Effect of Evapotranspiration on the Discharge Estimation in Baitarani Watershed, India, in the Context of Climate Change

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Abstract

This study aims to quantify the rainfall-runoff transformation process of tropical wet and dry Baitarani watershed at Anandapur using different evapotranspiration (ET) models along with geomorphological instantaneous unit hydrograph (GIUH) based Nash model in the context of climate change. Herein, four ET models were used to calculate the ET and the resultant runoff hydrographs were compared with the observed hydrograph. The FAO-24 radiation model as the ET estimation model along with GIUH-based Nash model performs well as compared to the other ET estimation models. Hence this model was further applied to evaluate the impact of climate change by the end of the 21st century using the climatic scenarios projected by Met Office Hadley Centre using CMIP3 model under A1B emission scenario. Two independent and one combined climatic scenarios were considered to analyse the effect of ET. The study reveals that increase in ET in the nearby future could be a cause for water stress in the study area especially in summer and winter which will be needed for prime uses.

INTRODUCTION

The natural hazards such as flood and drought events can destruct human life and having socio-economic-environmental consequences. They have direct impact on both individuals and communities. The consequences of these hazards vary greatly depending on the site of occurrence, extended area, time prevalence, and the vulnerability and value of the environments they affect. Hence, quantification of rainfall-runoff transformation process in a watershed is important for the water resources management. Estimation of discharge peak is required for the design of hydraulic structures and flood management. At the same time, the low flow assessment is also important for the sectoral water allocation.

The available rainfall-runoff models which needed long-term observed data for the discharge estimation cannot use in most of the ungauged watersheds. Hence the geomorphologic instantaneous unit hydrograph (GIUH)-based Nash model, one of the conceptual models, which uses the measurable watershed and rainfall characteristics to estimate its model parameters, could be a better option for estimating the discharge from any ungauged watershed. The concept of GIUH was first advocated by Rodriguez-Iturbe and Valdes (1979) in which the instantaneous unit hydrograph (IUH) was linked with the geomorphological parameters of the watershed. These geomorphological parameters are Horton's bifurcation ratio, area ratio, and length ratio (Horton 1945), in which the channel network is described using the Strahler (Strahler 1957) ordering scheme. Gupta et al. (1980) developed the above approach into a simplified one and generalized it. Subsequently, Van der tak and Bras (1990) introduced the gamma distribution-based GIUHs that better fit the data-driven IUHs without using the conventional exponential distributions of stream holding times of a water droplet. However, all these approaches generates a triangular hydrograph resulted from lumped manner calculations. Then to address these issue of triangular hydrograph generation and to get the natural shape of the runoff hydrograph, Bhaskar et al. (1997), Sahoo et al. (2006), and Kumar and Kumar (2008) linked the GIUH models with the conventional Clark and Nash IUH models for parameter estimation. Recently, the GIUH models have been advanced for hydrograph synthesis, adding a new extent to hydrologic simulations. All the necessary geomorphologic data can be obtained from the topographic maps or from digital elevation models (DEM). Further, the applicability of the Nash model requires the computation of incomplete gamma function along with the effective rainfall (ER) for the discharge estimation.

Evapotranspiration (ET) is a vital parameter for hydrological and climatological studies. Estimation of ET is one of the major component for determining the ER and also act as a controlling factor of runoff volume or river discharge. Hence it is important to have an authentic and consistent estimation of ET. During the past half century, empirical and/or physically based equations have been developed to estimate reference ET (ET_0) for different regions (Alexandris et al. 2008). But it may be confusing and critical for the sensible user to select the appropriate method, for the wide range of applications, because of significant differences between the values of different ET model which produces.

The commonly used method to estimate ET_0 is from climatic variables, such as solar radiation, air temperature, wind speed, and relative humidity. In connection with, various methods are available for estimating ET_0, involving equations ranging from the most complex energy balance method requiring detailed climatological data (Allen et al. 1989) to simpler method requiring less data (Hargreaves 1982). The Food and Agricultural Organisation (FAO)-24 Radiation model is a physically based combination model (Doorenbos and Pruitt 1977; Jensen et al. 1990) which deals with both energy budget and mass transfer. The Hargreaves method is quite simple that requires only two climatic parameters: the temperature and solar radiation. This method has been tested using some high quality lysimeter data and broad range in climatological conditions (Hargreaves and Samani 1994) whose results revealed as nearly accurate as Penman Monteith (PM) in estimating ET_0. Therefore, the use of the Hargreaves method is recommended in cases where reliable data are lacking. Irmak et al. (2003) simplified the FAO56-PM method by expressing a multi-linear regression function which requires less input parameters and computation. This uses only the solar radiation and mean daily temperature as input parameters to estimate the ET_0.

