

Rainfall–runoff simulations of extreme monsoon rainfall events in a tropical river basin of India

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Abstract The present study analyzes the runoff response during extreme rain events over the basin of Subarnarekha River in India using soil and water assessment tool (SWAT). The SWAT model is configured for the Subarnarekha River basin with 32 sub-basins. Three gauging stations in the basin (viz., Adityapur, Jamshedpur and Ghatshila) were selected to assess the model performance. Daily stream flow data are taken from Central Water Commission, India—Water Resources Information System. Calibration and validation of the model were performed using the soil and water assessment tool-calibration uncertainty programs (SWAT-CUPs) with sequential uncertainty fitting (SUFI-2) algorithm. The model was run for the period from 1982 to 2011 with a calibration period from 1982 to 1997 and a validation period from 1998 to 2011. The sensitivity of basin parameters has been analyzed in order to improve the runoff simulation efficiency of the model. The study concluded that the model performed well in Ghatshila gauging station with a Nash–Sutcliffe efficiency (NSE) of 0.68 during calibration and 0.62 during validation at daily scale. The model, thus calibrated and validated, was then applied to evaluate the extreme monsoon rain events in recent years. Five extreme events were identified in Jamshedpur and Ghatshila sub-basins of Subarnarekha River basin. The simulation results were found to be good for the extreme events with the NSE of 0.89 at Jamshedpur and 0.96 at Ghatshila gauging stations. The findings of this study can be useful in runoff simulation and flood forecasting for extreme rainfall events in Subarnarekha River basin.

Keywords Extreme rainfall events · SWAT · Sensitivity analysis · Rainfall–runoff simulations

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1 Introduction

Precipitation-induced flooding caused by extreme rainfall events is linked with rising tropospheric temperatures (Trenbert 2006). A change in extreme precipitation is governed by rise in temperature, variation in continental runoff, and evapotranspiration (Huntington 2006). Climatic changes associated with rising temperature increase anthropogenic influence on rivers (Arnell 1996). Changes observed in extreme rainfall are investigated globally with different criteria of analysis (Groisman et al. 2005; Fischer and Knutti 2014). Large variability in the Indian rainfall makes it challenging to study extreme rainfall events. Some studies discuss extreme rainfall projections under warming scenarios over India (Krishnakumar et al. 2011; Chaturvedi et al. 2012; Sharmila et al. 2015). In dry lands, rainfall characteristics significantly influence runoff dynamics, mainly with regard to the magnitude and frequency of rainfall–runoff events. It is distinctly possible that larger, more extreme events will overshoot the process of infiltration in soil and produce quick and large amount of runoff, while the opposite will be likely for rainfall events of less intensity. Moreover, variability in magnitude and frequency of runoff events caused by changing magnitude and frequency of rainfall alters the properties of nutrient redistribution and soil erosion in the region.

Some recent studies have pointed that the magnitude and frequency of extreme rainfall events are in notably increasing trend over India from 1951 to 2010 (Krishnamurthy 2012). Moreover, in recent times, India has experienced erratic rain with increasing frequency of flash floods in hilly regions (CSE 2014). The phenomena of Mumbai flood in July 2005, Uttarakhand flood in June 2013, and Jammu and Kashmir flood in September 2014 have compelled the researchers/policy makers to focus on predicting runoff, changing climatic pattern, and improvement in flood forecasting.

In this study, our main focus is on analyzing the underlying processes and adjusting the parameters based on regional knowledge for the better understanding of the runoff dynamics in extreme rain events. Borah et al. (2004) compiled 17 soil and water assessment tool (SWAT), 12 hydrological simulation program—Fortran (HSPF), and 18 dynamic watershed simulation model (DWSM) applications and concluded that the SWAT is suitable for monthly predictions, for all months barring months with extreme rain events and surface hydrological conditions. In such cases, SWAT is unsatisfactory in simulating daily extreme discharge-causing events. A sensitivity analysis was conducted by White and Chaubey (2005) wherein curve number (CN2), soil available water capacity (SOL_AWC), and soil evaporation compensation factor (ESCO) parameters were identified to be the most potent SWAT parameters in flow prediction of beaver reservoir (Arkansas State, the USA). Although many methods of sensitivity analysis are available (Beven 2001; Hamby 1994), these methods distinguish parameters based on their having or not having a substantial leverage on model simulations observations for a particular catchment or watershed (van Griensven et al. 2006). For a given watershed, sensitivity analysis of model parameters is a cause of apprehension in model calibration for the specific watershed. Sensitivity of SWAT parameters also fluctuates between the two watersheds, pointing to the significance of sensitivity analysis for any river basin or watershed subjected to under SWAT modeling (Cibin et al. 2012). In recent years, hydrological modeling with the application of SWAT has turned up as an effective tool to quantify the impacts of climate change on water resources included in references (Jha et al. 2006). During the last decade, SWAT has been exhaustively used for basin-scale hydrological modeling (Uniyal et al. 2015; Sharma et al. 2015). The objectives of this study are as follows: (i) to configure the SWAT model for the Subarnarekha River basin and to simulate discharge using SWAT-

calibration uncertainty programs (SWAT-CUPs) with sequential uncertainty fitting (SUFI-2) algorithm in SWAT-CUP; (ii) to perform sensitivity analysis of the model parameters and thereby to improve the model performance further in simulating runoff; and (iii) to analyze the runoff response during extreme rainfall events in the river basin.

