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Review article

Estimation of Streamflow Using SWAT Model under Climate Change in the Upper Wangchhu Watershed, Bhutan

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ABSTRACT

The objectives of this study were to assess the suitability of Soil and Water Assessment Tool (SWAT) model to simulate streamflow and study the effect of climate change on streamflow in the Upper Wangchhu Watershed (UWW) in Bhutan. The model was set up using the Digital Elevation Model, land use, meteorological data and soil data. The data were collected from various agencies in Bhutan to setup the model on a monthly time step. The Sequential Uncertainty Fitting (SUFI-2) in SWAT-Calibration and Uncertainty Procedures (SWAT-CUP) was used for calibration and validation of the model. The results from model calibration (NSE = 0.76, $R^2 = 0.79$, PBIAS = 15.80) and validation (NSE = 0.61, $R^2 = 0.66$, PBIAS = -5.00) indicate that the model performance was satisfactory. The calibrated model showed that the average annual streamflow was 752.89 m^3/s during 2003-2013, which was not significantly different ($p > 0.05$) from the measured average annual flow. The model also satisfactorily simulated the streamflow for a future climate change scenario RCP8.5. Compared to 2013, the streamflow in 2050 and 2070 is predicted to significantly decrease during the dry seasons ($p < 0.01$) and increase during the rainy seasons ($p < 0.05$). The climate change will affect streamflow in the UWW and the SWAT model is suitable for streamflow study in such a scenario. For future studies in the UWW with the SWAT model, it is recommended to have a better soil map, establish more hydro-meteorological stations, and also to include snowmelt, land use, and water removal processes as these can affect the SWAT output.

Keywords: Streamflow, climate change, SWAT model, calibration and validation.

INTRODUCTION

Streamflow from a watershed is affected by natural and man-made factors including land use change and climate change (Costa *et al.*, 2003). Climate change has a direct effect on the precipitation, interception, and evapotranspiration, which are important variables controlling the water yield (Beguería *et al.*, 2003).The average global temperature has increased by 0.85°C from 1880-2012, and the changes in precipitation pattern or melting ice in many regions of the world, have altered the hydrological systems thereby affecting the water resources in terms of quality and quantity (IPCC, 2014). Precipitation, an essential element in the hydrological cycle, affects the pattern of runoff and streamflow as a result of climate change.

Bhutan, a country situated in the Himalayas, is highly vulnerable to the adverse effects of climate change, as it can cause glaciers and snow to melt faster than expected (National Environment Commission, 2016a). The climate change will alter the hydrological cycle and affect the streamflow, biodiversity, forests, vegetation, agriculture, health, and water properties downstream (Tenzin and Ongsomwang, 2015). The Upper Wangchhu Watershed (UWW) in western Bhutan is, therefore, vulnerable to climate change. The Wangchhu river and its tributaries are an important source of water for drinking and irrigation in the UWW (National Environment Commission, 2016b).

The Wangchhu river also supports two hydropower stations located downstream. The revenue generated from the export of electricity to India from the two hydropower stations contributed about 8 percent to the gross domestic product in 2015 (National Statistics Bureau, 2016). However, during the dry months, these power stations are not able to operate entirely due to a reduced streamflow in the river and the electricity has to be imported from India to meet the country's electricity demand in winter (Druk Green Power Corporation Limited, 2009). Reports of storms and floods resulting in the loss of property in UWW have also been reported in the past.

Several studies on streamflow changes in rivers of Bhutan, including the Wangchhu river, have been done using various hydrological models such as HBV (Beldring and Voksø, 2011; Lhamo, 2015), CREST (Xue *et al*., 2013), SRM (Tenzin and Ongsomwang, 2015) and SHyFT (Ghimirey, 2016). However, no study investigated the impact of climate change on streamflow in the Wangchhu watershed using the Soil and Water Assessment Tool (SWAT) model. The SWAT model was selected for this study due to its advantage over the other hydrological models in terms of user-friendliness, ability to use readily available inputs, carry out long-term studies, and acceptance in watersheds with insufficient monitoring data (Neitsch *et al.*, 2011). Using only streamflow data, Jha *et al.* (2004) successfully studied the impact of climate change on streamflow in the Upper Mississippi river basin with SWAT and a regional climate model. Similarly, Salah and Abida (2016) used only five years of data to calibrate and validate the SWAT model in a study carried out in Wadi Hatab watershed in Tunisia.