Increasing pressure on natural resources having harmful consequences on vulnerable ecosystems and biodiversity, and thereby poses a serious global threat to sustainable development (Biswas et al. 2009; Oki and Kanae 2006). The ultimate threat to mankind in 21^{st} century will be the climate change, which has appeared as one of the most important worldwide environmental challenges. The world is expected to experience a net negative impact of climate change on water resources and vulnerable ecosystems. Some regions are likely to experience water stress, combined with increasing water demand; this will put more and more people under water scarcity threat. At the same time some regions will have a risk of flood inundation and loss of lives. The flood and drought frequency will increase in most parts of the world (Karim et al. 2009). It has been anticipated that direct impact of climate change on water resources will be mainly through ET by the increase of temperature. The climate change will cause a steady rise of temperature, changes in rainfall pattern and associated land use and cover pattern. Higher temperature will induce higher ET which in turn will affect the hydrological system and water resources (Shahid 2011). Thus, quantifying the changes in ET due to climate change is very important for the management of long-term water resources.

In order to perform adaptation strategies and activities to avoid the risk of climate change on water resources, it is important to quantify the physical impacts of climate change. Met Office Hadley Centre simulation using Coupled Model Intercomparison Project 3 (CMIP3) multi model ensemble for the end of 21st century indicates increased temperature and precipitation under the A1B emission scenario. In the southern part of India, the projected temperature increase is lower, up to 3°C, when comparing with that of Northern part of India (4.5°C). India is projected to experience increases in precipitation across most of the country. Increases of up to 20% or higher could occur in western regions with more widespread increases of 5-10% over the rest of the country. Water stress could increase in India with climate change and very large increase in average annual flood risk in the A1B emissions scenario. However, this result is subject to significant uncertainty (Gosling et al. 2011).

In light of the above discussion, this study has been undertaken to evaluate the rainfall-runoff transformation process of the Baitarani Watershed at Anandapur by using GIUH-based Nash model in the context of climate change. Also, the applicability of FAO-24 radiation ET model for the ER estimation are compared with the Hargreaves, Ritchie and Irmak ET models. Considering the data limitation in this watershed, relevant climatic scenarios as projected by Met Office Hadley Centre using CMIP3 multi model ensemble by the end of the 21st century have been considered for the climate change analysis.

MATERIALS AND METHODS

Study Area

The catchment area of the Baitarani River at Anandapur which lies in Eastern India between the longitudes of 85°10' E to 87°03' E and latitudes of 20°35' N to 22°15' N is about 8,580 km^2 (Figure 1). The annual rainfall in this river watershed varies from 642 mm to 3,094 mm with an average of 1,187 mm (1980-2010). The maximum temperature in the watershed is 48.5°C, recorded at Keonjhar station and the minimum is 6°C. There are three major seasons in the study area: (i) summer (February-May); (ii) rainy season (June-October); and (iii) winter (November-January). The daily rainfall data at 5 gauging stations were collected from Indian Meteorological Department (IMD). Other meteorological data, such as solar radiation, maximum temperature, minimum temperature, relative humidity and wind speed were downloaded from the NASA POWER website (http://power.larc.nasa.gov/) with a grid size of 1° × 1° at these gauging stations. The runoff and water stage data at daily scale was also collected for the Anandapur gauging station from the Central Water Commission (CWC), Bhubaneswar, Odisha for the year of 1999 (June-Dec). The DEM data of 90 × 90 m resolution for the study area was downloaded from the CGIAR-CSI website (http://srtm.csi.cgiar.org/), which was used for the delineation of the watershed by using the ERDAS Imagine 9.3 (ERDAS, 2008) and the ArcGIS software (ESRI, 2004).

For estimating the geomorphologic parameters of the GIUH-based Nash model, the stream ordering of the watershed was carried out using the ArcMAP9.3 software which envisaged that this is a fourth order watershed, having the length of the highest order stream L_{Ω} =19.39 km. The values of Horton's bifurcation ratio (R_B), length ratio (R_L), and area ratio (R_A) of this watershed are 4.05, 2.15, 4.89, and 19.39 km, respectively (Sahoo and Saritha 2014).