In the following section, a brief description of input datasets and river basin is given; Sect. 3 includes SWAT model detail and methodology adopted; and Sect. 4 combines the results and discussion. Section 5 concludes the study.

2 Physical descriptions of the river basin and dataset used

2.1 Study area

The Subarnarekha River basin, lying within the longitudes/latitudes of $85^{\circ}09'–87^{\circ}27'E/21^{\circ}33'–23^{\circ}32'N$ (Fig. 1), considered in this study has major tributaries such as Raru, Kharkai, Karkari, and Kanchi. The Subarnarekha River is one of the longest east-flowing interstate rivers, and it has a total catchment area of $19,296\text{ km}^2$. It originates near Nagri village (in the Chotanagpur plateau) of Jharkhand and outfalls into the Bay of Bengal after flowing over a distance of 395 km. The topography of the study area is characterized by an undulating terrain. The highland region is situated on the western and northwestern portions of the study area. The origin of the river is at an elevation of around 610 m. Plain

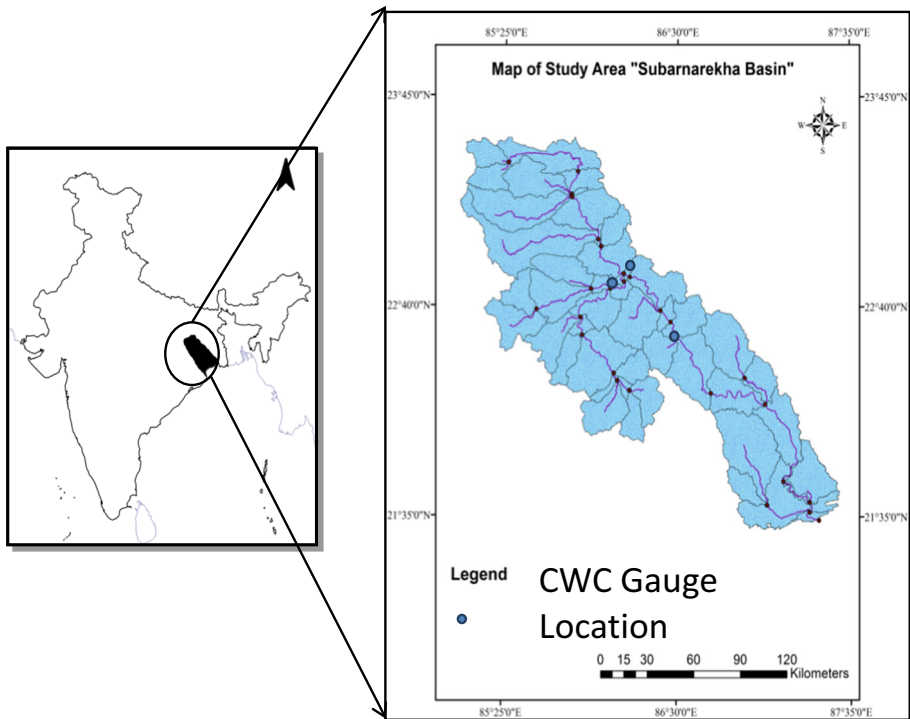


Fig. 1 Location map of the Subarnarekha basin

region is situated in the southern and southwestern parts of the study area as isolated fluvial pockets. Monsoon is the major source of rainfall in this tropical region where summers are hot and winters are mild. Annual average rainfall in the Subarnarekha basin is 1800 mm. There is a large variability of monthly average temperature with a minimum of 9.0 °C in December to a maximum of about 47.2 °C in the month of May. The annual average discharge for of this river is 392 m³ sec⁻¹.