In Bhutan, getting the required data on climate and streamflow is generally difficult because the meteorological and stream gauging stations are non-uniformly distributed throughout the country (Ghimirey, 2016; Hoy *et al.*, 2016). High altitude areas in the northern part of Bhutan have a limited number of stations due to the steep terrain and accessibility problems. Hence, the advantage of SWAT model to work with limited data makes it an ideal tool to study the impact of climate change on streamflow in the UWW. The objectives of this study were (i) to assess the suitability of SWAT model in simulation and estimation of the streamflow, and (ii) simulate the streamflow under climate change scenario to study its effect on the streamflow in the Wangchhu river in UWW.

MATERIALS AND METHODS

1. Overview of the SWAT model

SWAT is a river basin or watershed scale model. It allows the simulation of various physical processes, including hydrology in a watershed, and the simulation is divided into a land phase and water or routing phase. SWAT simulates the hydrological cycle based on the water balance equation (Neitsch *et al.*, 2011).

$$SW_t = SW_0 + \sum_{i=1}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \ldots(1)$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on the ith day (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on the ith day (mm H_2O), Q_{surf} is the amount of surface runoff on the ith day (mm H_2O), E_a *is* the amount of evapotranspiration on the ith day (mm H_2O), W_{seep} is the amount of water entering the vadose zone from the soil profile on the ith day (mm H_2O), and Qgw is the amount of return flow on the ith day (mm H_2O).

Readily available user-friendly manuals and the ArcGIS-based graphical user interface in SWAT makes it very attractive to the users, including decision-makers and government agencies (Stehr *et al.*, 2008). The more detailed description and processes used in the SWAT model can be found in the SWAT Theoretical Documentation version 2009 (Neitsch *et al.*, 2011) and SWAT Input/Output Documentation version 2012 (Arnold *et al.*, 2012a). SWAT Calibration and Uncertainty Procedures (SWAT-CUP) 2012 is a standalone program for calibration of the SWAT model and it is used for the validation and sensitivity analysis by making use of various inbuilt calibration procedures and functionalities (Abbaspour *et al.*, 2015).

2. Data collection

The climate and streamflow data for the study area were collected from the National Center for Hydrology and Meteorology in Thimphu, Bhutan. The data was collected for the last 21 years (1996–2016), but due to missing data for some stations, data for only 18 years (1996-2013) was considered in the study. The streamflow data from one hydro station at the outlet of the watershed was used. The climate data were available from the four stations located downstream of the watershed.

Since the complete data for stations in upstream areas was not available and the available stations were non uniformly distributed throughout the study area, it was decided to use the Climate Forecast System Reanalysis (CFSR) global meteorological dataset for at least one station located upstream of the watershed. The CFSR datasets have been used in un-gauged watersheds for stream discharge simulations with good results (Fuka *et al*., 2014). The daily CFSR data related to precipitation and temperature measurement in a file format, compatible with the SWAT model, was downloaded for one station (276n894e) from https://globalweather.tamu.edu/. Table 1 shows the average minimum and maximum temperature, precipitation, and relative humidity, calculated from the data collected, in the UWW area.

Table 1 Average temperature, precipitation, and relative humidity during 1996 - 2013 at the Upper Wangchhu Watershed (UWW).

	Temperature (°C)		**Precipitation**	**Relative humidity**
Month	**Max**	**Min**	**mm**	**%**
January	10.87	-3.94	9.66	64.71
February	12.30	-1.78	21.57	65.96
March	15.18	1.70	22.09	66.97
April	17.70	5.25	37.33	67.50
May	20.31	8.73	64.87	71.23
June	22.07	12.42	127.49	78.45
July	21.55	13.21	202.37	83.10
August	22.49	13.33	188.08	82.11
September	21.16	11.76	119.49	80.94
October	18.37	6.60	77.82	73.72
November	14.88	1.15	7.47	65.59
December	11.71	-2.03	3.32	60.60
Annual Average/Total	**17.38**	**5.53**	**881.56**	**71.74**

For the simulation of climate change scenario Representative Concentration Pathway (RCP) 8.5, the precipitation data for the year 2050 (average for 2041 and 2060) and 2070 (average for 2061 and 2080) was downloaded from www.worldclim.org. According to IPCC (2014), there are four RCPs (i.e., RCP2.6, RCP4.5, RCP6.0, and RCP8.5) which are scenarios for making projections that describe the alternative trajectories for Greenhouse Gases (GHG), emissions and atmospheric concentrations, air pollutant emissions, and land use, from the year 2000 to 2100. RCP8.5 assumes that the GHG emissions will continue to increase rapidly and stabilize by the year 2100. Under this scenario, the global mean surface temperature, relative to 1986-2005, is projected to change by 2.0°C during the period 2046-2065 and is likely to change by 3.7°C for the period 2018-2100 (IPCC, 2014).