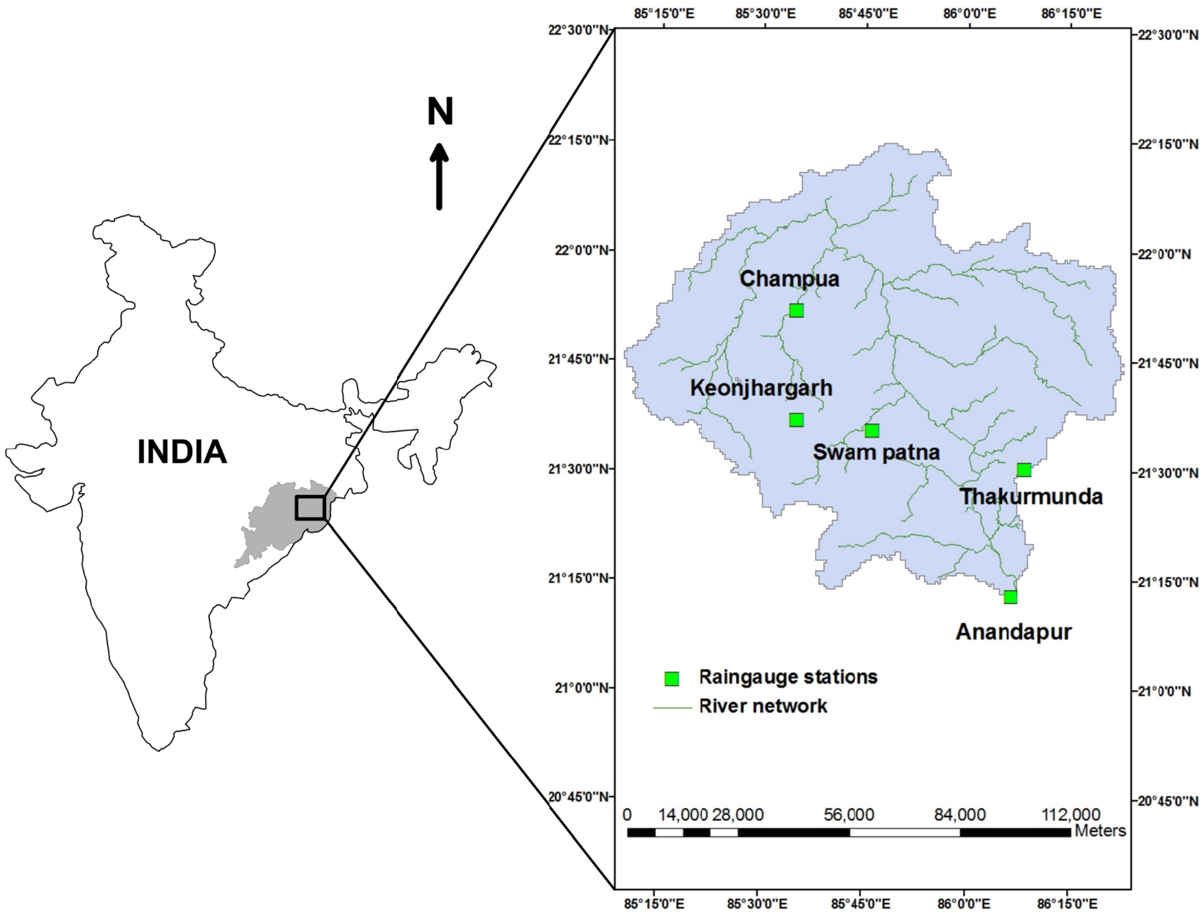

Figure 1. Location map of the study area.

Overview of ET Models

FAO-24 radiation model

The reference evapotranspiration (mm/day) is determined using the FAO-24 radiation method as (Doorenbos and Pruitt 1977; Jensen et al. 1990):

$$ET_0 = a + b\left(\frac{\Delta}{\Delta+\gamma}\right)R_s \quad (1)$$

where ET_0 = reference evapotranspiration (mm/day); R_s = solar radiation (mm/day); a = −0.3 mm/day; Δ = slope of saturation vapour pressure-temperature curve (kPa/°C); γ = Psychrometric constant (kPa/°C); and b is estimated as:

$$b = 1.066 - 0.0013RH_{mean} + 0.045U_d - 0.0002RH_{mean}U_d - 0.0000315RH_{mean}^2 - 0.0011U_d^2 \quad (2)$$

where RH_{mean} = mean relative humidity (%); and U_d = mean daytime wind speed (m/s).

