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Analysis of Streamflow Response to Changing Climate Conditions Using SWAT Model

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Abstract

The understanding of climate change is curial for the security of hydrologic conditions of river basins and it is very important to study the climate change impacts on streamflow by analyzing the different climate scenarios with the help of the hydrological models. The main purpose of this study is to project the future climate impact on streamflow by using the SWAT model. The multi-model projections indicated that Upper Ayeyarwady River Basin is likely to become hotter in dry season under low rainfall intensity with increasing temperature and likely to become wetter but warmer in both rainy and winter season because of high rainfall intensity with increased temperature in future. The impact of climate change scenarios is predicted to decrease the annual streamflow by about 0.30 to 1.92% under RCP2.6, 5.59 to 7.29% under RCP4.5 and 10.43 to 11.92% under RCP8.5. Based on the change in high and low flow percentage with respect to the baseline period, the difference between high and low flow variation range will increase year by year based on future scenarios. Therefore, it can be concluded that it may occur more low flow in the dry season which leads to increase in water scarcity and drought and more high flow in the wet season which can cause flooding, water insecurity, stress, and other water-related disasters.

Keywords: Climate Change; SWAT Model; Streamflow; High and Low Flow.

1. Introduction

The assessment of climate change impact on streamflow is one of the most interesting issues in hydrological research [1]. Changes in air temperature and precipitation cause a major impact on the hydrologic cycle directly and indirectly and moreover, the water resources [2]. Climate change altering the amount, intensity, form, and timing of precipitation as well as the rate of evapotranspiration also affects hydrological regimes by affecting the volume, peak rate, and timing of river flow [3]. For studying the impact on the regional water resource availability, the estimation of changes in river flow is the most common and is considered for decision-making processes in water-resource management [4].

Myanmar is situated in the tropical climate region with three dominant seasons: the hot season (16 February to May), the wet season (June to September), and the cold season (October to 15 February) [5] and a region that is highly vulnerable to impacts from climate change. There are about 60 rivers in Myanmar [6], the country's largest main river is Ayeyarwaddy and it is an important commercial waterway used for trade and transport. The Ayeyarwaddy River is divided into the upper and lower parts with the river confluence with the Chindwin River [7]. Upper Ayeyarwady river basin is one of the major river basins in Myanmar and consists of Central Dry Zone and the Northem Hilly Region. The central dry zone area is known as the "oil pot" of the country and the economic growth of the country through agricultural development is essential in prenatal economic life. However, current climate change effects such as high temperature,

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scarce rainfall, etc. are now threatening agricultural crops and farmers' livelihood. So, climatic condition in dry zone region is the key factor for the development of the agriculture and farmers' livelihood [8]. In the northern hilly region, it is already experiencing the problems of flood and heavy rains [9] and this effect may be more severe in the future due to climate change [10]. Therefore, information about the future streamflow related to climate change for this river plays as a fundamental role. It is essential to quantify and understand climate changes in the Upper Ayeyarwady river basin and those likely to occur over the coming century. This is also a starting point that Myanmar's stakeholders can use to plan for more summer monsoon rainfall in agriculture, hydropower, conservation areas, dams, flood management and so on [11].

It is important to understand Information derived from Global Climate Models (GCMs) and general characteristics of GCMs for assessing both past and future likely changes in climate scenarios and for assessing the climate change impact on hydrological analysis [12]. Future climate scenarios were produced based on a statistical relationship between climate variables at one or more GCM grid points with the variable of interest at a particular station [13]. Scenarios are images of how the world is likely to evolve in the future in terms of greenhouse gas [14]. In this study, climate information obtained from Representative Concentration Pathways (RCPs) is used to forecast future hydrological changes. There are so many hydrological models for understanding the impact of climate change on the nature of hydrological flow and for calculation of water discharge more accurately, easily and quickly than the traditional measurement method. Soil and Water Assessment Tool (SWAT) is one of the most popular modelling software for assessing hydrologic impacts. The main objective of this study is to forecast the impact of future climate projections on streamflow of the future period by using the projections of precipitation and temperature based on outputs of selected suitable climate models from downloaded 10 GCMs under RCP Scenarios across the Upper Ayeyarwaddy River Basin. The structure of this article is organized as follows: study area descriptions are presented in Section 1. Methodological framework is described in Section 2 and materials and methods of this study are described in Section 3. Section 4 presents the results and discussions of this study. Finally, conclusion is described in Section 5.

1.1. Study Area

In this study, climate change impacts on the water sector highlight the Upper Ayeyarwaddy river basin which is covering about 60% of the total area of Myanmar and originates at the confluence of the N'Mai Hka and Mali Kha rivers. The Upper Ayeyarwaddy is situated at 20˚22' - 28˚50' north latitude and 94˚56' - 98˚42' east longitude [15] and covered by Kachin State, Mandalay Division, the western part of Shan state and Southeastern part of Sagaing Division as shown in Figure 1. The outlet of the whole basin was selected at Sagaing and the watershed area for this Upper Ayeyarwaddy River is 152,264 km^2.

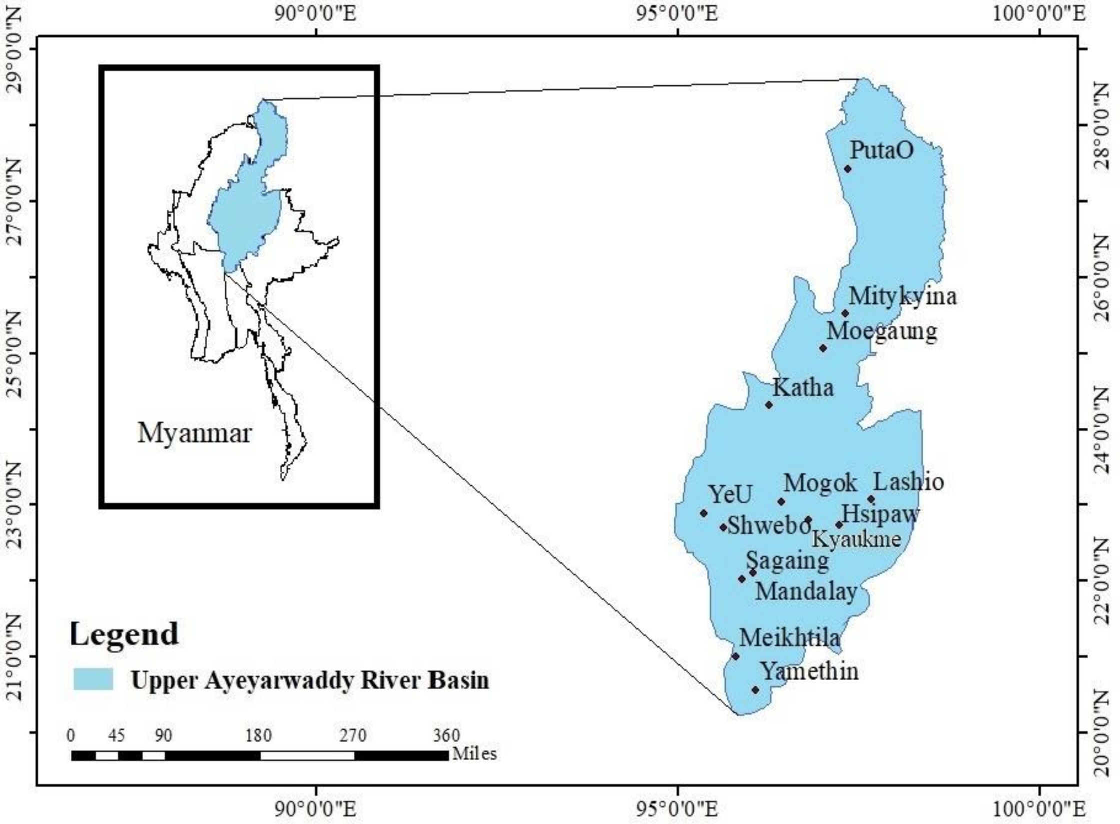

Figure 1. Location of the study area

2. Methodological Framework

The objective of this study has combined two aspects: firstly, assessment of climate change impacts on the climate variables (rainfall and temperature) and secondly, assessment of the response on the river's hydrologic system of climate variables. The Methodological Framework of this study is shown in Figure 2 and involves: (I) spatial and climate data preparation into SWAT format, (ii) model setup, including watershed delineation and Hydrologic Response Units (HRUs), (iii) model calibration and validation, and (iv) assessment of future climate change impacts on streamflow. SWAT model which is ArcGIS extension, ArcSWAT 2012 version was downloaded from the United States Department of Agriculture (USDA) website. SWAT is a partially distributed model and required digital elevation model (DEM), land use and soil map which are basic modeling requirements and daily weather data. Calibration and Validation were performed using the SWAT CUP program. At this stage, several hydrological model parameters were adjusted for achieving the best fit between the simulated and measured flow at the monitoring station. Finally, climate change impact on future streamflow is projected by using the SWAT model based on meteorological changes under climate change projection.

