Modeling the Impacts of Climate Change on Runoff in a River Basin of Eastern India

B. Uniyal[1], M.K. Jha[2], and A. K. Verma[3]

Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur, Kharagpur – 721 302, West Bengal, INDIA

ABSTRACT

Climate change is one of the most important global environmental challenges, which affects the overall system by affecting food production, water supply, health, energy, etc. This paper deals with assessing the impact of climate change on surface runoff using ArcSWAT in a river basin of eastern India. The ArcSWAT model was calibrated and validated using the daily observed streamflow data from 1998 to 2003 and 2004-2005, respectively. The calibrated model simulates streamflow reasonably well with the coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) of 0.882 and 0.88 for the daily time step, and 0.95 and 0.95 for the monthly time step, respectively.

The model was then validated, and the calibrated and validated model was used to assess the basin response to climate change over 21st century using the climate scenarios such as the increase of temperature and rainfall. Comparison of simulation results for different scenarios with the baseline indicated a reduction in surface runoff ranging from 4 to 40% when the temperature was changed from 1 to 5 °C. However, with an increase in rainfall by 5 to 10% results in the increase of surface runoff by 13.2 to 26.3% from the baseline period. It is concluded that changes in the climate will have a significant impact on the surface runoff in the study area. This study and follow-up studies in this direction will be useful for guiding suitable adaptation measures for efficient water management in the study area under changing climatic conditions.

Keywords: Climate change; runoff simulation; model calibration; baseline; climate scenarios

1. INTRODUCTION

Land and water are the most fundamental natural resources of the Earth. The rapidly increasing human population in conjunction with the changed lifestyle has put these natural resources under tremendous pressure, causing their degradation and posing a global threat. Climate change is one of the most important global environmental challenges, which affects the overall system by affecting food production, water supply, health, energy, etc. This is arising due to the increasing concentration of greenhouse gases in the atmosphere since the pre-industrial times. Intergovernmental Panel on Climate Change (IPCC) concluded that it is more than 90% likely that accelerated warming of the past 50-60 years is caused by the anthropogenic release of greenhouse gases, such as CO_2 (Wang et al., 2011). Nearly all regions of the world are expected to experience a net negative impact of climate change on water resources and ecosystems. IPCC projects that the global mean temperature may rise between 1.4 to 5.8 °C by 2100 (IPCC, 2007). Future climatic scenarios for mid to end of the twenty first century as simulated by Global Climate Models also show a warming trend over the entire world, however the intensity and characteristics of these impacts can vary significantly from region to region. The frequency of floods and droughts is expected to increase in most parts of the world resulting in declining crop yield thereby increasing the risk of poverty and hunger (Karim et al., 2009).

Climate change affects the hydrologic cycle of a region through changes in the timing, amount and form of precipitation, evaporation and transpiration rates and soil moisture. This has touched all parts of the world including India. India is a large developing country with nearly two-thirds of its population depending directly on the climate sensitive sectors such as agriculture, fisheries and forests. Thus, India has a significant stake in scientific advancement as well as an international understanding to promote mitigation and adaptation. This requires improved scientific understanding and implementation of latest techniques (Tyler and Moench, 2012). Many studies have implemented the approach of using hydrological models for simulating different climate change scenarios such as variations in temperature, rainfall and CO_2 (e.g., Fontaine et al., 2001; Kalogerophoulous and Chalkias, 2012).

This study deals with modeling the impacts of climate change on surface runoff in the eastern part of India using Soil and Water Assessment Tool (SWAT). It has emerged as a powerful tool to quantify the effects of climate change on water resources (Jha et al., 2006). ArcSWAT is a physically-based, semi-distributed hydrologic model, which has proven to be an effective tool for assessing water resource and non-point source pollution problems for a wide range of scales and environmental conditions across the globe (Neitsch et al., 2011).