2.2 River discharge data

River discharge data in the present study are taken from Water Resources Information System (WRIS) of the Central Water Commission (CWC), government of India. These data include gauge, discharge, silt, and water quality parameters as recorded by the CWC hydrometeorological stations up to the period of 2012. In the three river gauging stations, continuous data are available (viz., for Adityapur, Jamshedpur, and Ghatshila). Among them, Ghatshila is situated in the downstream of the river. No record of unmanaged river discharge is available. On an average, 30 years of daily data are available for Ghatshila and Jamshedpur (i.e., 1982–2011), whereas Adityapur has only 24 years of data (i.e., 1982–2005). Total number of gauging stations present in the Subarnarekha basin is 12. Detailed description of the CWC discharge sites for this river basin is given in Table 1

2.3 Meteorological data

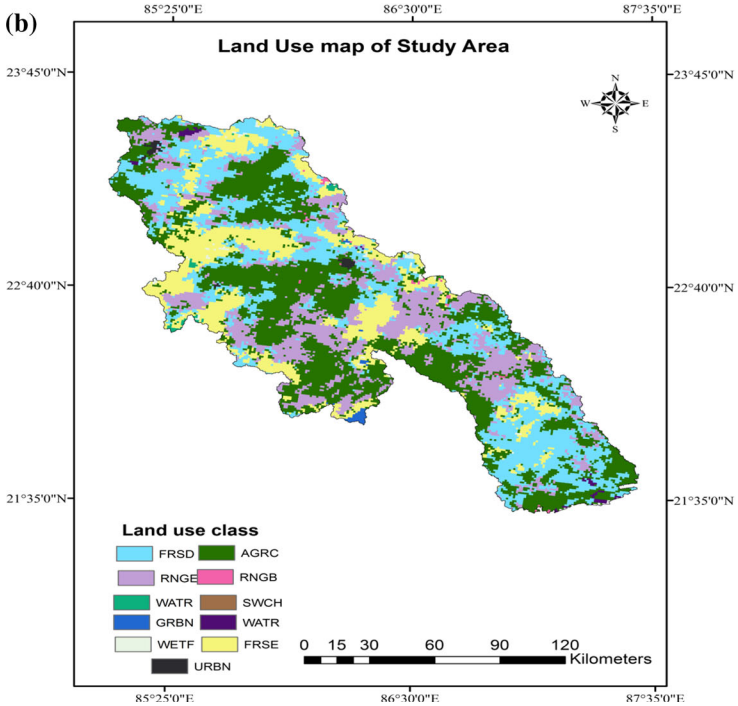
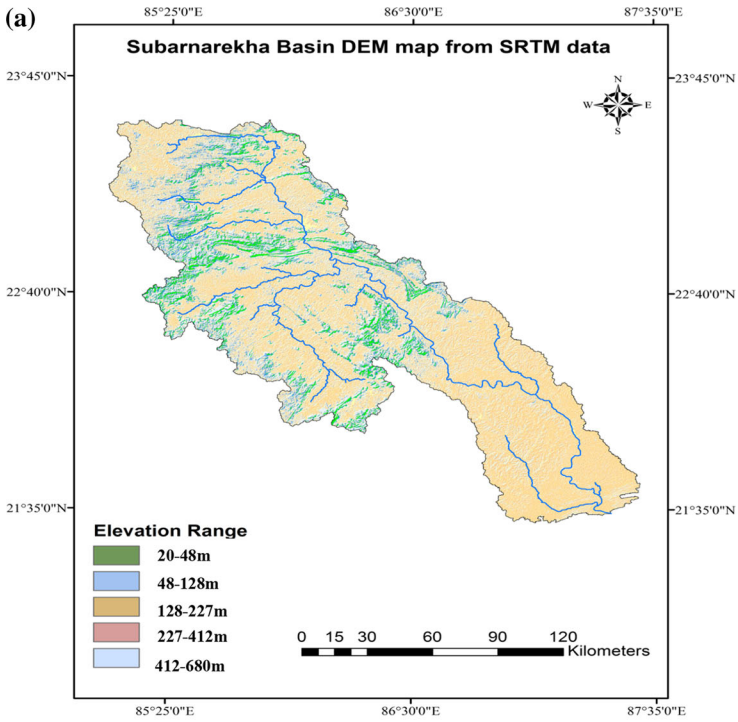
In the present study, the gridded (0.25° × 0.25° lat./long.) daily rainfall data over the entire Subarnarekha basin from 1982 to 2011 have been used. These gridded data have been put together at 0.25° resolution for the Indian region created out of a total of 6955 daily reporting stations of National Data Centre at IMD (Pai et al. 2013, 2014). Wind speed, temperature, relative humidity, and solar radiation data were taken from Global Weather Data for SWAT (<http://globalweather.tamu.edu/>) on the daily scale since 1979–2014 (Dile and Srinivasan 2014).

