitation-runoff was calculated by a hydrological model which is known as the Soil and Water Assessment Tool (SWAT). Calibration and validation were performed to optimize the model's results. Bias factors were calculated from the observed period data and used to adjust future runoff estimates. This research showed significant changes in storm magnitude and frequency due to climate change, providing insights for watershed management and development. However, the results may vary, if different climate scenarios and precipitation-runoff models are used.

Keywords-climate change; Nith River; watershed resiliency; SWAT model; precipitation-runoff model

I. INTRODUCTION

Adapting to climate change has gained momentum and the potential impact of climate change is considered one of the foremost factors influencing a watershed's hydrological characteristics. However, the potential impacts of climate change on floods are highly unpredictable [1]. Climate-induced changes in river flow at the basin scale can be used for flood simulation to support future development and adaptation of floodplain infrastructure [2]. Climate change is a growing concern in the field of water resource studies. A convective climate affects local, regional, and global scales [3]. Authors in [4] found significant increase in precipitation, temperature, stream flow, and base flow timing shifts in Nepal's Karnali River Basin under future climate scenarios. In [5], it was stated that water yield in Ethiopia's Genale Watershed is projected to decline under future climate scenarios [5]. Significant seasonal and annual streamflow increases occur under climate change, with varying trends across monsoon periods in India's Mahi River Basin [6]. Therefore, researchers are emphasizing the need for sustainable land and water management [7].

There are several ways in which uncertainties may emerge in climate change projections. The Global Circulation Model (GCM) is downscaled to a local resolution and incorporated into hydrologic model simulations to predict future scenarios [8]. Hydrological variables are very sensitive in spatial and temporal scale, with climate change influence being considered one of the governing factors. As a result, powerful modeling tools are required for depicting sensitive hydrological characteristics.

In this study, historical and projected climate datasets were downloaded from downscaled data of the North American Regional Climate Change Assessment Program (NARCCAP) and the Ministry of Natural Resources' (MNR) climate portal. The study area's observed station data are also taken into account. The dynamic NARCCAP's downscaled data provide an open source of higher resolution climate scenarios, which are widely used in regional and local scale studies, impact analysis and further downscaling in the region [9]. In Nith River basin scale impact analysis, these projected climate data from different sources are applied to examine potential extremes in the future climate data.

NARCCAP simulations are being widely used in climate assessment studies [10]. The NARCCAP model simulates CRCM data at the local scale with the boundary conditions of CGCM3, as well as the MNR. Data are analyzed before SWAT is used to simulate future conditions. SWAT, a basin-scale watershed hydrology transport model, is employed to assess and quantify the impact of physical properties in a large and complex watershed. The stochastic process of the model deals with the complexity of the natural systems to simulate surface runoff. The SWAT model is a highly capable tool for long-term simulations in the watersheds which are dominated by agricultural land uses [11]. SWAT has been modified and adapted for providing improved simulation [12].

The study's objectives are to identify the appropriate climatic dataset and use a complex hydrologic model simulation to illustrate how climate change affects river flow. A climate time series analysis is conducted using historical observed data (1973–2000) obtained from Environment and Climate Change Canada's Historical Climate Data portal [13], and future predicted data (2041–2070) sourced from NARCCAP [14] and the Ontario Climate Data Portal [15].

The Nith River basin (Figure 1) is characterized by a mixture of rural, agricultural, forest, and urban land uses. Flooding has periodically occurred throughout this basin. New Hamburg, Plattsville, Ayr, and Paris are especially prone to flooding. New Hamburg and Ayr flow records indicate an increase in natural flood peaks since 1975. The Grand River Watershed in Southern Ontario is where the research area is situated. Gads Hill and the New Hamburg area are in the northwest, the municipality of Ayr is in the center, and Paris lies in the southeast. The downstream of south-east part falls into the Grand River near Paris. The study area comprises mixed land use. The Nith River flows through the township and rural areas. New Hamburg, Ayr, Canning, and Paris are commonly impacted by the floods of the river. The Grand River Conservation Authority (GRCA) continuously monitors the floods, with flow-gauges into the river.