Hargreaves model

Hargreaves (1975) equation can be expressed as:

$$ET_0 = 0.0135 * 0.408(T_m + 17.8)R_s \quad (3)$$

where T_m = mean daily temperature

Ritchie model

The Ritchie method can be given as (Jones and Ritchie, 1990):

$$ET_0 = \alpha_1[3.87 \times 10^{-3} \times R_s\ (0.6T_{max} + 0.4T_{min} + 29)] \quad (4)$$

where T_{max} and T_{min} = maximum and minimum temperature (^{0}C) and the parameter α_1 is estimated as:

$$\left\{\begin{array}{ll} 5 < T_{max} \leq 35^\circ & ;\ \alpha_1 = 1.1 \\ T_{max} > 35^\circ & ;\ \alpha_1 = 1.1 + 0.05(T_{max} - 35) \\ T_{max} < 5^\circ & ;\ \alpha_1 = 1.1 \times \exp[0.18(T_{max} + 20)] \end{array}\right\} \quad (5)$$

Irmak model

The Irmak equation developed by Irmak et al. (2003) can be given as:

$$ET_0 = -0.611 + 0.149R_s + 0.079T_m \quad (6)$$

GIUH-Nash Model

To estimate the lumped runoff from an ungauged river watershed, the GIUH formulation by Rodriguez-Iturbe and Valdes (1979) provides a triangular runoff hydrograph with its peak and time to peak, respectively, expressed as:

$$q_p = 1.31{R_L}^{0.43}(V/L_\Omega) \quad (7)$$

$$t_p = 0.44(L_\Omega/V)(R_B/R_A)^{0.55}{R_L}^{-0.38} \quad (8)$$

where L_Ω = length of the highest order stream (km); V = expected peak velocity (m/s); q_p = peak flow (h^{-1}); R_B = Horton's bifurcation ratio; R_A = Horton's area ratio; R_L = Horton's length ratio; and t_p = time to peak (h).

The multiplication of peak flow and time to peak will produce a dimensionless ratio IR denoting the river watershed characteristics only which is independent of the climate forcing and is given by:

$$IR = q_p t_p = 0.5764(R_B/R_A)^{0.55}{R_L}^{-0.38} \quad (9)$$

Further, the Nash IUH model is given as (Nash, 1957, 1960):

$$u(t) = \left[1/\left(k\Gamma(n)\right)\right](t/k)^{n-1} \exp(-t/k) \quad (10)$$

where n = shape parameter of the Nash IUH model indicating the number of linear reservoirs cascades, k = scale parameter of the Nash IUH model indicating the storage effect of the watershed.

The preceding result in Eq. (9) is equated with the multiplication of Eq. (10) and the property of gamma pdf of the Nash IUH, t_p=k (n−1), to get (Sahoo et al. 2006):

$$(n-1)^n/\Gamma(n)[\exp(-\{n-1\})] = 0.5764({}^{R_B}/_{R_A})^{0.55}{R_L}^{-0.38} \qquad (11)$$

The shape parameter, n is obtained by solving Eq. (11) by the Newton-Raphson nonlinear optimization scheme; the scale parameter is obtained as: k=t_p / (n−1), and t_p is estimated by Eq. (8); and the GIUH-based Nash Model is computed by Eq. (10) using the final values of n and k. The IUH ordinates, thus obtained, produce the ordinates of DSRO hydrographs after their convolution with the excess rainfall.

Model Performance Evaluation Criteria

The performance of the GIUH-based Nash model was evaluated using four performance evaluation criteria:

1. Nash–Sutcliffe efficiency (NSE) = $NSE = \{1 - \frac{\sum_{i=1}^{N}(Q_o - Q_c)^2}{\sum_{i=1}^{N}(Q_o - \overline{Q_o})^2}\}100$

where Q_o = Observed discharge; Q_c = Computed discharge; $\overline{Q_o}$= Mean observed discharge

2. Percentage error in peak discharge:

   PEP = [1- (computed peak discharge/observed peak discharge)] ×100;

3. Percentage error in time to peak discharge:

   PETP = [1- (computed time to peak /observed time to peak)] ×100; and

4. Percentage error in volume:

   PEV = [1- (computed volume of discharge /observed volume of discharge)] ×100

RESULTS AND DISCUSSIONS

The estimated shape parameter (n) of the GIUH-Nash model is 2.994, whereas the scale parameter (k) varies between 0.417 and 3.30. The n value remains constant for the watershed as it is a function of the watershed geomorphology only. However, k is inversely proportional to the flow velocity and varies with the rainfall events.