Human settlements, deforestation, mining and faulty agricultural practices coupled with high-intensity monsoon rainfall have been continuously degrading the catchment of the study area. These factors along with the regular flood pose a threat to life and property of the inhabitants in the lower catchment of the river. Such studies play a key role improving the decision making for water resources planning and management. The major objectives of the study are: (1) to calibrate and validate the ArcSWAT for streamflow; (2) to project climate change impacts on surface runoff.

2. MATERIALS AND METHODS

2.1 Study Area

The study area as shown in Fig. 1 lies between 21° to 22.5° N latitude and 85° to 86° E longitude in the Baitarani River basin (1776.6 km^2) of eastern India, Odisha. The Baitarani River originates from Guptaganga hills in Keonjhar District of Odisha at an elevation of 900 m MSL. The elevation of the river basin ranges from 330 to 1120 m representing high topographical variation in over the study area. It receives on an average 1534 mm rainfall in a year, more than 80% of which occurs during June to October. The mean monthly maximum temperature is 34 °C in May whereas minimum temperature is 11 °C in the month of January.

2.2 Hydrological Model

For this study, we used the ArcGIS interface of SWAT (version 2009), which is a physically-based, semi-distributed and continuous time step hydrologic model used to predict the impact of different land use and land management practices and climate change on hydrology and water quality of the watershed (Neitsch et al., 2011). The hydrologic cycle simulated by ArcSWAT is based on water balance. The general equation is:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \qquad (1)$$

Where, SW_t = final soil water content (mm), SW_o = initial soil water content (mm), t = simulation period (days), R_{day} = amount of precipitation on the i^{th} day (mm), Q_{surf} = amount of surface streamflow on the i^{th} day (mm), E_a = amount of evapotranspiration on the i^{th} day (mm), W_{seep} = amount of water entering the vadose zone from the soil profile on the i^{th} day (mm), and Q_{gw} = amount of baseflow on the i^{th} day (mm).

Hydrology, weather, soil temperature, crop growth nutrient, bacteria and land management are the major components of ArcSWAT. The model calculates processes like streamflow, sediment and nutrients yield on HRU level, they are unique combinations of soil use, soil type and soil classes. In the present study, 15 sub-basins and 271 HRUs were created which shows a satisfactory representation of the basin heterogeneity. The model uses SCS Curve number (CN) method to estimate the surface runoff. Potential Evapotranspiration is estimated by using Hargreaves's Method.

2.3 Input Data

Date required for ArcSWAT include three spatial maps in GIS grid format, i.e., digital elevation model, land-use and soil map; weather and measured stream discharge data.

2.3.1 Spatial Data

Digital Elevation Model (DEM) is the result of digitization of contour lines (contour interval: 20 m) of the raster maps of study area by using ILWIS 3.3 GIS software. Raster maps were created by using toposheets (1:50, 000). The toposheets were obtained from Survey of India offices at Kolkata, Bhubaneswar, Ranchi and Dehradun. The produced DEM (30 × 30 m) is satisfactory for hydrologic analysis.

Land use Map: The cloud-free remote sensing image (Landsat ETM$^+$ imagery) of November 2, 2001 path 140 and row 45 of 30 m spatial resolution in three spectral bands for the study area were obtained from the Global Land Cover Facility website. To classify land use of the basin, we performed unsupervised classification using ERDAS IMAGINE 8.5 software.

Soil Map: Printed soil maps of Orissa and Bihar at a scale of 1: 5, 00, 000 were procured from National Bureau of Soil Science and Land Use Planning (NBSS&LUP), Nagpur. The available maps were scanned, rectified and digitized in ILWIS GIS to prepare the grid format map as required by ArcSWAT.