The precipitation data for the year 2050 and 2070 are downscaled at 30 seconds spatial resolution and are climate projections from the Global Climate Models (GCM) and the Coupled Model Intercomparison Project (CMIP5), provided by the Intergovernmental Panel on Climate Change (IPPC). The latest land use data for Bhutan, covering the study area, was collected from the Department of Forests and Park Services (DoFPS) and the Digital Elevation Model (DEM). The data for the study area, at 30 m resolution, was acquired from the National Soil Service Center in Thimphu, Bhutan.

3. Model setup

ArcSWAT version 2012.10.4.19 was used for running the SWAT model. The model was setup using the data collected. To setup the model, the data was prepared in accordance with the SWAT Theoretical Documentation version 2009 (Neitsch *et al.*, 2011) and input/output documentation version 2012 (Arnold *et al.*, 2012a). DEM at 30 m resolution was imported into the model and was used to generate stream network for the UWW. Thereafter, the watershed area was automatically delineated by the model after selection of the subbasin and watershed outlets. A total of 17 subbasins were created for the UWW. For defining the HRUs, land use map, soil map, and slope classes were used during the setup process. HRUs are lumped land areas that possess unique attributes related to soil, land cover, and management and it is assumed to have a similar hydrologic response (Neitsch *et al.*, 2011). The GIS shape file of recent land use and land cover map of Bhutan, from the year 2016, was acquired from the DoFPS and was used to classify the land use in the watershed area. Since a specific soil map for the study area was not available for the study area, FAO global soil data (1:5,000,000 scale) was used for the SWAT model. Five slope classes were provided for the watershed. The land use, soil and slope classes were reclassified before overlaying the layers and defining the HRUs. Five elevation bands were also assigned for the adjustment of snow/rainfall and temperature (Abbaspour *et al.*, 2015). A total of 129 HRUs were created within the UWW area.

After creating the HRUs, the climate data, which is a crucial input to study the hydrological process (Neitsch *et al.*, 2011), were imported for the model set up. The climate data prepared in SWAT format (.txt) included the daily data on precipitation and minimum and maximum temperature from five stations located within the study area. Other data such as relative humidity, solar radiation, and wind speed were to be generated by the SWAT model using the inbuilt weather generator. After this process, the SWAT input tables were written into the model.

The SWAT model was setup on a monthly time-step with data from 18 years (1996-2013). An initialization period of seven years (1996-2002) was chosen for the model to reach a hydrological equilibrium before running the model. Finally, the SWAT model was run for the period from 2003-2013. Calibration and validation of the model was done with Sequential Uncertainty Fitting (SUFI-2) in SWAT-CUP before carrying out the prediction of streamflow under climate change scenario RCP8.5. The flow chart (Figure 1) explains the SWAT model setup used in the study.

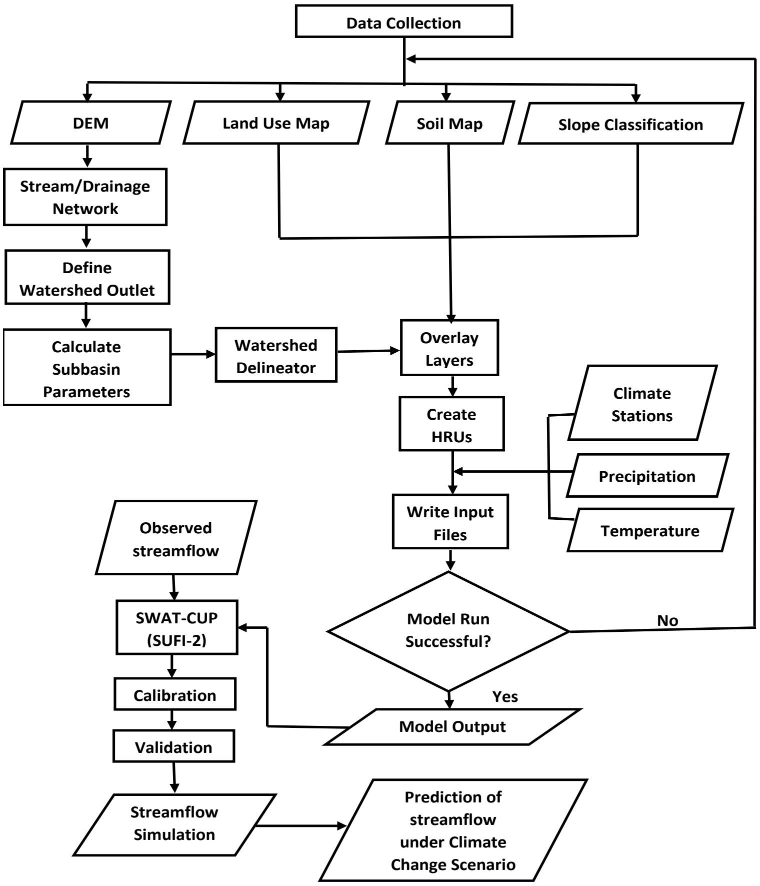

Figure 1 Steps in setting up the SWAT model.