In the western part of the Region of Waterloo, the river basin includes a portion of woodland, east of the township of Wellesley and northwest of Crosshill. The river flows north into Perth County before making a dramatic swivel to the southwest and passing through Perth East's Fernbank and Millbank neighborhoods. It travels further south, passes Smith Creek, a right tributary, and reaches the town of Nithburg. South of the Wellesley settlement in Wellesley township, the river runs eastward again into the Waterloo Region, receiving Silver Creek on the right and Firella Creek on the left. The river flows through the Ontario towns of Phillipsburg and New Hamburg before turning south into the municipality of Wilmot and receiving the left tributary, the Bamberg Creek. After continuing south, Nith enters Blandford-Blenheim, Oxford County, passes through the communities of Baden Creek and Hunsburger Creek on the left, and arrives at Plattsville. The river flows eastward, receiving the tributaries Black Creek on the right and Hiller, Alder, and Eden Creek on the left before returning to the Waterloo Region, arriving in the community of Ayr in North Dumfries township, where it receives the tributary Cedar Creek on the left. After making a sudden curve to the west, it flows back into Oxford County before turning to southeast and passing past the towns of Canning and Wolverton. After passing Barker's Bush, the Nith enters Brant County, where it receives the left tributary Charlie Creek and the right tributary Mud Creek before emptying. The MNR climate data portal provides access to climate data across Ontario, including data from the Grand River near Paris.

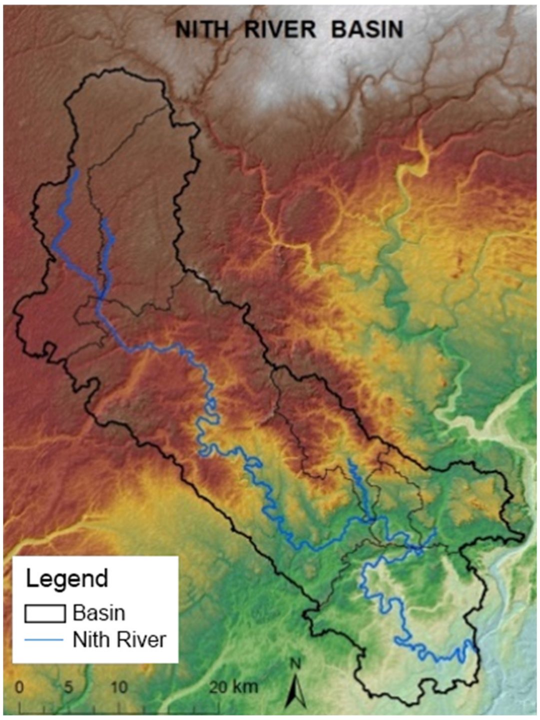

Fig. 1. Nith River basin.

II. MATERIALS AND METHODS

A. Data Analysis

1) Downscaling Method for NARCCAP Data

The NARCCAP is an international program that applied a dynamical method to downscale data from a coarse grid Atmospheric-Ocean General Circulation Model (AOGCM) to a finer grid (50 km) regional scale. The AOGCM is based on the A2 emission scenario from Special Report on Emissions Scenarios (SRES) for the 21st century, which simulates climate scenarios for currents (historical, 1971-2000) and future periods (2041-2070). The CGCM3 (T47 geographic resolution) was one of the four boundary conditions supplied by the AOGCMs. With the same land mask between the ocean grid and atmosphere, T47 version introduces a spatial surface grid including a resolution of about 3.75 degrees latitude/longitude and 31 levels vertically. The dynamical method is applied to Regional Climate Model (RCM) with atmospheric time-slice experiments in the downscaling process. Additional data and physical processes akin to GCMs at a greater resolution encompassing a regional portion are needed for the dynamic process. Although this approach has many benefits, it is computationally demanding and necessitates a high level of skill to apply and analyze the results. Since the RCM is nested to GCM, the overall quality of the dynamically downscaled outputs is tied with the coarse grid GCM data quality and biases [16]. Thus, the observed station data and MNR projections in the study area are considered to assess the reliability of the local scale climate data from different sources.