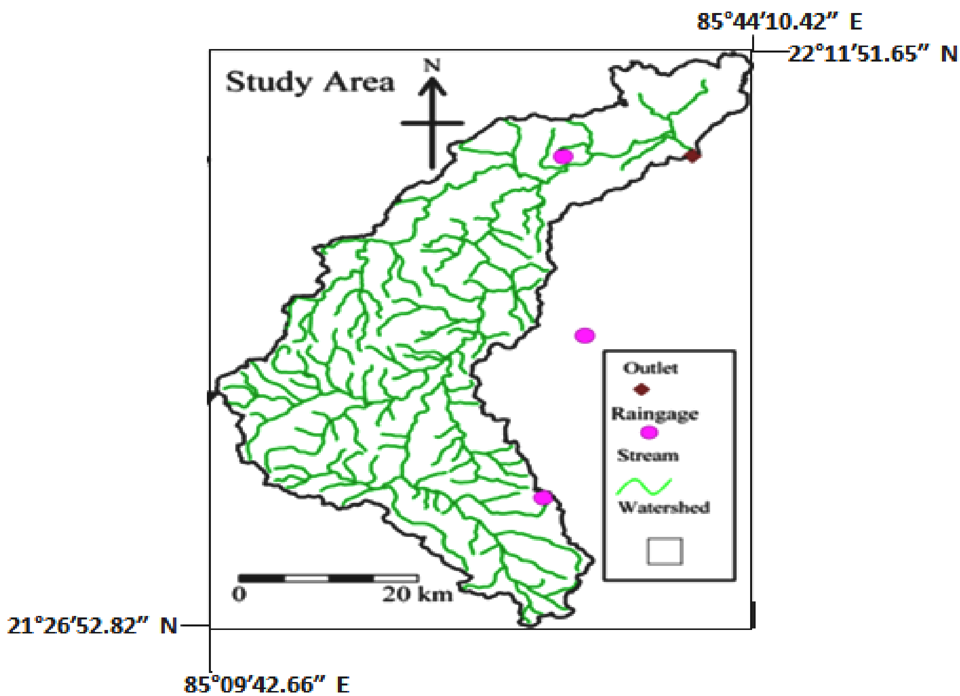

Fig. 1. Map of the study area showing outlet, raingauge and streams

2.3.2 Meteorological Data

Daily rainfall data of three rain gauge stations (Keonjhar, Champua and Jhumpura) and the daily data on temperature, relative humidity and wind velocity of Keonjhar station were obtained from the India Meteorological Centre, Bhubaneswar, Odisha for 8 years period (1998-2005).

Daily streamflow data from 1998 to 2005 of the Upper Baitarni River basin measured at the Champua gauging station were collected from Central Water Commission (CWC), Bhubaneswar, Odisha. Location of the stream gauging station is shown in Fig. 1.

3. CLIMATE CHANGE SCENARIOS

ArcSWAT has two different ways to quantify the impact of climate change on the hydrology of a watershed. The first calculates the basin behavior towards change in greenhouse gases' concentration in the atmosphere, and the second changes the temperature and/or the rainfall. For this study the second methodology was chosen (Fontaine et al., 2001; Kalogeropoulous and Chalkias, 2012). According to various scenarios given by Intergovernmental Panel on Climate Change (IPCC, 2007) the average surface temperature of the country could rise between 1 to 5 °C and rainfall increase from 5 to 20% over the area at the end of the 21st century (Kumar et al., 2006). Finally, different simulations were carried out for the study area according to various scenarios of climate change. These scenarios are shown in Table 1.

Table 1. Temperature and rainfall variation according to the climate change scenarios

Scenarios	Temperature Increase (°C)					Rainfall Increase (%)	
	1	2	3	4	5	5	10
Scenario 1	✓						
Scenario 2		✓					
Scenario 3			✓				
Scenario 4				✓			
Scenario 5					✓		
Scenario 6						✓	
Scenario 7							✓

4. RESULTS AND DISCUSSION

4.1 Model Calibration and Validation

The ArcSWAT model was calibrated for 5 years (1999-2003) using daily streamflow records and validated for another two years (2004-2005) with a one year warming period. The model performance was evaluated using graphical and statistical indicators (coefficient of determination

(R^2) and Nash-Sutcliffe efficiency (NSE)). The calibrated model simulates streamflow reasonably well with the coefficient of determination and Nash-Sutcliffe efficiency of 0.882 and 0.88 for the daily time step, and 0.95 and 0.948 for the monthly time step, respectively whereas in case of validation coefficient of determination and Nash-Sutcliffe efficiency were 0.85 and 0.80 for the daily time step, and 0.94 and 0.96 for the monthly time step, respectively.