Effect of ET Models on Discharge

Figure 2 shows the ET_0 estimated using four different ET models such as FAO-24 Radiation, Hargreaves, Ritchie, and Irmak. It can be envisaged from the figure that the ET_0 estimated using FAO-24 Radiation model is high during the summer and winter seasons comparing to the other models. This high value of ET_0 can be attributed to the influence of wind speed (WS) and relative humidity (RH). Only FAO-24 Radiation model uses RH and WS for the estimation of ET_0. The low RH and high WS during summer and winter season could be a cause for the high ET_0. On the other hand we can see that all the models showing almost similar trend in simulated ET_0 during rainy season. Because the effect of RH and WS is negligible compared to the solar radiation and temperature during the monsoon season. Hence selection of ET model is having a prime importance for the ER estimation. In the absence of a standard ET_0 estimation method, we compared the efficiency of ET models in terms of how accurately they are determining the discharge of the Baitarani watershed along with GIUH-Nash model.

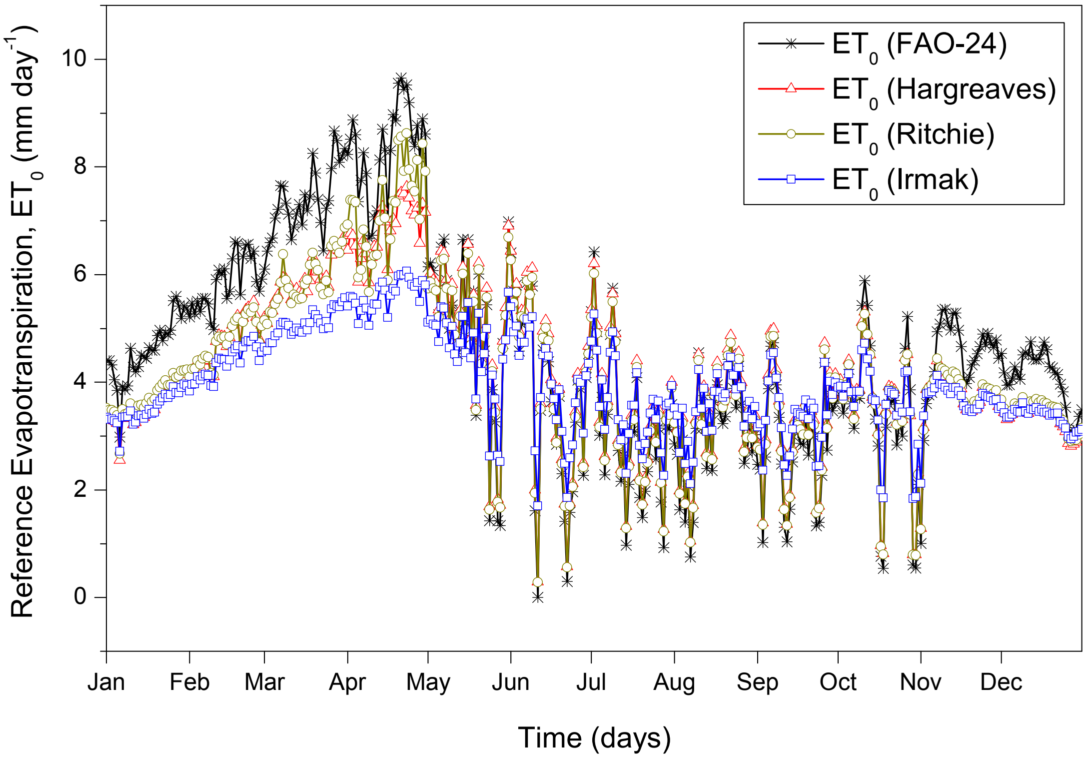

Figure 2. Daily ET_0 simulated by using different ET Models.

Figure 3 shows the reproduced daily discharge hydrographs for the Baitarani watershed at Anandapur using four different ET models as the ER evaluation methods. The GIUH-Nash model simulating almost the same discharge for all the ET models even though the models uses different set of parameters for ET_0 estimation. This is because there is no significant change in the quantified ER by using the four ET models. ER is the major component that is responsible for reproducing the discharge hydrograph. From Figure 3, it is clear that the GIUH-Nash model is very good in computing the flood peak and rising limb. But the recession limb is quite under estimating as there may be a time lag between the discharges contributed by the two third-order streams. Therefore, GIUH-Nash model along with all the ET models are not good enough in predicting the low flow. Hence, the four ET models can forecast more or less same discharge on annual basis with less available data.