2) NARCCAP Data Preparation

The NARCCAP data contain a high resolution climate change scenario covering CRCM boundary for 30 years of present and future climate datasets. The 3-hourly dataset runs at a 50-km spatial resolution over Canadian domain. The data are useful for impact analysis, further downscaling experiments, and uncertainties in the analysis of regional scale climate change projection. [9]. The Phase II experiment, which includes numerous RCMs as well as multiple runs with various boundary conditions supplied by various GCMs, is the most significant component of the NARCCAP experiment. Climate-change forecasts are accessible from the Phase II experiment since RCMs are run for both the present and subsequent periods, to gain a better understanding of how the current and future climates correlate with hydrology models used to calculate surface runoff.

3) MNR Data Preparation

The MNR climate data portal facilitates the availability of the climate data across Ontario [15]. The data are projected in 25 km x 25 km resolution and provide intuitive and easy access for users. The data are projected in different patterns of frequencies (annual, seasonal, monthly, daily, and hourly). The daily time series data were collected for this study, which includes the historical observed period (1973-2000) and future period (2041-2070).

B. Bias Correction

Bias correction is an essential approach to adjust future flow prediction. The bias in flow is a subsequent influence of the bias that occurs in precipitation and temperature [17]. The mean value or variance is employed as a common formulation to calculate an additive or multiplication factor. This process is also termed as Linear Scaled (LS) factor. The LS method is commonly applied to investigate the biasness in the estimated flows. The LS approach, which seeks to precisely match the monthly mean of corrected data with the observed one, was used in [18]. The LS method is applied in this study to correct the biasness of the monthly simulated flow using a multiplier calculated using:

$$Q_{corr} = Q_{sim} \times \frac{\mu(Q_{obs})}{\mu(Q_{sim})} \quad (1)$$

where Q_{corr} is the corrected flow, Q_{sim} is the simulated flow, $\mu(Q_{obs})$ is the mean of the observed flow and $\mu(Q_{sim})$ is the mean of the simulated flow.

C. Hydrologic Modeling

In this study, the SWAT hydrologic assessment model was used. This basin-scale model was created for evaluating the effects of land use in a sizable, intricate watershed. The Agricultural Research Services of the U.S. Department of Agriculture made the model available to the public. Surface runoff, climate, percolation, return flow, transmission losses, evapotranspiration, crop growth and irrigation, storage in ponds and reservoirs, groundwater movement are all included in the model. The model simulates flows for the observed and future period of climate data for the river basin. To maximize model performance, the output of the observed period model was calibrated and verified. The calibrated parameters set up in the observed period simulation were used to model the future period. The world land use data are available in the water base database, hosted by United Nations University (UNU). The resolution of the original data is 400 m and has been used to set land use classes in the model. Table I lists the seven land use classifications that are present in the Nith River basin.

TABLE I. LAND USE TYPES IN THE NITH RIVER BASIN

Land use types	Cover (%)
Agricultural land-generic	0.05
Agricultural land-row crops	9.24
Agricultural land-close grown	0.07
Hay	88.88
Forest mixed	0.49
Wetlands non-forested	1.24
Winter pasture	0.03

1) Soil Data

Soil and Landscape in Canada (SLC) uses the SLC v3.2 to gather the soil class data. The various soil types that are still present in the Nith River basin are shown in Table II. Each type of soil class contains different characteristics such as silt, clay, rock, bulk density, electric conductivity, soil albedo, pH, and water retention (K).

TABLE II. SOIL TYPES OF THE NITH RIVER BASIN

Soil class	% of Occupied area
FOXM	4.6
FOXS	2.2
HONEYWOOD	8.3
FOX	12.4
WATERLOO	1.1
BROOKSTON	9.4
BURFORD	19.2
HURON	33.4
HURONS	0.4
HARRISTON	0.3
PERTH	8.9

D. Model Calibration and Validation

The predicted observed period data were calibrated and validated to optimize the model performance by means of SWAT Calibration and Uncertainty Procedures (SWAT-CUP). The results of this process are summarized in Table III.