4.2 Climate Change Analysis

The method of assessing the impact of climate change which is discussed earlier can be used only at local scale because the considered scenarios are area specific. Fig. 2 shows a clear picture of the response of watershed towards different climatic scenarios. It is clear from the analysis that the increase of temperature by 1, 2 and 3 °C (i.e. scenarios 1, 2 and 3) causes a insignificant decrease in mean annual surface runoff in the study area. Slight decrease in surface runoff is acceptable because Baitarni River is not fed by glacier or lack of snowmelt in the study area. On the contrary, the increase in precipitation by 5 and 10% (scenarios 6 and 7) indicates a significant increase in surface runoff in the study area. From this comparison it is clear that the area is more sensitive to change in precipitation than temperature change.

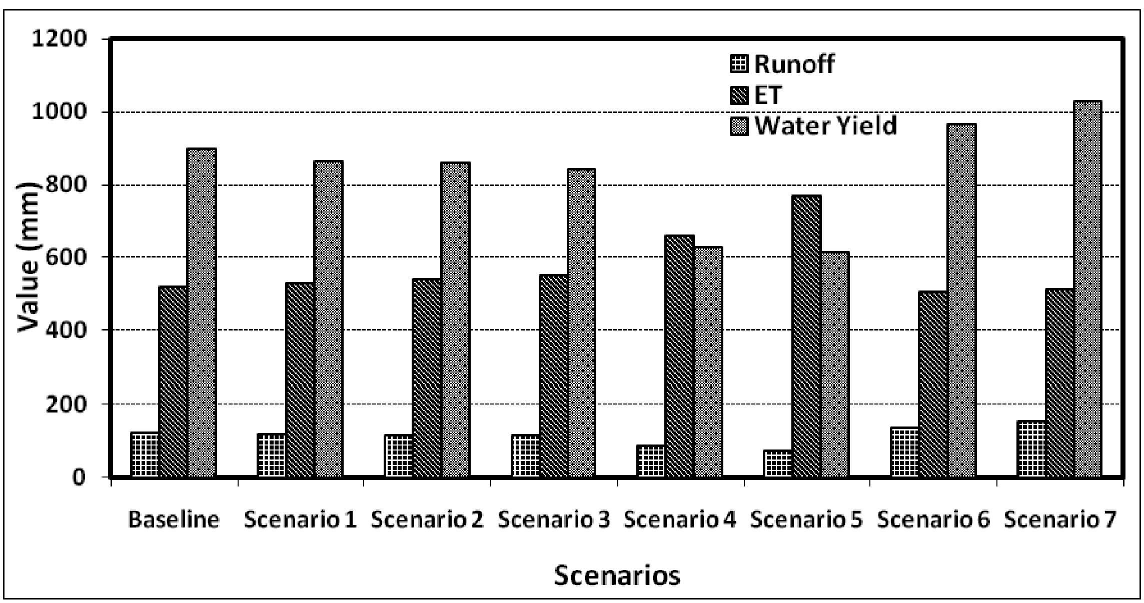

Fig. 2. Mean annual surface runoff, ET and water yield values for different climate change scenarios.

Table 2 shows the comparison of simulated results under different climate change scenarios with the baseline condition, which is the current condition of the study area. It is clear from the table that the change in temperature or rainfall affects all the components of water balance. Scenarios 1-5 which represent steady increase in temperature have mean annual surface runoff declining from 3.8 to 40.1%, and water yield from 3.8 to 31.8% whereas increase in ET from 2.3 to 47.9%. However scenarios 6 and 7 which represent percentage increase in precipitation have mean annual surface runoff increasing from 13.2 to 26.3%, and water yield from 7.2 to 14.4% whereas there is a reduction in ET from 2.7 to 1.4%.