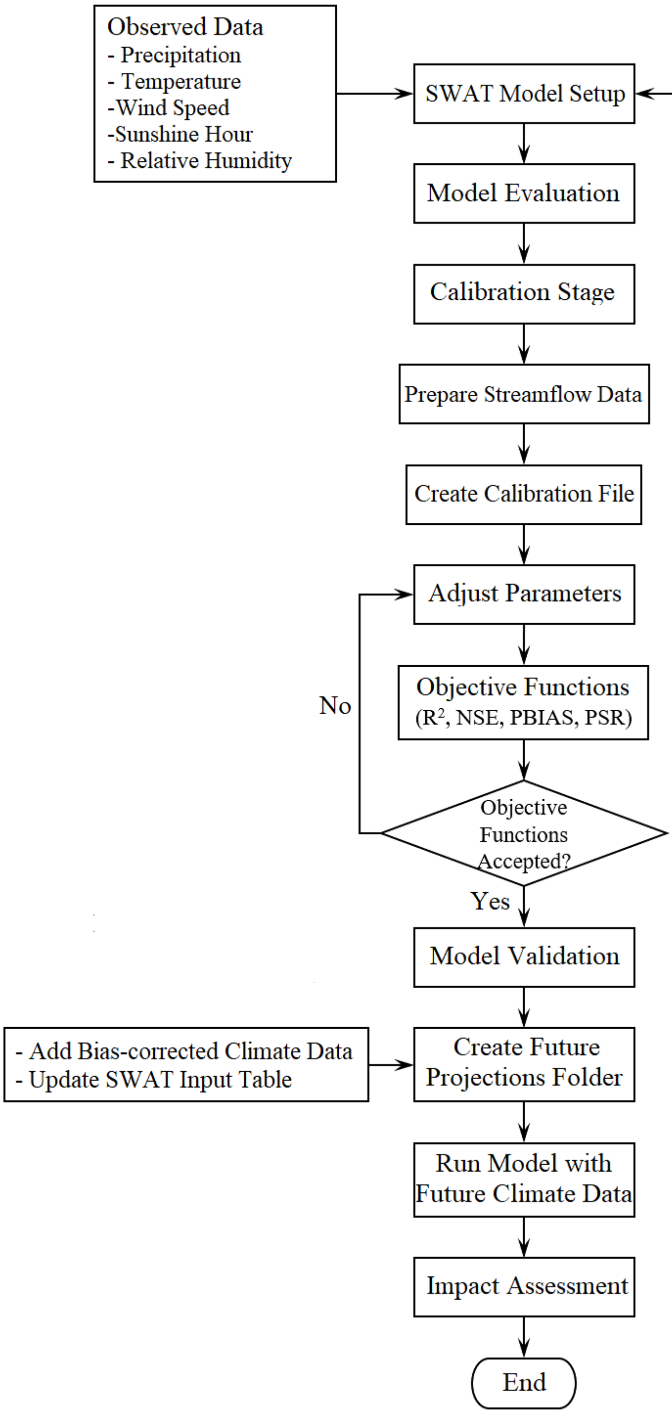

Figure 2. Methodology framework for the assessment of climate change impacts on future flows of the Upper Ayeyarwady River Basin

3. Materials and Method

3.1. Global Climate Models (GCMs)

GCMs are the primary tools that provide reasonably accurate global, hemispheric, and continental-scale climate information and are used to understand present and future climate scenarios under increased greenhouse gas concentrations [13]. The CMIP5 is a newly developed data archive and contains a great number of model output enhance the understanding of climate processes and their effects. These data will provide a basis of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). GCMs are models to generate a description of the state of the atmosphere and produce most of the meteorological variables, such as wind speed, relative humidity, rainfall, surface air temperature and solar radiation [16].

3.2. Representative Concentration Pathways

RCP based projections were used in the most recent IPCC Fifth Assessment Report (AR5). According to the change in radiative forcing by 2100, there are four RCPs. RCP 2.6 is representative of scenarios that lead to very low greenhouse gas concentration levels [17]. RCP 4.5 and RCP 6 are stabilization scenarios that lead to intermediate greenhouse gas concentration levels. RCP 8.5 is representative of scenarios that lead to high greenhouse gas concentration levels [18]. The future projections are based on the future radiative forcing of the atmosphere. Three of the RCPs: the low emission scenario (RCP2.6), the mitigation scenario (RCP4.5) and the high emission scenario (RCP8.5) which is characterized by increasing greenhouse gas emissions are used in this study.

3.3. Meteorological and Hydrological Data Collection

Weather data such as daily precipitation and temperature data of all fourteen stations within Upper Ayeyarwaddy River Basin are used in this study form 1981 to 2015 and these are acquired form the Department of Meteorology and Hydrology (DMH). Other data such as wind speed, solar radiation and relative humidity from the period 1981 to 2013 are collected from Global Weather Data for SWAT Website. The data availability period of the Sagaing hydrological station which is the outlet station of the Upper Ayeyarwaddy River Basin is 1991 to 2015.

3.4. Soil and Water Assessment Tool (SWAT) Model

Hydrological models are becoming more and more widespread, mainly due to their capacity to simulate the impact of environmental changes on water resources [19]. The Soil and Water Assessment Tool abbreviated as SWAT is a basin-scale model that was developed by the United States Department of Agriculture (USDA) – Agriculture Research Service (ARS) [20]. The SWAT model simulates hydrology as a two-component system, composed of land and channel hydrology. The land portion of the hydrologic cycle is based on a water mass balance. Soil water content is computed using the water balance equation [21]:

$$SW_t = SW + \sum_{i=1}^{t}\left(R_i - Q_i - ET_i - P_i - QR_i \right) \tag{1}$$

Where, SW is the soil water content; i is time in days for the simulation period t; R is the daily precipitation; and Q, ET, P and QR respectively, are runoff, evapotranspiration, percolation and return flow.

Other than the topographic, soil and LULC data, SWAT requires spatially explicit datasets of climatic data at daily/sub-daily time steps. Major input data for SWAT include DEM, LULC, soil properties, and daily weather data (precipitation, maximum and minimum air temperature, relative humidity, wind speed and solar radiation) [22].

3.5. SWAT - CUP

SWAT-CUP is a computer program that was developed for SWAT models. SWAT-CUP was employed for model calibration, validation, and sensitivity analysis by using the observed runoff data. The program links four calibration methods such as Generalized Likelihood Uncertainty Estimation (GLUE), Sequential Uncertainty Fitting Procedure Version 2 (SUFI2), Markov Chain Monte Carlo (MCMC) and Parameter Solution (ParaSol) [23]. SUFI2 method was chosen because it is the most suitable way to find the SWAT uncertainty under the condition that the parameter range was specified. Sequential Uncertainty Fitting Algorithm (SUFI-2) is very advantageous since it combines optimization with uncertainty analysis and can handle large number of parameter to achieve good prediction uncertainty ranges for the period of 6 years (2002 to 2007). Responded to parameter set more sensitive than any others [23, 24].