4. Model calibration and validation

To assess the suitability of SWAT model to simulate and predict the streamflow in UWW, calibration and validation of the model was done with the monthly measured streamflow data obtained from the outlet of the watershed (i.e., Damchu). Out of the available 18 years (1996-2013) of the streamflow data, the data for 1999 to 2002 was missing, so the calibration at Damchu station was done for seven years, from January 2003 to December 2009. The model was calibrated using SUFI-2 algorithm in SWAT-CUP and was validated for the period from 2010-2013. Before the calibration, the simulated and observed flow were compared and based on the differences between the two flows, parameters were considered for adjustment and tested for the model calibration and validation. The steps outlined in the calibration protocol by Arnold *et al.* (2012b) and Abbaspour *et al.* (2015) were followed for the calibration and validation. A total of 14 parameters were used for calibration namely ALPHA_BF.gw, CH_K2.rte, GW_DELAY.gw, SOL_K2.sol, CN2_mgt, GW_REVAP.gw, GWQMN.gw, RCHRG_DP.gw, REVAPMN.gw, CANMX.hru, ESCO.hru, SOL_AWC.sol, SURLAG.bsn and EPCO.bsn. These parameters were also used by Zhou *et al.* (2014) to calibrate their model for streamflow and uncertainty analysis for the Lake Dianchi Basin in China.

After the validation in SWAT-CUP, the SWAT model was calibrated with the best-fitted calibrated parameters from the SWAT-CUP. The calibrated SWAT model was used to simulate the calibrated streamflow. Following the simulation of calibrated streamflow, the precipitation data for the RCP8.5 scenario for the year 2050, downloaded from www.worldclim.org, was loaded into the calibrated model. The predicted streamflow for 2050 was simulated with the calibrated model. Similarly, the predicted streamflow for the year 2070 was also simulated separately, using the calibrated model, to study the changes in streamflow under future climate change scenario RCP8.5 in UWW.

The coefficient of determination (R^2) was used to evaluate the goodness of fit between the calibrated and measured streamflow. Nash-Sutcliffe model efficiency (NSE) was used to evaluate the efficiency of the model. These metrics were selected as they are the most widely used statistical tests for calibration and validation in SWAT modeling (Arnold *et al.*, 2012b). Percent bias (PBIAS) was also used to evaluate the performance of the SWAT model. The following formulas were used for the analysis:

a) R^2

$$R^2 = \left[\frac{\sum_{i=1}^{n}(o_i - o_m)(p_i - p_m)}{\sqrt{(\sum_{i=1}^{n}(o_i - o_m)^2} \sqrt{(\sum_{i=1}^{n}(p_i - p_m)^2}}\right]^2 \quad ....(2)$$

b) NSE

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(o_i - p_i)^2}{\sum_{i=1}^{n}(o_i - o_m)^2} \quad ....(3)$$

c) PBIAS

$$\text{PBIAS} = \left[\frac{\sum_{i=1}^{n} o_i - p_i}{\sum_{i=1}^{n} o_i}\right] \times 100 \quad ....(4)$$

where o_i is observed value, p_i is the predicted value, o_m is the average observed value, p_m is the average predicted value and n are the number of observations, respectively.

When the value of R^2 and NSE is equal to 1, it indicates perfect prediction while negative values indicate less reliable predictions compared to the use of sample mean (El-Nasr *et al.*, 2005). The optimal value of PBIAS is 0, with a positive value indicating underestimation while a negative value means overestimation of the observed discharge values (Stehr *et al.*, 2008).

5. Study Area

The study area of UWW is located in western Bhutan between 89°07’25.01” E - 89°46’00.00” E longitude and 27°14’33.69” N - 27°51’25.65” N latitudes covering an area of about 2,520 sq.km (Figure 2). It forms the upper catchment area of the more prominent Wangchhu river basin with an area of 4,596 km^2 (National Environment Commission, 2016b). About 48 percent of the study area, estimated from the latest land use map, is under forest cover and conifer forests dominate most of the cover. When shrubs and alpine scrubs are included, the area under the forest in the watershed increases to more than 70 percent.