In order to analyse the performance of the GIUH-Nash model along with four ET models for single storm events, we chose two events, E1 (August 1, 1999) and E2 (October 27, 1999) shown as shaded portion in figure 3 and was evaluated based on the criteria's such as Nash-Sutcliffe efficiency, error in peak discharge estimate, error in time to peak estimate, and error in discharge volume (Table 1). Table 1 shows that the FAO-24 Radiation exhibits better NSE, PEP, PETP, and PEV in case of single storm events. Therefore, FAO-24 Radiation method can be used for forecasting the discharge with GIUH-Nash model in situations where comprehensive study of discharge volume is needed with substantial amount of meteorological data. Hence, herein we are using the FAO-24 Radiation model as the ET estimation method for forecasting the discharge to the anticipated climate changes by the end of the 21st century along with GIUH-Nash model.

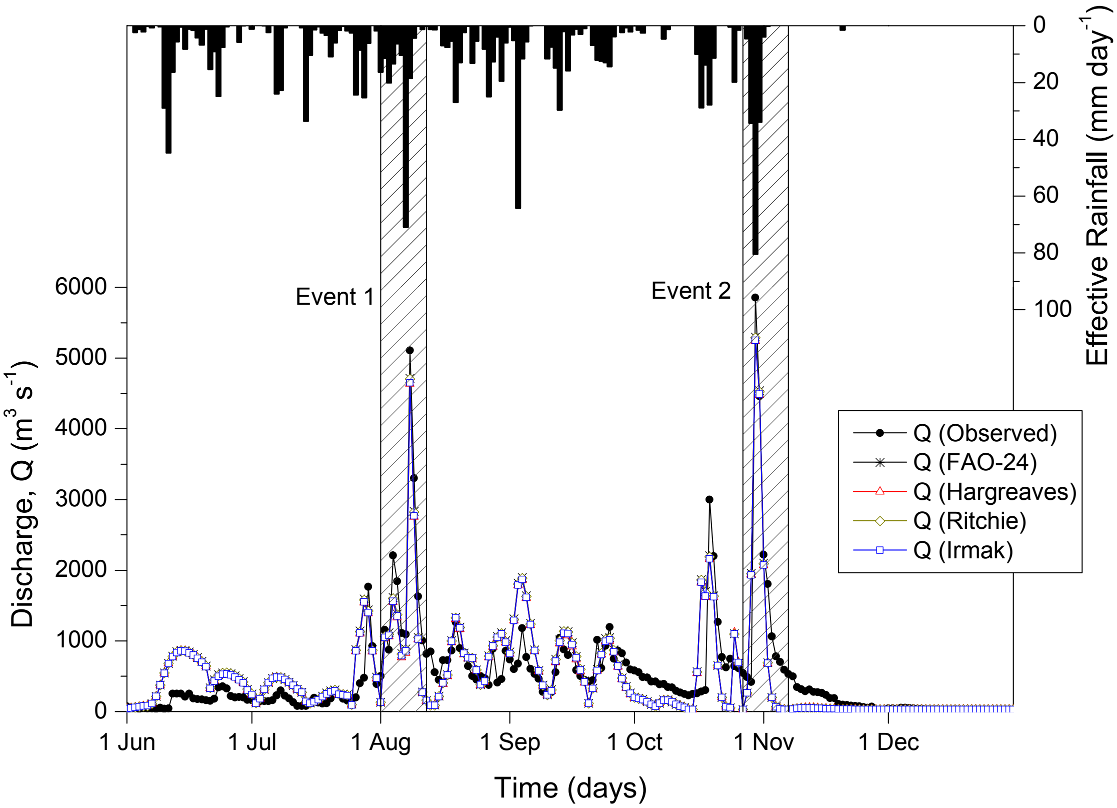

Figure 3. Reproduction of streamflow hydrograph by the GIUH-Nash and ET models for the year 1999.

Table 1. Performance evaluation measures of four ET models with GIUH-Nash model.