3.6. Model Performance Evaluation Procedure

There are many kinds of error parameters which are widely used for testing and accuracy assessment of the SWAT model; such as Nash-Sutcliffe coefficient of efficiency (NSE), percent bias (PBIAS), coefficient of determination (R^2) and RSR (ratio of the root mean square error to the standard deviation of measured data). These parameters indicate the goodness of fit of the observed value with the simulated value. The model calibration was aimed to achieve a satisfactory model efficiency of NSE ≥ 0.5, PBIAS ≤ ± 25%, and RSR ≤ 0.7.

The determination coefficient, R^2 is used to determine the agreement between the simulated and observed flow data. Model prediction evaluation was categorized as satisfactory if R^2 is greater than 0.6 [25].

4. Results and Discussion

4.1. Selection of Suitable Climate Models and Scenarios

Ten global climate models such as CanESM2, CCSM4, CMCC-CMS, GFDL-CM3, GFDL-ESM2G, MRIOC ESM, MIROC ESM CHEM, MPI ESM LR, MPI ESM MR, MRI- CGCM3 for the 5th Coupled Model Intercomparison Project (CMIP5) are used to consider to climate projections.

Here, the multi-GCMs approach is applied rather than using single GCM because different GCMs have different grid-sizes and their coverage area. R^2 and RMSE (root mean square error) parameters are used for the performance of the bias correction method in model selection. GCM with higher agreement on performance indicators is selected. Suitable climate models for precipitation and temperature for selected stations within the basin are shown in Table 1.

Table 1. Lists of Suitable Climate Models [26]

Stations	Maximum Temperature	Minimum Temperature	Rainfall
Hsipaw	GFDL CM3	MRI CGCM3	CanESM2
Katha	GFDL CM3	MRI CGCM3	CCSM4
Kyaukme	MPI ESMMR	MRI CGCM3	CanESM2
Lashio	MPI ESMMR	MRI CGCM3	CanESM2
Mandalay	MPI ESMMR	MRI CGCM3	CanESM2
Meikhtila	GFDL CM3	MRI CGCM3	MIROC-ESM-CHEM
Moegaung	GFDL CM3	MPI ESMMR	CCSM4
Moegok	MRI CGCM3	MRI CGCM3	CanESM2
Myitkyina	MRI CGCM3	MRI CGCM3	GFDL CM3
PutaO	MRI CGCM3	MPI ESMMR	GFDL-ESM2G
Sagaing	GFDL CM3	MRI CGCM3	CanESM2
Shwebo	MPI ESMMR	MRI CGCM3	CanESM2
Yamethin	GFDL CM3	MRI CGCM3	CanESM2
YeU	MPI ESMMR	MRI CGCM3	CanESM2

4.2. Projected Precipitation

Future climate projection baselines (2021-2095) were compared to the meteorological data (1991-2015). Precipitation projections are performed under three horizons: near future for 2021-2045, future for 2046-2070, far future for 2071-2095. Projections of precipitation under RCP2.6, RCP4.5, and RCP8.5 are shown in the following Table 2. This table shows the values of average seasonal changes in precipitation as a fraction of the base period corresponding to scenarios. The seasonal climate in Upper Ayeyarwaddy River Basin is classified into three seasons such as summer from 16 Feb to 31 May, Rainy (Monsoon) from 1 June to 30 Sept and winter from 1 Oct to 15 Feb. RCP2.6 shows an increase in basin average annual precipitation by 20.2, 25.7, and 22.1% respectively for the near future, future, and far future. RCP 8.5 has a slightly higher increase rate of 27.1, 18.5, and 29.1% for the same periods. The highest increase of 29.1% and the lowest increase of 18.7% will be obtained respectively under RCP8.5 and RCP4.5 in the far future. According to the average seasonal changes, there is a clear estimation in predicted future precipitation amounts of RCP 2.6, RCP4.5 and RCP8.5 receiving reduced rainfall for all future periods in summer season and increased rainfall in rainy and winter season. But, seasonal changes in winter are predicted to become double in the future and it can be said that changes in future precipitation for the winter season are much higher than that of changes in the rainy season.

Table 2. Average Changes in Future Precipitation

Future Period	Average Seasonal and Annual Changes in Precipitation as a Fraction of Base Period Corresponding to Scenarios		
	RCP2.6	**RCP4.5**	**RCP8.5**
	Rainy Seasonal Changes		
Near Future	1.30 (30.5%)	1.24 (24.5%)	1.26 (26.1%)
Future	1.29 (29.3%)	1.15 (19.9%)	1.26 (26.1%)
Far Future	1.20 (20.5%)	1.16 (15.7%)	1.27 (27.2%)
	Summer Seasonal Changes		
Near Future	0.59 (-40.3%)	0.86 (-14.2%)	0.61 (-38.7%)
Future	0.72 (-28.1%)	0.95 (-4.6%)	0.69 (-30.8%)
Far Future	0.82 (-18.2%)	1.10 (9.8%)	0.82 (-18.0%)
	Winter Seasonal Changes		
Near Future	2.17 (116.9%)	1.81 (80.8%)	1.78 (78.2%)
Future	1.77 (76.9%)	1.66 (66.6%)	1.58 (58.7%)
Far Future	1.88 (88.3%)	1.36 (36.3%)	1.38 (38.2%)
	Average Annual Changes		
Near Future	1.20 (20.2%)	1.30 (29.7%)	1.27 (27.1%)
Future	1.26 (25.7%)	1.28 (28.5%)	1.28 (28.5%)
Far Future	1.22 (22.1%)	1.19 (18.7%)	1.29 (29.1%)

4.3. Projected Temperature

The future projection of average temperature changes on fourteen stations under climate scenarios, which are RCP2.6, RCP4.5 and RCP8.5, are analysed in there periods, near future for 2021-2045, future for 2046-2070, far future for 2071-2095. According to the future seasonal temperature changes, both maximum and minimum temperature is projected to increase in all scenarios for three future periods and shown in Table 3 and Table 4. However, the slight increment is occurred under RCP2.6 and ranged from 0.19˚C to 1.57˚C for maximum seasonal temperature. Under RCP4.5, maximum seasonal temperature changes increased with the range from 0.53˚C to 2.28˚C and the highest increment occurs between 0.55˚C to 3.76˚C under RCP8.5. However, the slight increment is occurred under RCP2.6 and ranged from 0.19˚C to 1.57˚C for maximum seasonal temperature. Under RCP4.5, maximum seasonal temperature changes increased with the range from 0.53˚C to 2.28˚C and the highest increment has occurred between 0.55˚C to 3.76˚C under RCP8.5. The seasonal increases in the average minimum temperature range from 0.78˚C to 1.48˚C under RCP2.6, 0.98˚C to 2.25˚C under RCP4.5 and 1.12˚C to 3.92˚C under RCP8.5.

Table 3. Average Seasonal and Annual Changes in Future Maximum Temperature

Future Period	Average Maximum Temperature Changes Based on Base Period Corresponding to Scenario (˚C)		
	RCP2.6	**RCP4.5**	**RCP8.5**
	Rainy Seasonal Changes		
Near Future	0.84	0.69	0.88
Future	0.93	1.4	2
Far Future	1.09	1.67	3.17
	Summer Seasonal Changes		
Near Future	1.25	1.08	0.96
Future	1.45	1.72	2.2
Far Future	1.57	2.28	3.73
	Winter Seasonal Changes		
Near Future	0.19	0.53	0.55
Future	0.5	1.37	1.94
Far Future	0.76	1.72	3.36
	Average Annual Changes		
Near Future	0.59	0.75	0.78
Future	0.81	1.48	2.05
Far Future	1	1.88	3.41