Table 2. Changes in the mean annual surface runoff, ET and water yield under different scenarios

Scenarios	Percentage Increase or Decrease from the Baseline		
	Surface Runoff	**ET**	**Water Yield**
Scenario 1	−3.8	+2.3	−3.8
Scenario 2	−4.2	+4.0	−4.5
Scenario 3	−6.2	+5.9	−6.2
Scenario 4	−28.0	+27.4	−30.0
Scenario 5	−40.1	+47.9	−31.8
Scenario 6	+13.2	−2.7	+7.2
Scenario 7	+26.3	−1.4	+14.4

Note: − indicates decrease; + indicates increase; Water Yield = Surface runoff + Baseflow.

5. CONCLUSIONS

The ArcSWAT model has been used successfully for exploring the hydrological characteristics of Upper Baitarni River basin. Irrespective of different assumptions taken and model limitations, the proposed analysis provides valuable information about the response of watershed towards climate change on surface runoff. The obtained results can be summarized as follows:

(1) An increase in temperature by 1, 2 and 3 °C (scenarios 1, 2 and 3) causes a slight decrease in mean annual surface runoff by 3.8%, 4.2% and 6.2% respectively, from the baseline condition whereas a significant decrease in mean annual surface runoff can be seen when temperature is raised by 4 and 5 °C (scenarios 4 and 5). In this mean annual surface runoff will be decreased by 28.0% and 40.1% from the baseline condition.

(2) With increase in rainfall by 5 and 10% (scenarios 6 and 7) results in increase in the surface runoff by 13.2% and 26.3% from the baseline condition.

(3) From the analysis it is also revealed that the study area is more sensitive towards change in precipitation than the temperature.

It is concluded that changes in the climate will have significant impact on the surface runoff in the study area. This study and follow-up studies in this direction will be useful for guiding suitable adaptation measures for efficient water management in the study area under changing climatic conditions.

REFERENCES

[1] C A Karim, M Faramarzi, S S Ghasemi and H Yang (2009), Assessing the impact of climate change on water resources in Iran, *Water Resources Research*, 45, pp. 1-16.

[2] IPCC (2007), Fourth Assessment Report of the Intergovernmental Panel on Climate Change 2007. *Intergovernmental Panel on Climate Change*, http://www.ipcc.ch (accessed on July 20, 2013).

[3] K Kalogerophoulous and C Chalkias (2012), Modelling the impacts of climate change on surface runoff in small Mediterranean catchments: empirical evidence from Greece, *Water and Environment Journal*, DOI:10.1111/j.1747-6593.

[4] K R Kumar, A K Sahai, K K Kumar, S K Patwardhan, P K Mishra, J V Revadekar, K Kamala and G B Pant (2006), High-resolution climate change scenarios for India for the 21st century, *Climate Science*, 90, 3, pp. 334-345.

[5] M K Jha, J G Arnold, P W Gassman, F Giorgi and R R Gu (2006), Climate change sensitivity assessment on Upper Mississippi River Basin streamflows using SWAT, *Journal of the American Water Resources Association*, 42, 4, pp. 997-1016.

[6] S L Neitsch, J G Arnold, J R Kiniry and J R Williams (2011), *Soil and Water Assessment Tool Theoretical Documentation Version 2009*, Grassland, Soil and Water Research laboratory, East Blackland Road, Temple, Texas.

[7] S Tyler and M Moench (2012), A frame work for urban climate resilience, *Climate and development*, 4, 4, pp. 311-326.

[8] T A Fontaine, J F Klassen, T S Cruickshank and R H Hotchkiss (2001), Hydrological response to climate change in the Black Hills of South Dakota, USA, *Hydrological Sciences Journal*, 46, 1, pp. 27-40.

[9] Z Wang, D L Ficklin, Y Zang and M Zhang (2011), Impact of climate change on streamflow in the arid Shiyang River Basin of northwest China, *Hydrological Processes*, 26, pp. 2733-2744.