2.4 Physical data

Digital elevation model (DEM) data are very important in SWAT. Slope, area, field slope length, and other topographic parameters of the sub-basin are analyzed using DEM (Fig. 2a) (<http://csi.cgiar.org>). The same is done for channel width, channel length, channel depth, and channel slope. Land use, land cover (LULC) contributes substantially to the determination of the amount of runoff. Curve number (CN) works as an index to estimate the precipitation amount in runoff event along with the infiltrate water. LULC (Fig. 2b) and soil datasets (Fig. 2c) are taken from WaterBase, which is a project undertaken by the

Table 1 Gauging stations' details

S. no.	Gauging station	Latitude (N)	Longitude (E)	Duration (1982–2011)	Catchment area (km ²)	Distance to outlet (km)
1	Adityapur	22°47'60"	86°10'28"	1982–2011	6309	237
2	Ghatshila	22°35'08"	86°27'42"	1982–2011	14,176	187
3	Jamshedpur	22°48'55"	86°12'58"	1982–2011	12,649	230



◀ **Fig. 2** **a** Digital elevation model (DEM) map of the Subarnarekha River basin as the SWAT model input. **b** Land use map for the SWAT model input. **c** Soil map as the SWAT model input

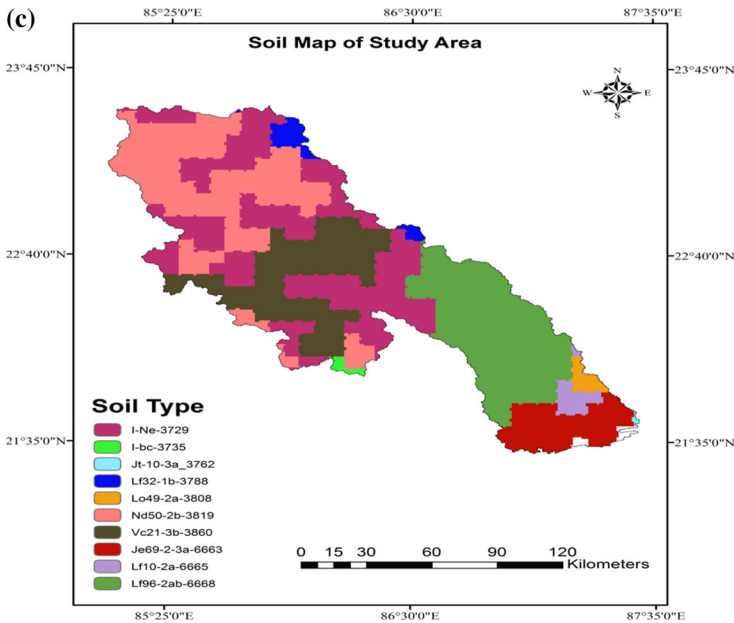


Fig. 2 continued

United Nations University. The LULC map is used to derive curve numbers (CNs) needed to run the SWAT model for various locations along the Subarnarekha River (http://edc2.usgs.gov/glcc/globdoc2_0.php). Approximately 27.65% of the Subarnarekha basin area is under deciduous forest cover, 36.82% is under agricultural land, and the remaining 35.53% is under urban, pasture, land, water bodies, etc. Fertile alluvial soil deposited by the Subarnarekha and its tributaries covers the plain area of the basin. The rolling interfluvial deposits in the Subarnarekha basin (i.e., interfluves) are characterized by spatially confined (which generally result in a non-static water table) and also massive laterites which result in a seasonally static water table. The higher parts of the basin having interfluves around the hillocks are locally known as “dungri.” The areas of degraded forest are covered with exposed plantation surfaces lying over laterites of massive proportion, which are locally known “adahida.” Their surface is also extended up to the margins of the river valleys containing alluvium deposits.

3 Materials and methods

3.1 SWAT model description

Being a physically based, semi-distributed, continuous hydrological model, SWAT simulates different hydrological responses of river basins utilizing process-specific equations. Within a watershed or a basin, spatially distributed modeling is done by splitting the area

into several sub-watersheds. These sub-watersheds are additionally divided into hydrological response units (HRUs) on the basis of their land cover, slope, and soil attributes.

SWAT model uses the master water balance approach (i.e., Eq. 1) to compute runoff volumes and peak flows (Arnold et al. 1998) expressed as:

$$SW_t = SW_0 + \sum_{i=1}^t (R_{dayi} - Q_{surf,i} - E_{a,i} - W_{seep,i} - Q_{gw,i}), \tag{1}$$

where SW₀ is initial soil water content and SW_t is the soil water content on day t. All other measurements are taken in millimeters, and the time (t) is measured in days. The equation subtracts all forms of water loss on any day i from precipitation for that day (R_{day}), including surface runoff (Q_{surf, i}), evapotranspiration (E_{a, i}), loss to vadose zone (w_{seep, i}), and return flow (Q_{gw, i}) (Neitsch et al. Arnold 2011). By working with this equation, the model can predict changes in variables of interest like runoff and return flow. Runoff (Eq. 2) is derived from the USDA soil conservation service runoff curve number (CN) method (USDA 1972) as follows:

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)}. \tag{2}$$

Here, Q_{surf} is accumulated rainfall excess (i.e., runoff), R_{day} is the rainfall depth for that day, and I_a is the initial abstraction, which is a function of infiltration, interception, and surface storage. S (Eq. 3) is the retention parameter estimated from the curve number (CN).