Table 4. Average Seasonal and Annual Changes in Future Minimum Temperature

Future Period	Average Minimum Temperature Changes Based on Base Period Corresponding to Scenario (˚C)		
	RCP2.6	RCP4.5	RCP8.5
		Rainy Seasonal Changes	
Near Future	1.05	1.16	1.28
Future	1.28	1.7	2.3
Far Future	1.43	2	3.32
		Summer Seasonal Changes	
Near Future	1.13	1.37	1.21
Future	1.24	1.89	2.63
Far Future	1.48	2.25	3.92
		Winter Seasonal Changes	
Near Future	0.78	0.98	1.12
Future	1	1.52	2.3
Far Future	1.26	1.96	3.17
		Average Annual Changes	
Near Future	0.98	1.16	1.24
Future	1.16	1.71	2.41
Far Future	1.39	2.06	3.66

4.4. Soil and Water Assessment Tool (SWAT) Model Data Requirements and Set-up

SWAT is a partially distributed model and required digital elevation model (DEM), land use and soil map which are basic modeling requirements and daily weather data. There are many available global sources for DEM data and the 90m resolution DEM derived from SRTM (NASA Shuttle Rader Topographic Mission) is used to set up for the hydrological modeling by SWAT. The DEM in Figure 3 shows that the elevation in the Upper Ayeyarwady river basin ranges from 50m in the lower plains to 5711m in the upper region. The DEM is an important parameter for SWAT to classified topography, landscape, elevation, and slope and used in Streamflow network construction for modelling simulation. In SWAT, the first process was automatic watershed delineation and it can define the detail of flow direction and accumulation of each and every part of the large watershed which was divided into 23 sub-watersheds. These sub-basins were then divided into Hydrologic Response Units (HRUs) to predict runoff separately.

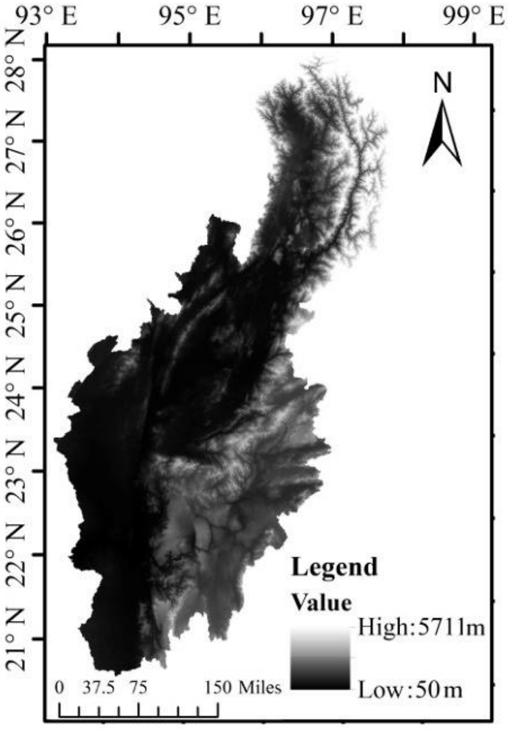

Figure 3. Digital Elevation Map

For the rainfall-runoff relationship, landcover and soil digital map are used to simulate the model. Land cover in Figure 4 has a 90m grid resolution with a 15 class landcover classification scheme and is obtained from the Servir Mekong Land Cover Portal. Soil dataset with 90m grid resolution is generally classified into 17 classes in Figure 5. For this study, thresholds for defining HRUs to compute a water balance based on snow, soil, shallow aquifer and deep aquifer were set at 20% for soil and 10% for land use [27]. Land cover map and soil map were prepared with their lookup tables to join raster data in the SWAT database file. SWAT model requires a soil map and a database table of soil texture for available water content, hydraulic conductivity, bulk density and organic carbon content for different layers of each soil type. The main hydrological processes include infiltration, runoff, evapotranspiration, lateral flow, and percolation [28]. Precipitation, maximum and minimum temperature, relative humidity, sunshine hours and wind speed of 1991 to 2013 were prepared in the text file for each station to compute weather generator parameters for the simulation of hydrological process on the basin. After that, different methods of water balance, surface runoff and reaches are defined.

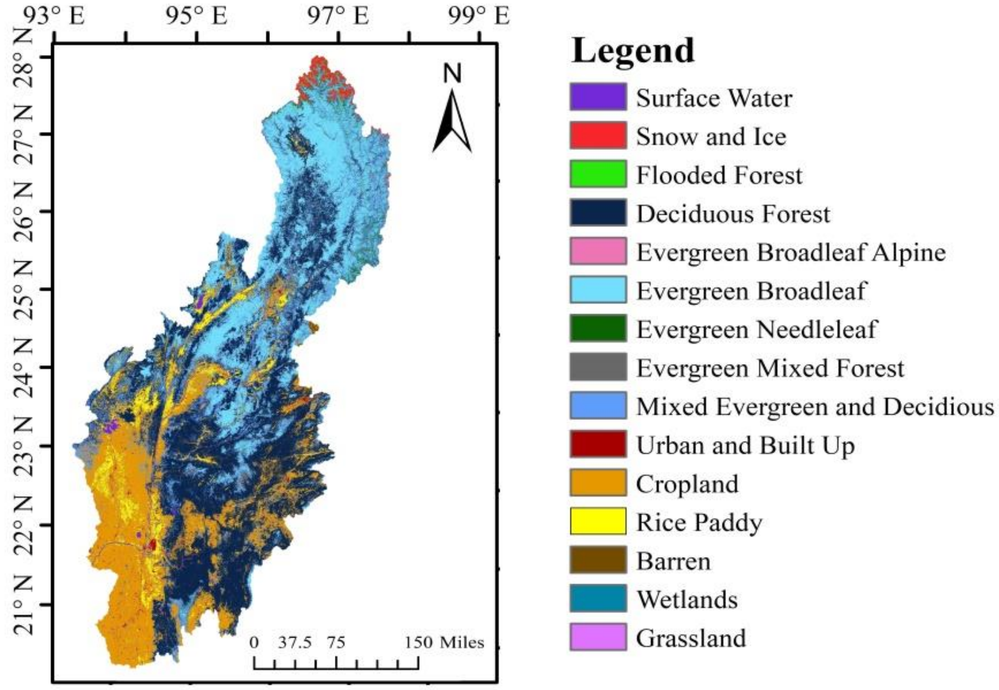

Figure 4. Landcover Classification Map

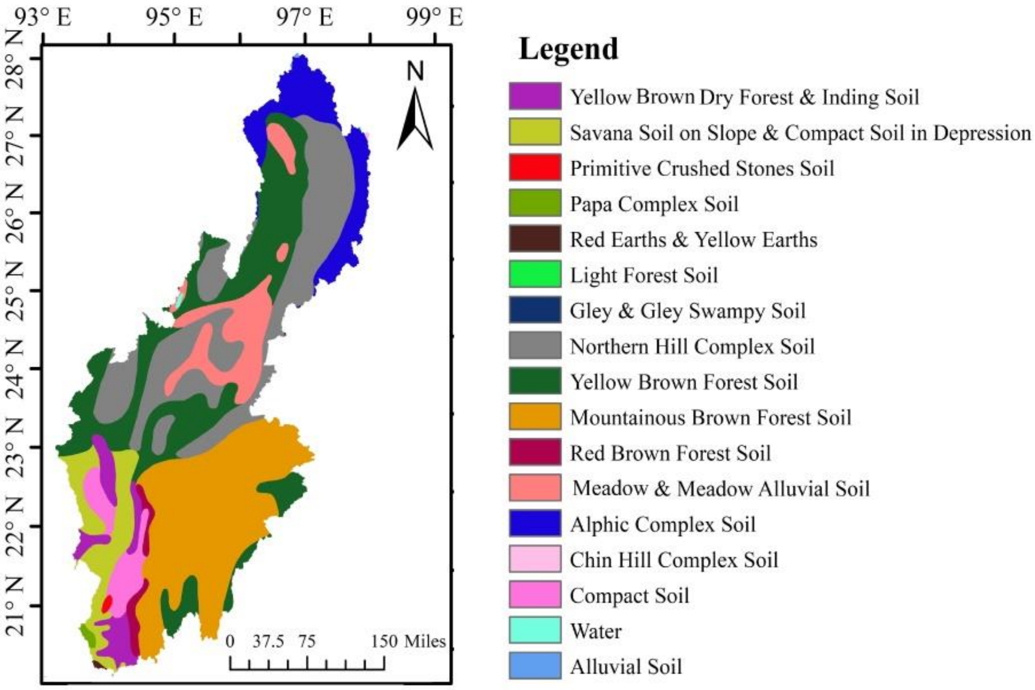

Figure 5. Soil Classification Map

Surface runoff can be simulated by two methods in the SWAT model: the modified Soil conservation Service Curve Number Method and the Green-Ampt Infiltration Method. In this study, surface runoff was estimated using the SCS Curve Number. Among three methods for estimating potential evapotranspiration: Priestley & Taylor, the Panmen-Monteith and Hargreaves & Samani, Panmen-Monteith method is used for calculation of evapotranspiration and soil and snow evaporation. Variable Storage routing was used for channel routing [29].