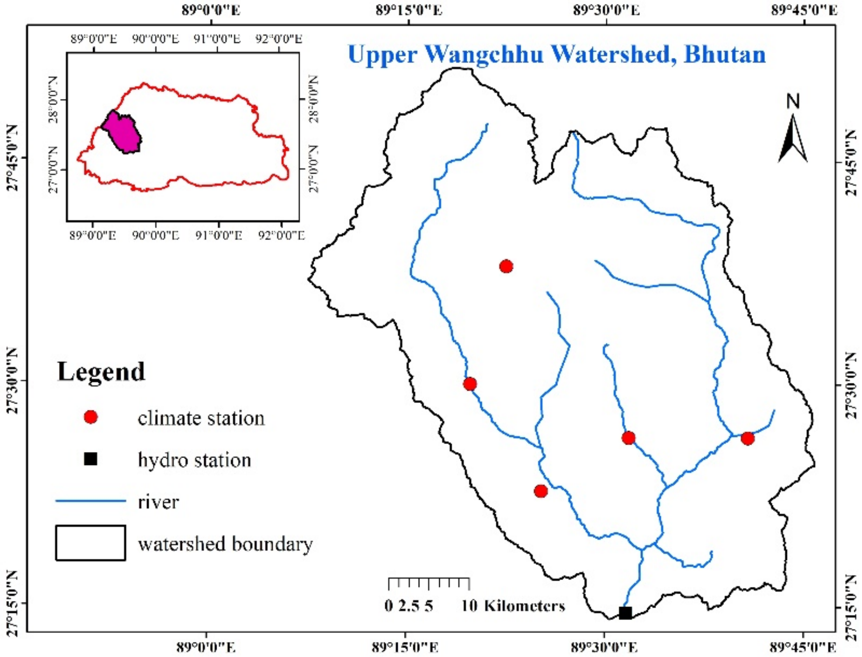

Figure 2 Map of the of study area. The inset indicates the locationof the watershed in the country of Bhutan.

Snow and glaciers are prevalent in the northern parts of UWW. The elevation of UWW ranges from 1,969 meters to over 7,000 meters above sea level. The human population in the watershed area is estimated at 159,000 people while there are about 13,365 yaks and 15,802 cattle (National Statistics Bureau, 2016). The UWW receives its rainfall from the monsoon starting from June till September and the dry season starts from October and lasts till May (Lhamo, 2015). The mean annual rainfall varies from 500 to 1000 mm (Lhamo, 2015).

RESULTS AND DISCUSSION

The estimation of streamflow in UWW using the SWAT model and prediction of streamflow in a climate change scenario is explained as follows:

1. Streamflow simulation

The streamflow from 2003-2013 was simulated with the SWAT model using the rainfall and temperature data from five meteorological stations located within the watershed. Since the first seven years (i.e., 1996-2002) were used for the model initialization, the streamflow for this period was not estimated. The SUFI-2 in SWAT-CUP was used for the calibration and validation process.

1.1 Streamflow calibration and validation

The calibration results for the period between 2003–2009 (Figure 3) indicated that the *P-factor* was 0.76, which indicate that 76 percent of the observed data are bracketed by a 95% prediction uncertainty (95PPU), while the *R-factor* was 0.92. The recommended value of *P-factor* for discharge is > 0.70 and *R-factor* is < 1.50, depending on the situation (Abbaspour *et al.*, 2015). The NSE and R^2 were 0.76 and 0.79 respectively, indicating that the model performed well in simulating the streamflow and the correlation between the calibrated flow and the observed flow was satisfactory (Arnold *et al.*, 2012b).

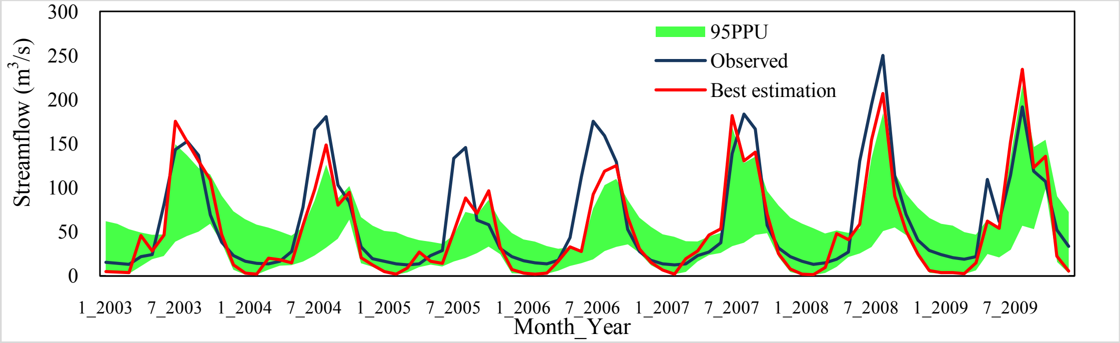

Figure 3 Streamflowcalibration output from SWAT-CUP for the years 2003-2009.