3.2 Description of sequential uncertainty fitting (SUFI)-2

In SUFI-2, deviation between measured and simulated variables is defined as the uncertainty. The SUFI-2 clubs together uncertainty analysis along with calibration to obtain parameter uncertainties that ensure prediction uncertainties grouping the bulk of the measured data, while developing minimum possible prediction uncertainty band. Input parameter uncertainty in SUFI-2 is illustrated as homogeneous, i.e., uniform distribution, whereas model output uncertainty is measured at the 95% parameter prediction uncertainty (i.e., 95PPU). The P factor, which represents the percentage of underlying data in bracketed 95PPU, computed at 2.5% significance level confidence and the 97.5% significance level confidence intervals during output simulation, shows the quantity of uncertainty which is being captured, while the D factor indicates the soundness of calibration, since a smaller 95PPU band implies a finer calibration outcome.

3.3 Identification of extreme events

According to the classifications of India Meteorological Department (IMD), the rainfall events are segregated into six heads ranging from “light event” to “exceptionally heavy event” on the basis of the quantum of rainfall in a day. The same segregation is applied in the present study to create three groups of rainfall events. “Extreme events” category is created as a combination of “exceptionally high events” and “very heavy events.” It is done because “exceptionally high events” are very rare (> 244.4 mm rainfall in a day). Similarly, “rather heavy,” “moderate,” and “light” rainfall events are combined together to make a broad category of “low events” (≤ 64.4 mm rainfall in a day). “Heavy events”

range from 64.4 mm in a day to 124.4 mm in a day. They are kept as the broad category of “medium events” for the present study.

3.4 Model calibration and validation procedure

The SWAT model has been calibrated using the SUFI-2 optimization technique for the Subarnarekha basin using the daily observed data for three gauging stations. Calibration period is taken to be 1984–1997, and validation period is taken as 1998–2011 along with two years of warm-up period before calibration. Model initialization starts with warm-up of datasets, which move nearer to rational first values of state variable of the model. Many studies emphasized on warm up period of 3 years for obtaining satisfactory results (Joh et al. 2011; Daggupati 2015). In Ghatshila, Jamshedpur, and Adityapur, the calibration and validation periods are kept the same, i.e., 1982–2011. In the present study, the first step for the calibration and validation in SWAT is the establishment of highly sensitive parameters for the watershed (Table 2).

3.5 Statistical techniques for model evaluation

To assess the proficiency of the model for the data obtained at the three rain gauging stations, a set of generally used goodness-of-fit indicators are calculated as under: (i) coefficient of determination (R^2) and (ii) Nash–Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970). A better assessment of model in the course of calibration and validation can be analyzed by computing P and R factors.

The first technique used is the Nash–Sutcliffe efficiency. The overall fit of a hydrograph can be best reflected by this objective function (Sevat and Dezetter 1991). Its value lies between $-\infty$ and 1, where $NSE = 1$ is the best value. Negative values suggest that the mean observed value is a superior predictor as compared to the simulated values. NSE reflects the degree of fitness by plotting 1:1 line for observed versus and simulated data (Moriassi et al. 2007; Abbaspour 2011). Equation (2) shows computation of the NSE:

$$NSE = 1.0 - \frac{\sum_{i=1}^N (o_i - p_i)^2}{\sum_{i=1}^N (o_i - \bar{o})^2}, \quad (3)$$

Table 2 Descriptions of stream flow parameters

S. no.	Parameter	Description
1	r_CN2.mgt	Curve number
2	v__ALPHA_BF.gw	Base flow alpha factor
3	v__GW_DELAY.gw	Groundwater delay time
4	v__GWQMN.gw	Threshold depth of water in shallow aquifer
5	v__GW_REVAP.gw	Required for return flow
6	v__ESCO.hru S	Groundwater “revaporation” coefficient
7	v__CH_N2.rte	Soil evaporation compensation factor
8	v__CH_K2.rte	Manning roughness for main channel
9	r__SOL_K.sol	Effective hydraulic conductivity

where o_i is the i th observation for the observed runoff, p_i is the i th simulated value for the predicted runoff, \bar{O} is the mean of observed data for the observed runoff evaluated, and N is the total number of observations. Coefficient of determination (R^2) illustrates the proportion of the total variance, described by the equations. Its range is from 0.0 to 1.0, where better agreement is indicated by higher value. R^2 lies between 0 and 1, and 0.5 is considered as satisfactory (Van Liew et al. 2003). Equation for the computation of R^2 is as follows:

$$R^2 = \left[\frac{\sum_{i=1}^N (O_i - \bar{O}) \times (P_i - \bar{P})}{\left[\sum_{i=1}^N (O_i - \bar{O})^2 \right]^{0.5} \times \left[\sum_{i=1}^N (P_i - \bar{P})^2 \right]^{0.5}} \right]^2, \tag{4}$$

where O corresponds to observed runoff and P to simulated runoff. \bar{O} and \bar{P} represent the mean values of observed and simulated runoff.