4.5. Calibration and Validation of Streamflow

Daily river flow (m^3/sec) observed at the Sagaing gauging station which is the outlet of the Upper Ayeyarwady river basin was used for the model calibration and validation analysis. Generally, hydrological models require a "warm-up" period, defined as the time the model will run before starting to generate the actual outputs, in order to eliminate the initial bias. In this study, the period 2000-2001 was used as "warm-up" periods to allow the model to initiate the hydrological parameters. The period of 2002 to 2007 of the streamflow data was used for calibration to estimate the model parameters values and the stability of these parameters were tested in the validation period of 2008 to 2013. Calibration was performed using the SWAT CUP program. Among the four calibration methods, calibration, and validation were conducted using the Sequential Uncertainty Fitting Algorithm (SUFI-2). Several hydrological model parameters were adjusted for achieving the best fit between the simulated and measured flow at the monitoring station. The total of twenty parameters as relating to surface hydrology, groundwater hydrology, snowpack accumulation, snowmelt, and base flow was selected and the lists of initial and fitted parameter range over all the study basins are reported in Table 5. Both calibration and validation on simulated streamflow with observed data were done by using the final parameters ranges.

Table 5. Parameters for Sensitivity Analysis

Parameters	Initial Parameter Range (Default)		Final Parameter Range		Fitted Parameter Range
	Min	Max	Min	Max	
Groundwater Parameters					
GW_DELAY.gw	0	500	250	500	406.2
ALPHA_BF.gw	0	1	0.001	0.01	0.002
GWQMN.gw	0	5000	1500	3000	1612.5
GW_REVAP.gw	0.02	0.2	0.005	0.05	0.035
REVAPMN.gw	0	500	250	300	283.7
RCHRG_DP.gw	0	1	0.07	0.7	0.49
Surface Parameters					
CN2.mgt	35	98	-1	3.5	-0.887
SURLAG.bsn	0.05	24	0.05	6	5.85
OV_N.rte	0.01	30	15	30	27.38
CH_N2.rte	-0.01	0.3	5	10	7.38
CH_K2.rte	-0.01	500	-0.01	10	9.75
HRU_SLP.hru	0	1	7.5	10	9.44
SLSUBBSN.hru	10	150	145	150	147.9
Soil Parameters					
SOL_AWC.sol	0	1	0.8	1	0.86
SOL_K.sol	0	2000	10	20	12.75
SOL_BD.sol	0.9	2.5	0.9	1	0.913
ESCO.hru	0	1	0.001	0.01	0.008
EPCO.hru	0	1	0.5	0.9	0.59
Snow Parameters					
SFTMP.bsn	-20	20	-5	5	3.25
SMTMP.bsn	-20	20	-5	5	2.75

1) Statistical Approaches for model performance evaluation: For the accuracy of simulated model results, the model calibration has to be done to match modelled streamflow results with observed discharge. Surface runoff was calibrated many times by adjusting the parameters to compare with observed data. In this study, the model performance was checked with Nash-Sutcliffe efficiency (NSE), coefficient of determination (R^2), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR). The calibration process was does until NSE >

0.5, $R^2 > 0.5$, $RSR \leq 0.7$, $PBIAS < 25\%$. The validation process is also performed to check the calibrated model accuracy. The statistical result of model validation indicates that the model can be used with calibrated basin parameters to simulate flow for the future period with considerable reliability and the model can give reliable results with projected discharge data for the future period. Model fitness between the daily observed and simulated runoff during the calibration and validation period is presented in Table 6.

Table 6. Statistical Analysis of Streamflow Simulation for Calibration and Validation period

Period	R^2	NSE	PBIAS	RSR
Calibration (2002-2007)	0.88	0.88	22.1	0.35
Validation (2008-2013)	0.88	0.87	22.8	0.36

2) *Monthly Time Series Simulation for Model Calibration:* When the R^2 and NSE values improved to 0.88 and 0.88 while decreasing the value of PBIAS and RSR to 22.1 and 0.35 respectively, simulation is seen to be better. According to Figure 6, the time of maximum rainfall intensity was also corresponded to the time of peak flow during the year.

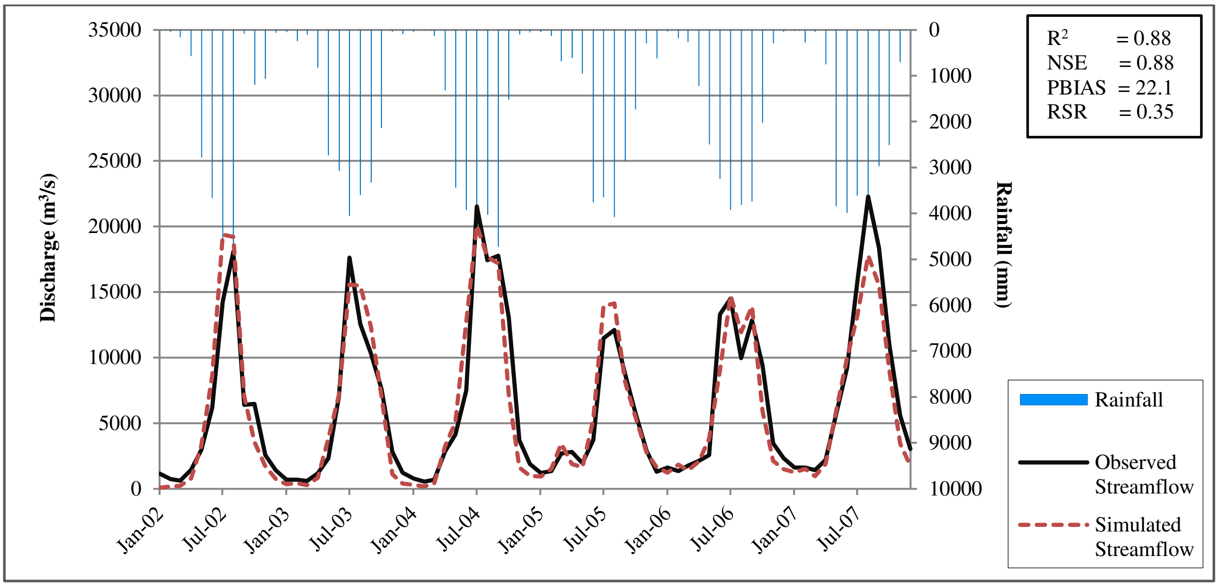

Figure 6. Hydrograph of Monthly Simulated and Observed Flow for Calibration Period (2002-2007, Sagaing Outlet)

3) *Monthly Time Series Simulation for Model Validation:* The values of statistical indicators: R^2, NSE, PBIAS, and RSR are all satisfied with the value of 0.88, 0.87, 22.8 and 0.36. The hydrograph of observed and simulated discharge for the validation period is shown in Figure 7 and better model performance results were attained during monthly time series calibration periods.