TABLE III. MODEL PARAMETERS USED FOR OPTIMIZING MODEL PERFORMANCE

Parameter name	Fitted value	Minimum value	Maximum value
1:R__CN2.mgt	-0.24	-0.33	0.3
2:V__ALPHA_BF.gw	0.38	0.1	1.2
3:V__GW_DELAY.gw	1.92	1	4.68
4:V__GWQMN.gw	962.50	750	1000
5:R__SOL_AWC(..).sol	0.28	0.1	0.6
6:V__ESCO.bsn	0.06	0	0.43
7:R__SOL_K(..).sol	0.29	-0.87	0.5
8:R__SOL_BD(..).sol	0.27	-0.43	0.5
9:V__REVAPMN.gw	5.50	0	10
10:V__GW_REVAP.gw	0.10	0	0.4
11:V__RCHRG_DP.gw	0.37	0	0.39

The results of the model were calibrated for 1973–1977 and validated for 1978–1982. Table IV and Figure 2 provide a summary of the calibration performance parameters' output. The Nash Sutclif efficiency value is 0.54 which is in an acceptable limit. Other researchers accepted a Nash Sutclif value of 0.4 or more in their studies [19].

TABLE IV. MODEL PERFORMANCE PARAMETERS

Parameters	Calibration	Validation
p-factor	0.45	0.40
r-factor	0.84	0.91
R2	0.73	0.69
Nash Sutclif	0.54	0.52

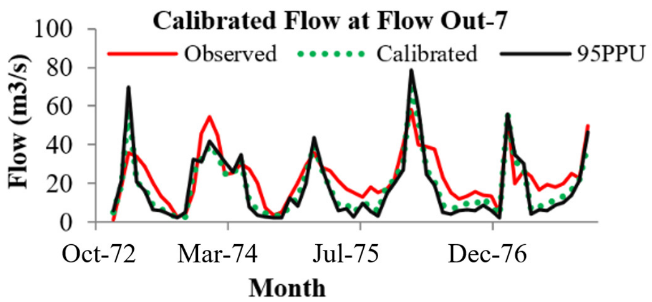

Fig. 2. Calibrated outflow hydrograph at Outflow-7 (downstream outlet).

III. ASSESSMENT OF PREDICTION SCENARIOS

A. Kolmogorv-Smirnov Test

Different statistical methods are applied to assess the data distribution patterns. A popular method for examining the relative variability of precipitation data is the Kolmogorov-Smirnov (K-S) test. This is one of the most useful and nonparametric methods for comparing two samples to investigate the similarity of distribution [20]. The principle of K-S test observes the maximum vertical distance between empirical distribution functions of the two samples.

Let the data be a random sample of size x_1, x_2, x_3,…, x_n with an unknown distribution function F(x). The fraction of x_i's that is less than or equal to x for each x, $-\infty<x<\infty$, is equivalent to the empirical distribution function S(x), which is a function of x:

$$S(x) = \frac{1}{n}\sum_{i=1}^{n} I_{\{x_i \leq x\}} \qquad (2)$$

As an estimator of F(x), the unknown distribution function of Xis, the empirical distribution function S(x) is helpful. To find out if there is a good distribution agreement, the empirical distribution function S(x) and the proposed distribution function F*(x) will be compared. The comparison is measured with the largest vertical difference of these two functions. If the test statistic D is defined as the largest (denoted by "sup" for supremum) vertical distance between the two functions, it can be written as:

$$D = \sup_{x} |F^{*}(x) - S(x)| \qquad (3)$$

The K-S test is applied for Woodstock and Roseville stations' time series data located in the study area to assess the distribution patterns between historical observed and simulated precipitation datasets, projected by the NARCCAP and MNR. The following tables represent the results of the analysis. Tables V and VI present the results of the K-S test and indicate that the significance values are greater than 0.05, which represents an approximation of the normal distributed datasets.