ET estimation method	NSE (%) (*)		PEP (%) (**)		PETP (%) (**)		PEV (%) (**)	
	Event 1	Event 2	Event 1	Event 2	Event 1	Event 2	Event 1	Event 2
FAO-24 Radiation	86.40	81.14	7.69	9.53	0	0	22.20	21.64
Hargreaves	84.44	80.97	9.18	10.52	0	0	24.70	22.56
Ritchie	85.99	81.06	7.85	9.72	0	0	22.66	21.87
Irmak	84.95	81.00	8.89	10.38	0	0	23.99	22.51

*higher value implies better performance and **lower values implies better performance

Climate Change Analysis

Three incremental climatic scenarios were analysed to know about the effect of meteorological parameters such as temperature and precipitation on the discharge (Table 2). The first scenario includes the change in temperature from the baseline condition by adding 3.5°C in order to understand the effect of ET whereas the second scenario includes the percentage change in precipitation from the baseline line condition. An increment of 10% was given to the baseline precipitation. Furthermore, one combined scenario was also considered to analyse the combined effect of temperature and precipitation for the 21st century.

Table 2. Climatic scenarios based on temperature and rainfall.

Scenario	Temperature increase (°C)	Rainfall increase (%)
Scenario 1	3.5	-
Scenario 2	-	10
Scenario 3	3.5	10

The response of daily discharge hydrographs to the three climatic scenarios are not clearly distinguishable due to the hydrograph overlapping. Hence we averaged the daily discharge into mean monthly discharge and the monthly hydrograph response to three climatic scenarios are shown in Figure 4. It can be seen that there is a decreasing trend in discharge when the temperature is increased by 3.5 °C, i.e. scenario 1. But in scenario 2 and 3, the stream discharge is increased with the increase in rainfall. However, the increase become negligible during summer and winter season. This may be attributed to the increase in ET during summer and winter (Figure 2). Scenario 1 can predicts the discharge better than other scenarios during summer season as there is no rainfall. Furthermore, the monsoon and winter flows can be well predicted in scenario 3 (combined) as there will be an increase in both rainfall and temperature.

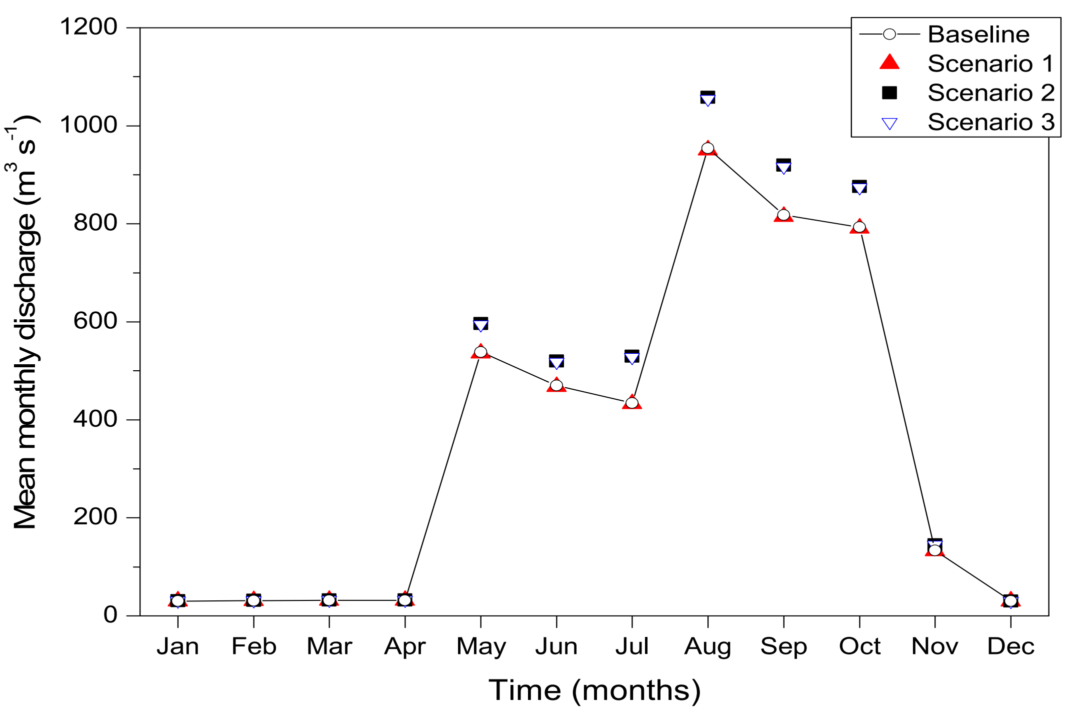

Figure 4. Hydrograph response to the climatic scenarios.