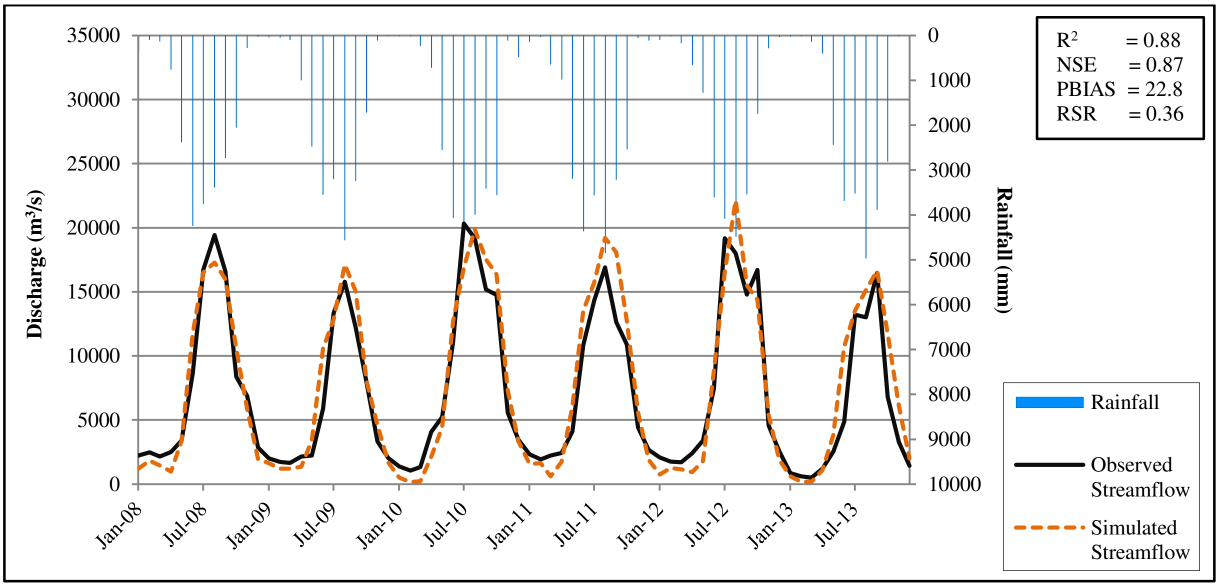

Figure 7. Hydrograph of Monthly Simulated and Observed Flow for Validation Period (2008-2013, Sagaing Outlet)

All the statistical parameters are satisfactory at both calibration and validation period. R^2 with the value of 0.88 also indicates good agreement of the simulated flows with the observed flows during calibration and validation period. NSE values are 0.88 and 0.87 for the calibration and validation period, respectively. The monthly PBIAS values are within the limitations indicating in the value of 22.1% in calibration and 22.8 % in validation period. RSR also reduces to acceptable limit and all these values indicate that the simulated and observed discharge has a reasonable agreement and the model performance is acceptable.

4.6. Changes in Average Annual and Seasonal Streamflow at Sagaing Station

The same values of calibrated SWAT model parameters are applied to evaluate the future climate impact simulations on water resources analysis. The bias-corrected future climate parameters such as precipitation, maximum and minimum temperature obtained from the selection suitable climate models for each station in the study area are used as input climate data for the analysis of hydrological changes under future climate. To evaluate the impact of climate change on the hydrology of the Upper Ayeyarwady river basin, future hydrological projections divided into three-time horizons Near Future (2021-2045), Future (2046-2070) and Far Future (2071-2095) were compared with their baseline average discharge (1991-2015). And then, analysis of future streamflow at Sagaing Outlet is performed under RCP2.6, RCP4.5, and RCP8.5 climate scenarios. The results of average annual and seasonal change (%) in the basin relative to the base period are shown in Figure 8. According to this figure, seasonal streamflow shows a decreasing trend in all scenarios and periods of the near future, future and far future. But the decrease rate in summer is higher than in the other two seasons. The future average seasonal streamflow shows a definite decrease ranging from 12.9% to 84.5% will be lower than the current conditions in the summer season. Average seasonal streamflow will also decrease ranging from 2.8% to 15.9% in the rainy season and from 10.6% to 14.6% in the winter season. A slight increment of about 13.6 % occurs under RCP2.6 in the far future for winter. There is still clear agreement that the projected annual streamflow during near future, future and far future will be 6.1% to 30.9% lower than observed annual streamflow amounts as compared to the observed annual streamflow. About 1.3% increment occurred under RCP2.6 in the far future of annual streamflow projection.

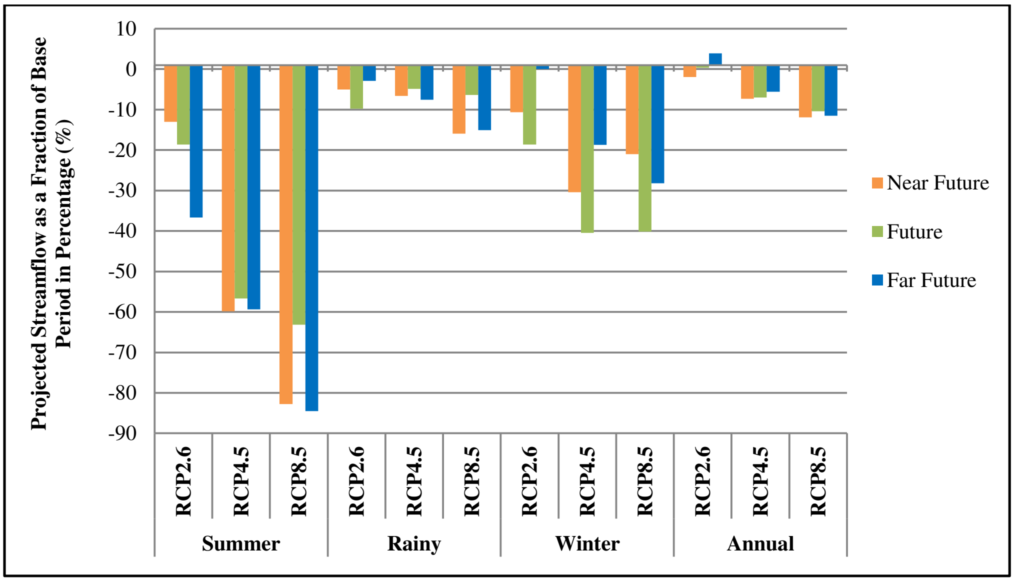

Figure 8. Future Average Annual and Seasonal Streamflow Changes at Sagaing Station

4.7. Changes in Monthly Streamflow at Sagaing Station

The comparison between observed and projected average monthly streamflow at the Upper Ayeyarwady river basin for each future period is described in the following Figures. Figure 9 shows the projection of average monthly streamflow for the near future period under three RCP scenarios and figure 10 shows near future average monthly streamflow changes relative to the baseline period. In these figures, the average monthly streamflow is higher than the baseline period from January to May for all RCP scenarios, June for RCP8.5, and October to December for RCP 4.5 and RCP 8.5. In near future, slight increase streamflow is observed under RCP 4.5 in June, July, August, and September, under RCP2.6 in June and September, and under RCP8.5 in August and September. For the summer season (15February to 31May) for near future, streamflow projection under all RCP scenarios indicates a decrease projection change in average of 1932.1 m^3/s under RCP2.6, 1465.11 m^3/s under RCP4.5, and 845.9 m^3/s under RCP 8.5. The average change in streamflow in summer is at the lowest level under RCP8.5 compared with other RCP scenarios. During the rainy season, the highest and lowest streamflow changes are ranging from about 10106.6 – 16441.5 m^3/s under RCP 2.6, 9415.6 - 15324 m^3/s under RCP4.5, and 9252.4 - 16908 m^3/s under RCP8.5 in near future.