TABLE V. STATISTICAL DATA PROPERTIES AT WOODSTOCK STATION

		Monthly precipitation at Woodstock station			
		Observed	**MNR**	**CRCM**	**RCM3**
Most extreme differences	Absolute	0.070	0.073	0.053	0.050
	Positive	0.070	0.073	0.053	0.050
	Negative	-0.042	-0.041	-0.030	-0.042
Kolmogorov-Smirnov Z		1.288	1.330	0.966	0.910
Asymp. Sig. (2-tailed) (p-value)		0.072	0.058	0.308	0.379

TABLE VI. STATISTICAL DATA PROPERTIES AT ROSEVILLE STATION

		Monthly precipitation at Roseville station			
		Observed	***MNR***	***CRCM***	***RCM3***
Most extreme differences	Absolute	0.091	0.095	0.071	0.073
	Positive	0.091	0.095	0.071	0.073
	Negative	-0.055	-0.059	-0.046	-0.043
Kolmogorov-Smirnov Z		1.668	1.737	1.300	1.330
Asymp. Sig. (2-tailed) (p-value)		0.077	0.058	0.068	0.058

B. Histogram Test

A histogram analysis is performed to find the distribution of frequency and the normality of a sample. In this study the histograms are plotted to find the similarities of the data frequency and their normality in a given range of population. Tables VII and VIII, and Figures 3 and 4 show that the frequency distributions between the observed precipitation and predicted precipitation (MNR) are closely correlated for both Woodstock and Roseville stations in terms of mean value, standard deviation, and visual curve patterns. It is also indicated that the ratios (Z-values) of skewness to its standard error and of kurtosis to its standard fall within the ranges of ±1.96. Therefore, it is concluded that although the data setsare skewed and kurtotic in all cases, they do not differ significantly from normality.

TABLE VII. STATISTICAL PROPERTIES OF HISTOGRAM ANALYSIS FOR WOODSTOCK STATION

	Precipitation			
	Observed	***MNR***	***CRCM***	***RCM3***
Mean	75.26	84.09	81.07	118.96
Std. Deviation	34.31	37.76	34.07	42.88
Skewness (SK)	0.819	0.772	0.751	0.874
Std. Error of Skewness (SESK)	0.453	0.453	0.453	0.453
Ratio (SK/SESK)	1.807	1.704	1.657	1.928
Kurtosis (K)	1.069	0.639	1.020	1.984
Std. Error of Kurtosis (SEK)	0.666	0.666	0.666	0.666
Ratio (K/SEK)	1.003	0.599	0.957	1.862

TABLE VIII. STATISTICAL PROPERTIES OF HISTOGRAM ANALYSIS FOR ROSEVILLE STATION

	Precipitation			
	Observed	***MNR***	***CRCM***	***RCM3***
Mean	80.80	81.01	84.68	107.16
Std. Deviation	40.48	40.80	38.65	39.65
Skewness (SK)	1.103	1.304	0.607	0.525
Std. Error of Skewness (SESK)	0.833	0.833	0.833	0.833
Ratio (SK/SESK)	1.323	1.565	0.729	0.630
Kurtosis (K)	1.766	3.010	0.019	0.204
Std. Error of Kurtosis (SEK)	1.666	1.666	1.666	1.666
Ratio (K/SEK)	1.060	1.807	0.011	0.122

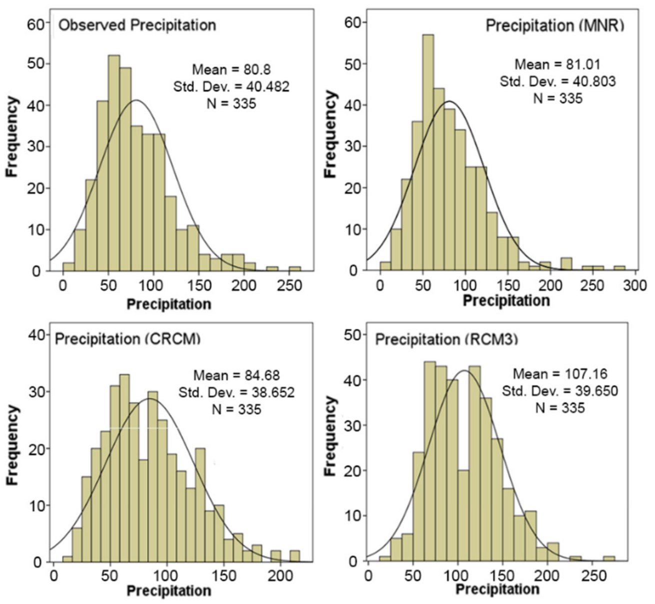

Fig. 3. Histogram plots of observed data (1973-2000) at Woodstock station.