4 Results and discussion

4.1 Evaluation of rainfall and river flow data

The climatological annual cycle of the monthly discharge from all three sub-basins and monthly rainfall for the basin for the period (1982–2011) are presented in Fig. 3. The long-term monthly rainfall average varies from 22.98 mm in December to 703.89 mm in August. Most of the rainfall is received in monsoon season from June to September. Rainfall over the basin has large variability in interannual and intraseasonal timescales. The variability of rainfall has a significant impact on runoff characteristics. The discharge amount is quite high in the Ghatshila and Jamshedpur sub-basins compared to Adityapur due to the locations of gauging stations at Ghatshila and Jamshedpur in the downstream of the river basin. During the months of June and July the overall discharge is high at the Jamshedpur sub-basin though Ghatshila is located in the lowest part of basin. Due to the

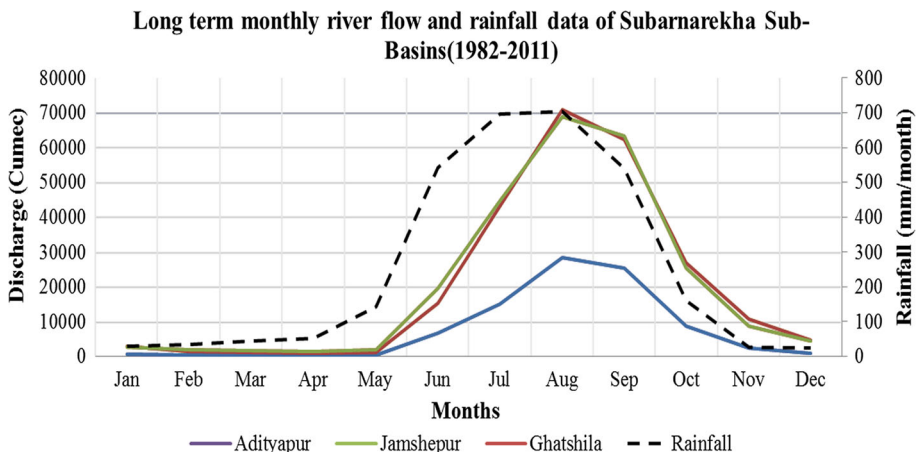


Fig. 3 Monthly mean of long-term river discharge and rainfall data

reservoir operations and the effect of dams upstream of the Ghatshila sub-basin, the amount of discharge is less.

4.2 Sensitivity analysis

In order to find out the most influential parameters, a sensitivity analysis was performed for the data obtained from the three gauging stations. Parameter optimization was done using a SUFI-2 algorithm (Abaaspour et al. 2007), which provides reasonable results as any other auto-calibration method used to perform uncertainty analysis through SWAT model (Shrestha et al. 2013). The initial parameters used in the SWAT model are presented in Table 3, which outlines the general hydrological characteristics of the basin. The minimum and maximum ranges of the parameters fitted for the daily calibration in the SUFI-2 algorithm are demonstrated in Table 4.

During calibration, the model parameters are tuned in such a manner that their simulated values match closely with the observed/measured values in the field. SWAT model is run here using 30 years of hydrometeorological data collected on a daily basis (out of this, 2 years of data are used for warm-up period, 14 years of data are considered for calibration, and the remaining 14 years of data are used for validation). Hydrological study is performed over 32 sub-basins. Three gauging stations (viz., Jamshedpur, Adityapur, and Ghatshila) are selected in the middle portion of the Subarnarekha River basin located in Jharkhand.

Dotty plots show objective function values as a function of input parameters. It also shows whether the objective function is sensitive to the selected parameter or not. Scattered and haphazard points indicate that the sensitivity is low. If a clear trend is seen then sensitivity to that parameter is higher. The dotty plots from the present set of sensitivity experiments during the calibration period are shown in Fig. 4. The threshold value of NSE considered is 0.5. If the parameters provide NSE value of more than 0.5, they are considered as behavioral parameter set. The likelihood functions for all the parameters covering entire range are shown. It is seen that the dotty plots do not have a structure in them. The objective function seems pretty random relative to most of the selected parameters. From the dotty plots it is also seen that for most parameters, the response surface is flat and that sharp peaks and valleys are not clear for all the parameters. In such a case of highly dimensional parameter space it is expected that one or many parameters will not be well identified (Yang et al. 2008). It is also seen that different behavioral parameter sets lead to similar model prediction. This originates from the imperfect knowledge of the basin characteristics, approximate model structure of the real basin, and error in the stream flow data. In the present study, the soil evaporation compensation factor (ESCO) shows that the lower the values of ESCO, the better the skill.