The PBIAS was 15.8% which showed some underestimation bias of streamflow by the model. The model performance is considered to be good if the PBIAS value satisfies the inequality ±10% < PBIAS < ±15% (Dile and Srinivasan (2014). The underestimation of the base and peak flows could have resulted from the inability to adequately account for the snowmelt and hydrological processes, such as ground water delay, evapotranspiration, and surface runoff in the model. Further, the non-uniform distribution of climate stations in the watershed area resulted in a poor representation of precipitation for the model (Zhou *et al.,* 2014)

The validation results for the period from 2010-2013 showed a *P-factor* = 0.88, *R-factor* = 1.38, R^2 = 0.66, and NSE = 0.61 (Figure 4). The values of R^2 and NSE indicate that the model predicted the streamflow satisfactorily and there was a slight overestimation bias of flows (PBIAS = -5.0) during the validation period. The overestimation occurred due to high precipitation experienced at the station located upstream of the watershed. Due to this reason, the peak flows increased from 2011 to 2013. The study had limitations in terms of some missing data in precipitation and temperature, no data on snow cover, relative humidity and solar radiation, and non-uniform distribution of climate stations and hydro stations. All these factors could have contributed to the uncertainties reflected by the model in terms of the *R-factor*. According to Abbaspour *et al.* (2015), the prediction errors in a model occur due to the quality of data, with conceptual uncertainties, inclusion and non-inclusion of processes in the watershed including snowmelt, soil erosion, evapotranspiration, and irrigation adding to the overall uncertainty.

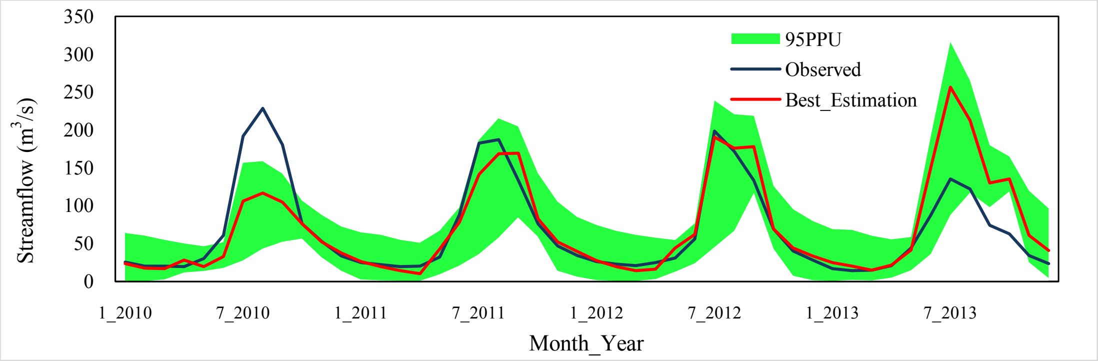

Figure 4 Validation output from SWAT-CUP for the years 2010-2013.

1.2 Variation of streamflow at UWW

There were some variations in the flows simulated by the calibrated model at the UWW during the study period. For the period 2003-2013, the average annual streamflow was estimated at 752.89 m^3/s by the calibrated model, which was slightly less (by 4.06%) than the observed average annual streamflow of 784.77 m^3/s. The annual calibrated flow was highest in 2013 at 1,209.82 m^3/s, while the lowest was in 2005 at 417.15 m^3/s (Figure 5). The above variations in streamflows resulted because in 2013, the average annual precipitation was the highest while the region received the lowest precipitation during 2015. The model predicted the streamflow satisfactorily as the La Niña years (2008, 2011 and 2012) had relatively high streamflow peaks while the El Niño years (2003, 2007 and 2010) had lesser streamflow peaks. The monthly variation of streamflow shows that the highest average monthly streamflow was 334.10 m^3/s in July 2013 and the lowest flow was 0.63 m^3/s in February 2010. The model was able to predict the streamflow well, since July falls in the rainy season in the watershed while February falls in the dry winter months. In 2013, the station located the upstream of the watershed received a high amount of precipitation during the rainy season and could have led to more streamflow. The lowest flow, observed in 2010, could be caused by El Niño effects leading to dry winter months with less precipitation and more evapotranspiration. The estimated streamflow follows the precipitation pattern indicating that the model performed satisfactorily and it was responsive to variations in the rainfall amount.