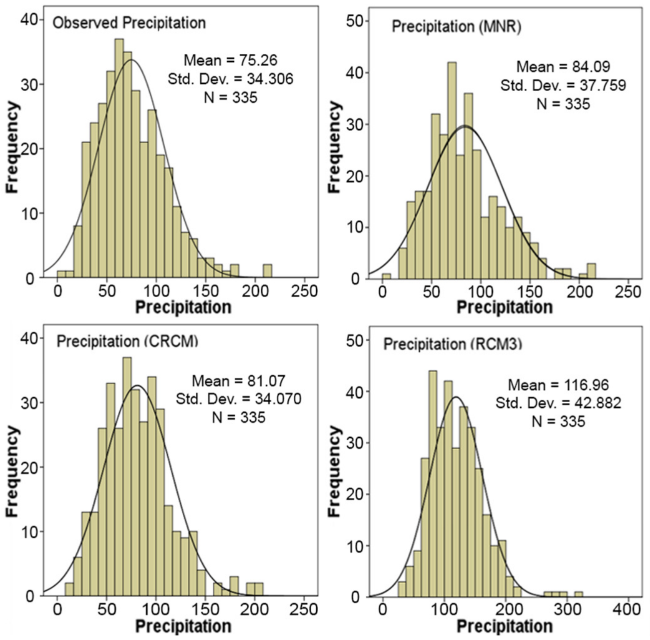

Fig. 4. Histogram plots of observed data (1973-2000) at Roseville station.

IV. RESULTS

A. *Flow Simulation Results*

As a result of the flow simulation using the SWAT hydrological model, the daily predicted flows of the Nith River were obtained for the 2041–2070 time period. All predicted future scenarios and observed period climate data were used in the hydrologic model simulation and the simulated results were compared for assessment. The predicted observed-period data were used together with the station observed data to calculate the bias factors of the model. The model-simulated future flows were then adjusted with the bias factors.

B. *Results of Simulation with Bias Correction of Flows*

The historically observed station flow data of the research area were compared with the simulated flows for the observed periods in future climatic scenarios. The calculated factors resulted in $\mu(Q_{obs}) = 12.22$, $\mu(Q_{sim\text{-}MNR}) = 15.84$, $\mu(Q_{sim\text{-}CRCM}) = 18.45$, and $\mu(Q_{sim\text{-}GCM3}) = 34.02$. The linear-scaled bias correction factors were applied to adjust the simulated flows for the future period. Figure 5 provides an example of bias correction of the future period data.

C. *Future Period (2041-2070) Simulation*

All the climate data considered in this study were used in the SWAT hydrologic model simulation. The model incorporated with temperature, precipitation, relative humidity, solar radiation, and wind speed data for the Nith River basin. The model outputs of the daily flow simulation, corrected using the bias factors, are presented in Figure 6. The results indicate that the overall potential increase in flow due to climate change is 15.55% using MNR data, 7.88% using CRCM data, and 10.46% using GCM3 data for the 2041-2070 time period. It is indicated that MNR data may predict greater climate-induced flow in the river, resulting in a peak flow of 390.2 m^3/s compared to the historical peak flow of 320.0 m^3/s.

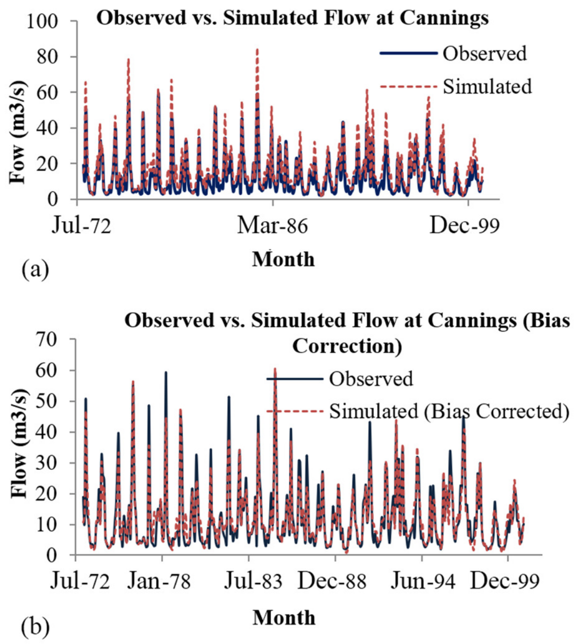

Fig. 5. Observed and simulated flow hydrograph (a) before and (b) after bias correction.