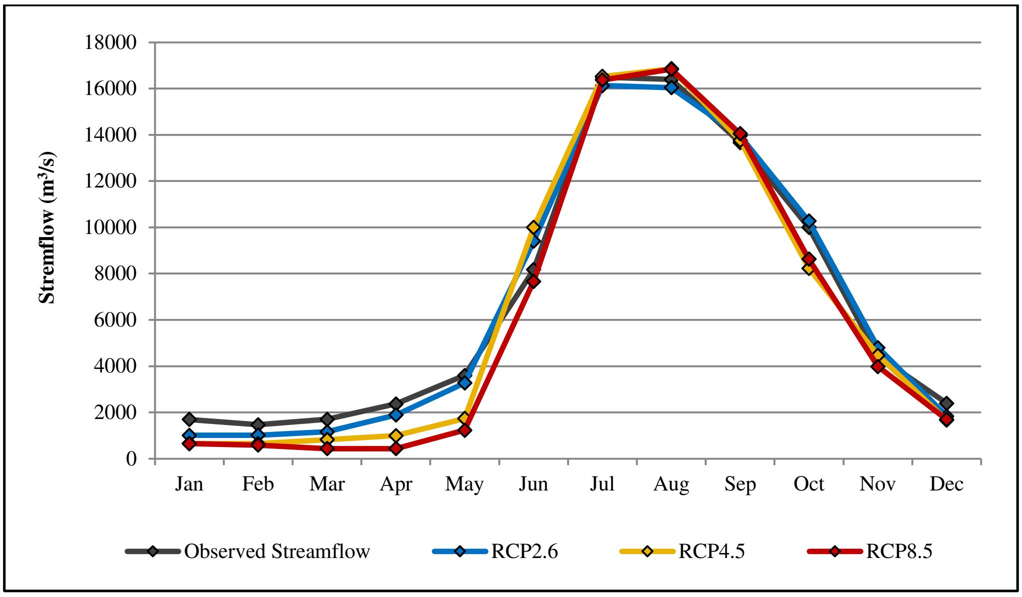

Figure 9. Projected Average Monthly Streamflow in Near Future (2021-2045)

In the future, the average monthly streamflow is higher than the baseline period from January to May for all RCP scenarios, June for RCP8.5, and October to December for RCP 4.5 and RCP 8.5. Simulated streamflow higher than observed streamflow is given for three months: July, August, and September under all RCPs and for June under RCP2.6 and RCP4.5. The summer season is also affected by average decreasing changes in future of 1530.6 m^3/s under RCP2.6, 1213.1 m^3/s under RCP4.5, and 724 m^3/s under RCP8.5. The rainy seasonal flow projections under RCP2.6, RCP4.5 and RCP8.5 conditions for future are also ranging from about 10060 – 16333.9 m^3/s, 10680 – 16889.4 m^3/s, and 9701.3 - 17566 m^3/s, respectively.

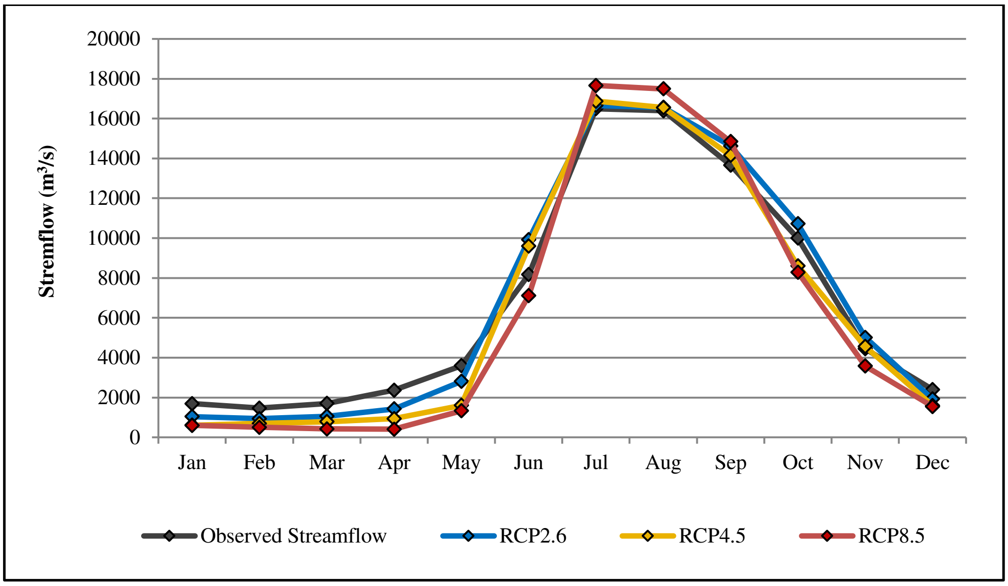

Figure 10. Projected Average Monthly Streamflow in Future (2046-2070)

The projection of average monthly streamflow with respect to the baseline under all RCPs for the future is shown in Figure 11. This figure shows the declining streamflow changes during the summer and winter season (from January to May and from October to December) under all scenarios. In July and August, for the far future period, the simulated flow of RCP8.5 is higher than the flow of RCP2.6 and RCP4.5 after comparing it with the baseline period. Average decrease changes of streamflow projection for summer season in far future is about 992.9 m^3/s under RCP 2.6, 751.1 m^3/s under RCP4.5, and 448.7 m^3/s under RCP8.5. The rainy seasonal flow projections are also ranging from 10159.5 - 16368.4 m^3/s under RCP2.6, 9701.3 - 17066 m^3/s under RCP4.5, and 8486.3 - 17918 m^3/s under RCP8.5.

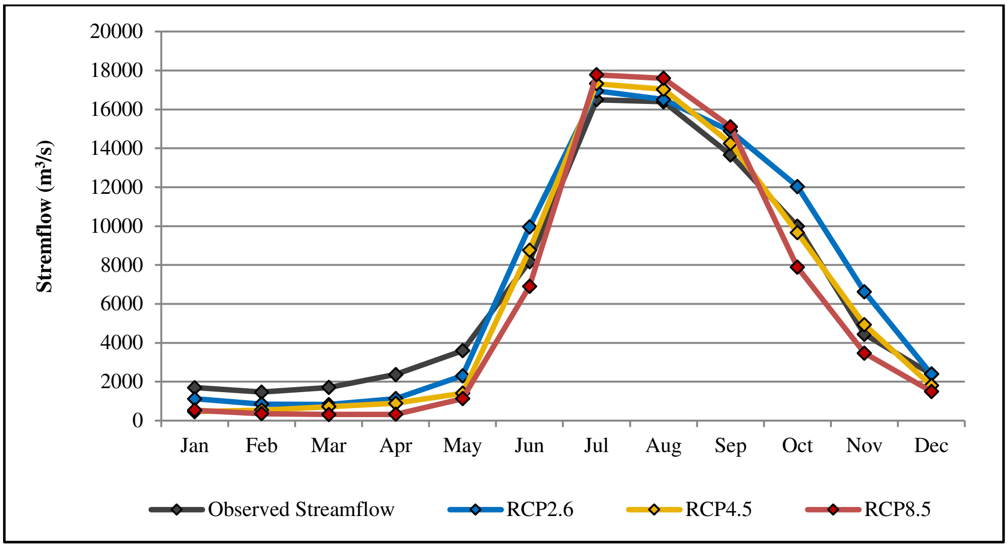

Figure 11. Projected Average Monthly Streamflow in Far Future (2071-2095)

In terms of seasonal scale, it is clear that the projected streamflow will decrease in the summer period. Both increasing and decreasing streamflow are found in the rainy and winter period according to their RCP scenarios.

4.8. Impact on High and Low Flow of Upper Ayeyarwady River Basin at Sagaing Outlet

According to the future high flow results shown in Figure 12, projected future streamflow has an increasing trend from RCP2.6 to RCP8.5 from the year 2021 to 2095 indicates severe floods will ever experience in the future. It also means that water-related disasters such as floods, landslides, etc. will be more encountered in RCP4.5 and RCP8.5 conditions than in RCP2.6.