Table 3 SWAT model input parameters used for the simulation

1	Simulation period length (years)	30
2	Warm-up period (years)	2
3	Hydrological response units considered	276
4	Sub-basins	32
5	Rainfall grid size along latitude and longitude	0.25°
6	Frequency of observed stream flow data	Daily
7	Land use, land cover maps' spatial resolution	1 km
8	Spatial resolution used for soil data	10 km

Table 4 Stream flow calibration parametric values used in SWAT

S. no.	Parameters	Fitted value	Minimum value	Maximum value
1	r_CN2.mgt	− 0.0089	− 0.35	0.009
2	v_ALPHA_BF.gw	0.43	0.01	0.79
3	v_GW_DELAY.gw	312.50	200.00	400.00
4	v_GWQMN.gw	1.46	0.90	2.50
5	v_GW_REVAP.gw	0.16	0.07	0.29
6	v_ESCO.hru S	0.84	0.84	1.00
7	v_CH_N2.rte	0.18	0.15	0.27
8	v_CH_K2.rte	3.67	− 22.54	74.67
9	r_SOL_K.sol	0.54	− 0.7	0.8

4.3 Calibration and validation

The calibration and validation runs have been made by modifying five parameters in basin input file. We have experimented with five parameters (Refer to Table 5) to examine the runoff during extreme events. Several combinations of calibration and validation for all the three stations are performed. Results obtained from the different simulations for these three gauging stations are presented in Table 6. In the present study, calibration is done at the sub-basin level to assure that variability in the predominant processes for each sub-basin is captured instead of determining basin-wide processes. In the Adityapur sub-basin, the first calibration without changing the default values for all five parameters mentioned in Table 6 has a NSE of 0.49, while for Jamshedpur it is 0.47 and for Ghatshila station it is 0.51. Firstly, experiment is performed by changing routing method (IRTE). The default value is set for the variable storage method. Muskingum method (Chow et al. 1988) is used for the Adityapur sub-basin, and there is an increase in NSE up to 0.52 (Fig. 5).

The same procedure is applied for Ghatshila and Jamshedpur sub-basins, and similar results are found. NSE increases from 0.51 to 0.56 for Ghatshila and from 0.47 to 0.55 for Jamshedpur. Second parameter considered for the study is the curve number. The daily curve number is determined by adjusting it for average soil moisture conditions (i.e., CN2). This can be done in two ways, firstly as a function of the soil moisture and secondly as a function of plant evapotranspiration. In the present work, daily CN value is considered as a function of plant evapotranspiration because shallow soils are usually generating excess runoff while employing the soil moisture method. Value of daily CN becomes less dependent on soil storage and more dependent on antecedent moisture if it is calculated as a function of plant evapotranspiration (Kannan et al. 2007). The behavior of all three sub-basins for this parameter is quite similar. Model performance is quite satisfactory when curve number method is a function of soil moisture; however, as we change this to function of evapotranspiration, all the computed statistical parameters increased at all three gauging stations with better statistical parameters. Storage constants are modified in the Muskingum method used for the channel routing. Default value for low flow is 0.25 and for normal-flow condition is 0.75. The fourth parameter, ET weighting coefficient, is used to estimate the retention coefficient for the curve number estimation based on evapotranspiration function. Retention coefficient expresses the response of the catchment to the rain event. Default value for ICN is 1. Modified value for this is 1.7, which is high in case of