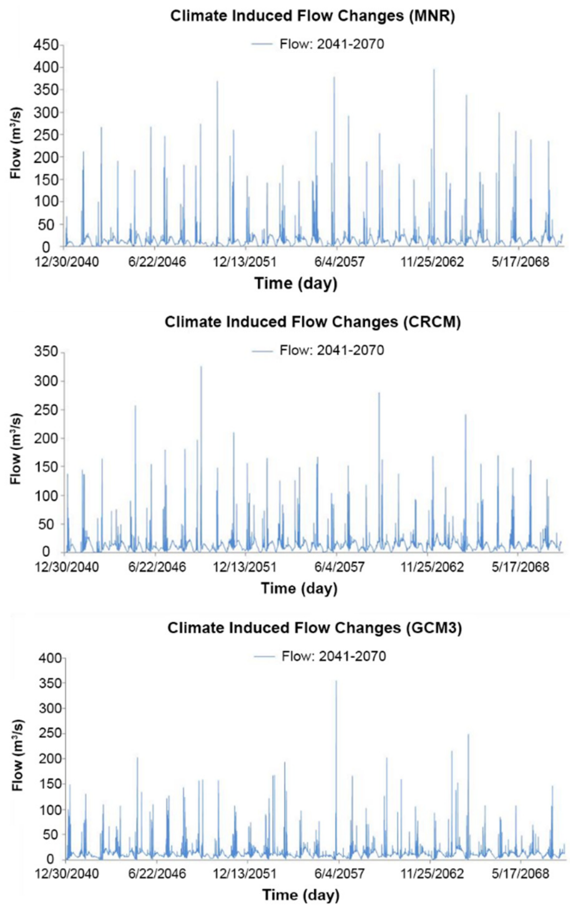

Fig. 6. Simulated (2041-70) flow hydrographs.

V. CONCLUSION

The analysis of future climate change impact on hydrology is essential for floodplain and watershed management. However, information on the potential impact of climate change is limited. This study presents and discusses the downloaded data as well as the downscaling procedure of various sources of forecasted climatic data. Using these data, a thorough semi-distributed SWAT hydrological model was used to calculate precipitation-runoff. The findings indicate that, by the 2070 time frame, there is a considerable chance that the Nith River basin will be impacted by future climate change. An ensemble of the most suitable climate data scenario was determined through a rigorous statistical analysis of NARCCAP and MNR prediction datasets. The climate scenarios were then converted into basin runoff using the hydrologic model. The impact of future climate change on Nith River watershed is the cause of the alterations in flow projections.

The results of this research are:

- The maximum magnitude of the overall climate change-induced daily flow is projected to increase by 15.6%.
- The magnitude of the probable annual extreme event flow is expected to increase by 23.5%.
- The observed magnitude of the historical extreme event flow is 320 m^3/s; whereas the occurrence of future magnitude of extreme event flow is expected to reach 390.2 m^3/s.
- The variability of the magnitude of the annual maximum flow is expected to be more frequent in the future period than the observed period.
- The average magnitude of the observed annual extreme event flow is 186 m^3/s. The results show that the probability of occurrence for this magnitude was 0.39 in the observed period and 0.55 in the future period.

The research review suggests that the Nith River basin may be significantly impacted by climate change, with a greater likelihood of larger flow magnitudes and more frequent occurrences. As climate change impact involves with numerous uncertainties, the projected changes presented in this research may differ if other climate scenarios and precipitation runoff models are used. These results are limited to the Nith River basin, as physical properties (land use, topography, permeability, drainage density) vary across basins. However, the procedures and methodology applied in this research can be used in other study areas.

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