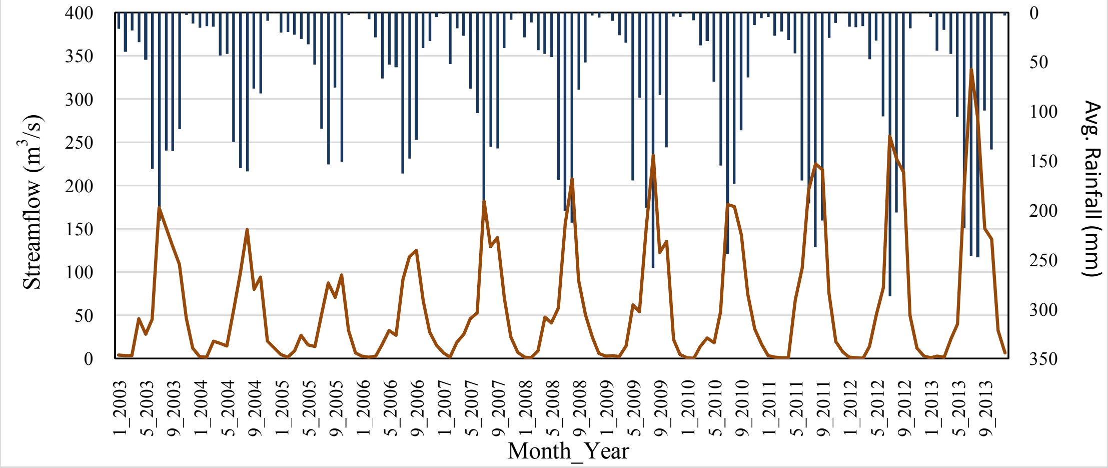

Figure 5 The calibrated flow (continuous line) and monthly average rainfall (bars) from year 2003 through 2013,

The high streamflow peaks during 2012 and 2013 were due to a high precipitation recorded during the rainy seasons at the station located the upstream of UWW. Dile and Srinivasan (2014) also estimated a high streamflow due to high rainfall generated by the CFSR weather data they used for their study in the Blue Nile River Basin. The melting of snow and glaciers is another factor that can lead to an increased streamflow mostly during the summer season. The coarse FAO soil data used in the model can also affect the simulation results (Cao *et al.*, 2003). The weak hydrologic predictions in SWAT could be due to the techniques employed for the collection and recording of streamflow data (Harmel *et al.*, 2006) and also due to short-term streamflow records (Muleta and Nicklow, 2005). The data used in this study is a secondary data, so there is possibility of errors in the data, as it was collected over many years in the past. However, the t-test indicated that there was no significant difference ($p > 0.05$) between the calibrated and observed flow in the UWW.

2. Prediction of streamflow in a climate change scenario

The RCP8.5 was adopted as a climate change scenario for the prediction of streamflow in UWW after more than 35 years and 55 years from the baseline year 2013. The simulation of streamflow for the RCP8.5 scenario, with a calibrated SWAT model, showed that the years 2050 and 2070 are predicted to experience the lowest streamflows in January and February with less than 2 mm while highest streamflow will be experienced during July, August, and September (Table 2).

Table 2 Predicted flow and rainfall in 2050 and 2070 under a climate change scenario.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
2050													
Flow (mm)	0.0	0.9	71.	48.4	50.3	106.9	184.0	201.5	169.9	109.0	54.3	25.8	**958.2**
Precipitation (mm)	6.0	12.0	37.5	86.3	139.8	247.3	310.8	268.0	171.8	47.3	5.0	2.0	**1333.8**
Flow/Precip ratio (%)	0.0	7.2	19.0	56.1	36.0	43.2	59.2	75.2	98.9	230.5	1086.2	1291.4	**71.8**
2070													
Flow (mm)	0.0	1.1	6.8	44.8	43.9	70.4	176.5	199.1	172.1	107.1	51.8	24.3	**898.0**
Precipitation (mm)	5.8	13.0	33.3	85.8	126.5	249.8	347.3	272.3	178.8	38.3	3.0	1.0	**1354.9**
Flow/Precip ratio (%)	0.0	8.1	20.4	52.3	34.7	28.2	50.8	73.1	96.2	279.7	1728.0	2433.9	**66.3**

The driest months in the watershed are November, December, January, and February. These winter months receive relatively less precipitation than during rest of the year. The precipitation in winter mostly comes in the form of snow. The contribution from snow and glaciers to streamflow may be less in winters as the melting will be at its minimum during the winter freeze. The rainy season in the watershed starts from June and lasts until September and receives precipitation from the monsoon. The UWW will receive more annual precipitation in future than in 2013. The melting of snow from the northern high mountains could also lead to an increase in the streamflow during the months from June to September.