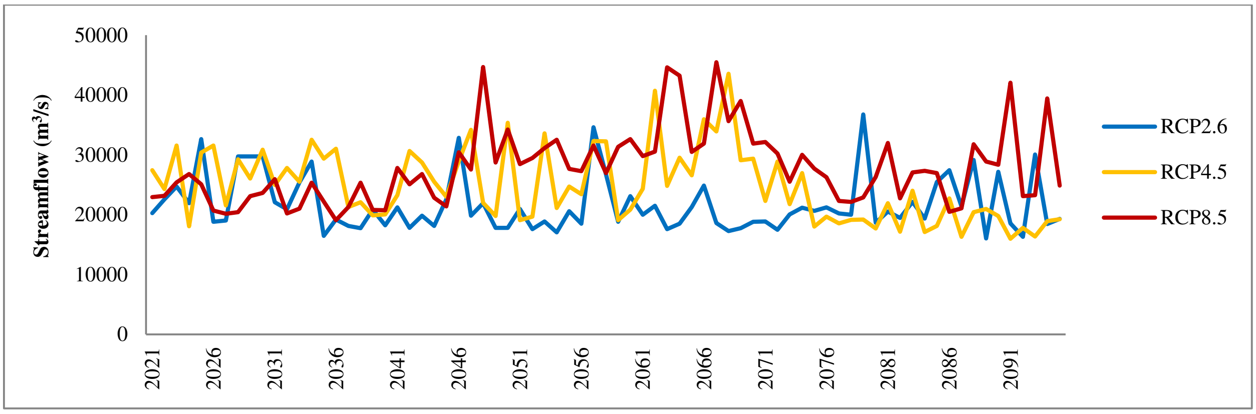

Figure 12. Projected Maximum Discharge in Sagaing Outlet for Wet Season

Figure 13 describes the projected future low flow from the year 2021 to 2095 and it is forecasted as the streamflow will decrease more and more in relation to their future scenarios and that indicates water problem will grow worse in the future.

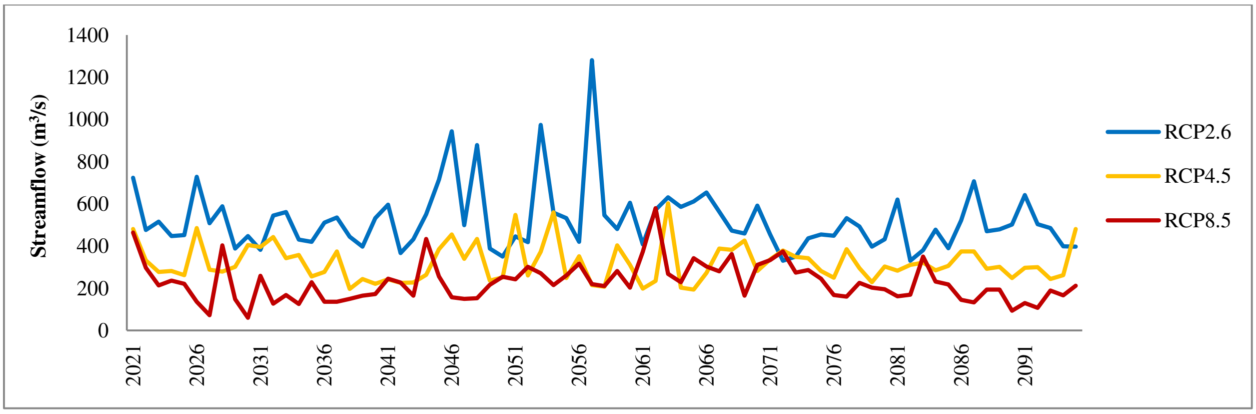

Figure 13. Projected Minimum Discharge in Sagaing Outlet for Dry Season

The relative changes of high and low flow of Upper Ayeyarwady River Basin concerning the baseline period (1991-2015) are presented in Figure 14. The projected high flow indicated that the flow will be increased ranging from 3.1% to 12.7% under RCP2.6, 2.8% to 33.5% under RCP4.5, and 25.7% to 28.9% under RCP8.5. The range of changes in low flow is 5.1% to 13% under RCP2.6, 37.1% to 48.3% under RCP4.5, and 64.2% to 74.2% under RCP8.5. Here, changes percentage in low flow is greater than that of high flow. Both increasing rates in high flow and decreasing rate in low flow are more serious under RCP8.5 than RCP2.6 and RCP4.5.

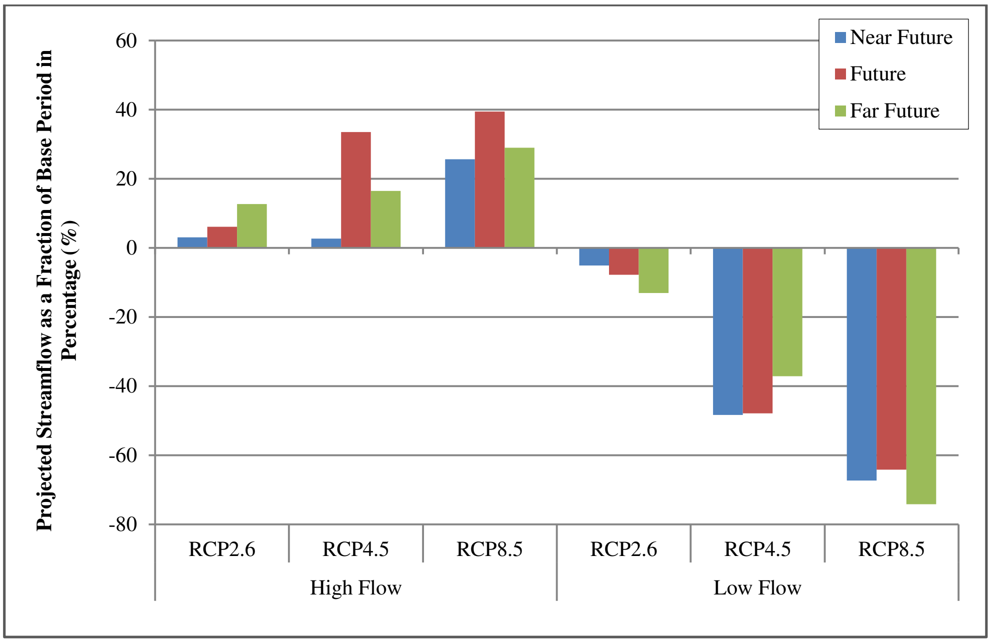

Figure 14. Projected Changes Percentage in High and Low Flow of Upper Ayeyarwady River Basin

5. Conclusion

The assessment of climate change impacts on hydrology is related to the climate change scenarios and hydrological model. Runoff projection with GCMs, emission scenarios and future periods is investigated as well. Changes of Upper Ayeyarwaddy river flow during 2020-2100 were predicted by using projected precipitation and temperature related to outputs of selected best climate models form 10 GCMs under RCP2.6, RCP4.5, and RCP8.5 scenarios. Estimating the impacts of possible future climate change on hydrological behaviour is done by calibration and validation of the SWAT hydrological model by using current climatic inputs, land-use map, and observed river flow. Better model performance results were attained a satisfactory value of $R^2 = 0.88$, NSE = 0.88, PBIAS = 22.1 and RSR = 0.35 during monthly time series calibration period and value of $R^2 = 0.88$, NSE = 0.87, PBIAS = 22.8 and RSR = 0.36 during validation period. The overall conclusion of this research is that the Upper Ayeyarwady area predicted to encounter excessive precipitation especially in the rainy season and extreme temperature especially in the future summer season. And then, it can also be concluded that river flow followed the rainfall pattern because the river flow is found as the low flow in the dry season and high flow in the wet season. Moreover, changing climate conditions are getting worse with the increased rate of GHG emissions levels in the atmosphere and increasing in frequency and intensity of rainfall lead to floods and increasing in water scarcity and drought. It is found that current Myanmar's climate condition is still below the RCP2.6 level according to the comparison between observed and simulated data and therefore, it is necessary to control and reduce flood potentials in the wet season and the severity of drought in the dry season. But, if the greenhouse gas emissions rate in Myanmar cannot reduce, the level of gas will keep going up and face to reach the RCP4.5 and RCP8.5 conditions. Therefore, stronger efforts and finding ways to reduce and to mitigate carbon dioxide emissions should be undertaken to lower global warming and climate change in the atmosphere.

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7. Conflicts of Interest

The authors declare no conflict of interest.

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