The seasonal wise percentage variation (increase or decrease) in the stream discharge is shown in Table 3. The discharge decreased by 0.11 – 10.57 % compared to the baseline in scenario 1. On the contrary, increase in rainfall by 10% resulted in an increase in the discharge by 0.14-48.93%. For the combined scenario, the change in discharge vary from 0.11-21.65% from the daily basis baseline. Here scenario 1 shows maximum reduction in discharge, whereas scenario 2 shows maximum increase in discharge from the baseline. The combined scenario (scenario 3) shows a value which lies between scenario 1 and 2.

In scenario 1, the annual discharge reduction is higher during the summer season due to anticipated increase in evapotranspiration from 3.03-7.49%. On the other hand, the reduction is less during monsoon and winter season compared to the summer. In scenario 2, the annual discharge is increased by 48.93% from the baseline. Finally for scenario 3, the combined effect of temperature and precipitation will cause an increase in annual discharge by 21.65%. Overall there will be an increase in annual discharge over the watershed. But notably, the % increase of annual discharge during summer is very small compared to that in monsoon. Thus the study area is more sensitive to future changes in rainfall during monsoon and less during summer and winter. That implies the increase of temperature can significantly reduce the stream discharge by the increased ET under the A1B emission scenario.

Table 3. Seasonal wise change in stream discharge for the climatic scenarios.

Scenario		Summer (%)	Monsoon (%)	Winter (%)
Scenario 1 (% decrease)	ET_0	3.03-7.49	1.57-5.78	2.53-4.23
	Q	4.26-10.57	0.11-1.89	4.8-6.63
Scenario 2 (% increase)	ET_0	0	0	0
	Q	0.14-2.12	3.25-48.93	0.25-7.78
Scenario 3 (% increase)	ET_0	3.03-7.49	1.57-5.78	2.53-4.23
	Q	0.11-1.66	2.91-21.65	0.20-6.15

CONCLUSIONS

The study demonstrates the application of GIUH-Nash model along with four different ET models to simulate the discharge of the Baitarani watershed at Anandapur. ET_0 was estimated by using four different ET models such as FAO-24 Radiation, Hargreaves, Ritchie, and Irmak models. These estimated ET_0 were incorporated into the ER estimation and the resultant discharge hydrographs were compared with the observed hydrograph. The performance of these simulated hydrographs were evaluated using NSE, PEP, PEV, and PETP criteria's. Among the different ET models used, the FAO-24 Radiation model exhibits better performance in terms of performance criteria's. Hence the GIUH-Nash model along with FAO-24 Radiation model was further applied for climate change analysis of the watershed. Considering the data limitation in the watershed, relevant climatic scenarios as projected by Met Office Hadley Centre using CMIP3 multi model ensemble under A1B emission scenario by the end of the 21st century have been considered for the climate change analysis.

Two independent and one combined climatic scenarios were considered to understand the effects of temperature and precipitation on the watershed discharge. In the absence of ideal time period (1960-1990) data, 1999 data was used as the baseline climate, which represents the average condition of the watershed. Scenario 1 (3.5°C increase in temperature) shows a decrease in the discharge from 0.11-10.57% compared to the baseline and the decrease is more pronounced during summer season. In this scenario, the ET is also showing a continuous increasing trend (1.57-7.49 %) and resulted in low discharge. However scenario 2 (10% increase in precipitation) revealed a maximum increase in discharge from baseline by 48.93%. During this scenario, the ET become negligible due to low temperature and high RH. But the combined scenario (3.5°C increase in temperature and 10% increase in precipitation) is more realistic and effective in the discharge simulation for the future as it will be the case most probably occur. The combined scenario revealed that the river discharge will increase to a maximum of 21.65% during monsoon. But the increase in discharge is negligible during summer to a maximum of 1.66%. Herein, the ET shows the same trend as that of scenario 1.

The proposed climate change analysis discloses that the watershed is more sensitive to the changes in precipitation as compared to the changes in temperature. However, the effects of changes in precipitation become very negligible and the effects of temperature changes is significant during summer and winter. The high temperature will induce the ET. Hence the discharge will become very low during summer and winter which will put the watershed under water stress and resultant reduction in groundwater. Therefore we need to pay attention to perform adaptation strategies and activities, to avoid the risk of climate change on water resources, such as rainwater harvesting, groundwater recharge, afforestation, and reuse and recycling of water.

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