The lowest predicted streamflows in the Wangchhu river during the year 2050 and 2070 are significantly less ($p < 0.01$) than the observed flow during the baseline year 2013 (Figure 6). Similarly, the predicted streamflow in July, August, and September is significantly higher ($p < 0.05$) than the streamflow during the same period in 2013. Therefore, the scarcity of water for hydropower in the Wangchhu river is predicted to increase during the dry periods in the future, while there could be a risk of floods during rainy season in the areas downstream of the basin.

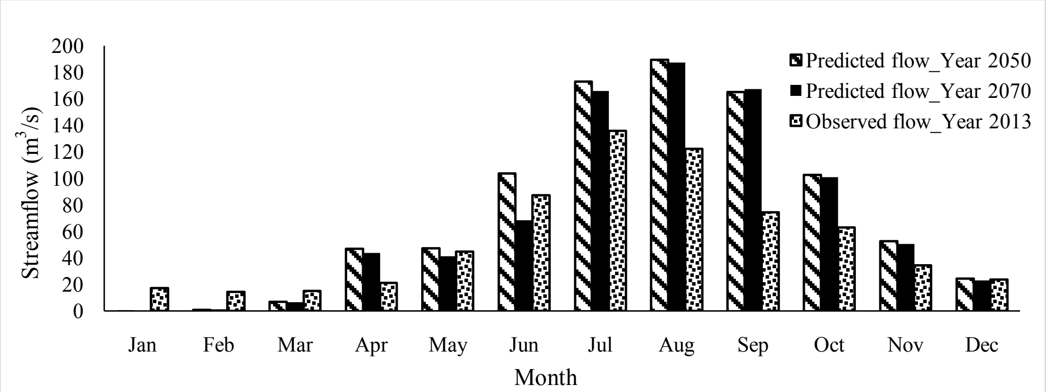

Figure 6 Comparison of streamflow for the 12 months in a future climate change scenario compared to the measured values of 2013.

However, the overall streamflow quantity is predicted to increase during 2050 and 2070 under the climate change scenario RCP8.5 in the UWW. The prediction of increase in streamflow in the watershed agrees with the findings of National Environment Commission (2016b) while it contradicts the result of Beldring and Voksø (2011). Beldring and Voksø (2011), in their study of climate change impact on rivers of Bhutan using HBV model, mentioned that Lungtenphu and Damchhu catchments, which have a small glacier covered fractionand fall in the UWW, will experience a reduction in streamflow by 2100. The reason for the reduction in streamflow in these catchments was due to no contribution from melting ice as the glacier there would have all melted by then and also due to less precipitation received.

The results indicate that the SWAT model can predict the streamflow in the UWW satisfactorily under the climate change scenario RCP8.5. The streamflow in the UWW will be affected by climate change in future, especially during the winter dry seasons and summer rainy seasons, in the form of reduced and increased flows, respectively.

CONCLUSION

The study used the SWAT model to simulate the streamflow of the Wangchhu river in UWW. The precipitation and temperature data from five stations and streamflow data from one station at the outlet of the watershed were used for modeling. The calibration and validation showed that the SWAT model can estimate and predict the streamflow satisfactorily in the UWW, despite the limitations of the data. Some under and overestimation in the baseflows and peakflows was due to missing data, errors from data collection, use of coarse soil data, and the inability to adequately address processes like snowmelt, groundwater, and surface runoff, in the model. The model was also able to satisfactorily simulate and predict the streamflow for future climate change scenario RCP8.5. There will be variations in streamflows during the dry seasons and rainy seasons. The streamflow in the dry winter season in 2050 and 2070 will be less than that in 2013 while the flow during rainy seasons will be more than the 2013 flow. The results from the model indicate that the streamflow in UWW will be affected by climate change in future and the SWAT model is suitable for streamflow study in UWW.

For future studies and better results with SWAT modeling, there is a need for a good soil map and establishment of more meteorological (real-time) stations in the UWW, which will help in building a better hydrological model and reliable predictions. More streamflow gauging stations at the outlets of sub-basins in the upstream area of the UWW are also required. Future studies in the watershed should also look at addressing processes such as snowmelt factors, land use, and removal of water through irrigation. Also, studies on sediment and water quality could be taken up in the watershed using the SWAT model.

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