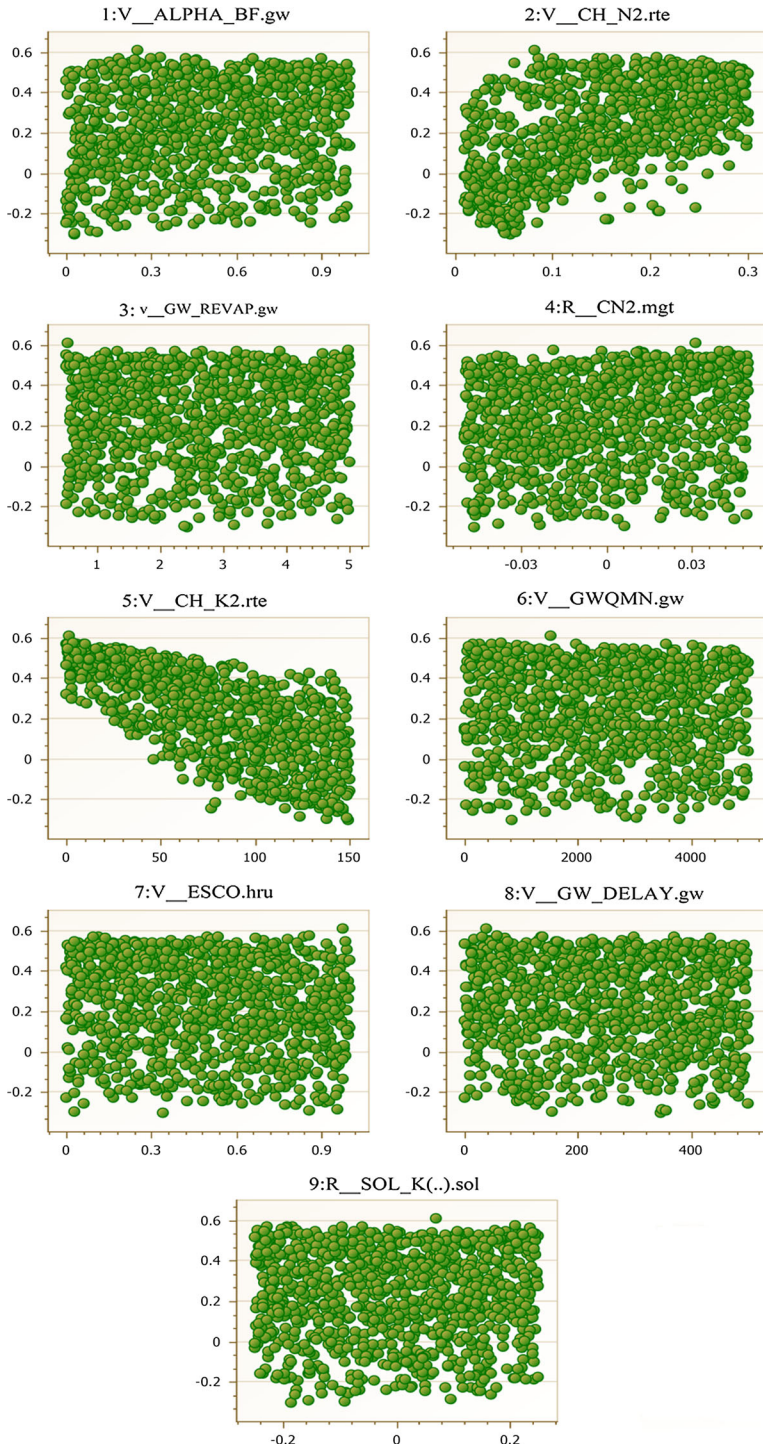


Fig. 4 Dotty plot maps for stream flow simulations: x-axis: sensitive parameters, y-axis: NSE

Table 5 SWAT model settings to improve model efficiency for the sub-basins of Subarnarekha

Serial no.	Parameters in bsn file	Purpose(s) of these parameters	Default value	Modified value
1	IRTE	Carrying out the channel water routing method	0 (variable storage method)	1 (Muskingum method)
2	ICN	Daily curve number estimation	0 (as a function of soil moisture)	1 (as a function of plant evapotranspiration)
3	CNCOEF	Plant ET curve number coefficient estimation	1.0 (ranges between 0.5 and 2.0)	1.7
4	MSK_CO1	Storage time constant estimation for normal flow	0.75	0.9
5	MSK_CO2	Storage time constant estimation for low flow	0.25	0.1

Table 6 Calibration and validation statistics of runoff simulations for Adityapur, Jamshedpur, and Ghatshila sub-basins

Calibration years 1984–1997	Calibration statistics				Validation years 1998–2011	Validation statistics			
	<i>P</i> factor	<i>R</i> factor	<i>R</i> ²	NSE		<i>P</i> factor	<i>R</i> factor	<i>R</i> ²	NSE
<i>Adityapur Gauging Station</i>									
Reference	0.53	0.52	0.5	0.49	Reference	0.52	0.58	0.43	0.37
IRTE	0.51	0.68	0.52	0.52	IRTE	0.60	0.59	0.36	0.42
ICN	0.67	0.58	0.49	0.47	ICN	0.62	0.57	0.35	0.38
MSK_01_02	0.70	0.58	0.49	0.48	MSK_01_02	0.69	0.59	0.47	0.44
CNCOEF	0.73	0.72	0.56	0.54	CNCOEF	0.72	0.69	0.52	0.48
<i>Jamshedpur Gauging Station</i>									
Reference	0.65	0.61	0.51	0.47	Reference	0.62	0.57	0.5	0.41
IRTE	0.74	0.65	0.58	0.55	IRTE	0.71	0.59	0.53	0.48
ICN	0.73	0.66	0.54	0.51	ICN	0.69	0.58	0.49	0.47
MSK_01_02	0.75	0.69	0.56	0.54	MSK_01_02	0.73	0.61	0.48	0.46
CNCOEF	0.78	0.62	0.57	0.56	CNCOEF	0.76	0.65	0.54	0.53
<i>Ghatshila Gauging Station</i>									
Reference	0.67	0.61	0.52	0.51	Reference	0.62	0.59	0.56	0.42
IRTE	0.75	0.68	0.57	0.56	IRTE	0.67	0.60	0.57	0.45
ICN	0.79	0.82	0.53	0.52	ICN	0.72	0.60	0.53	0.49
MSK_01_02	0.85	0.74	0.59	0.62	MSK_01_02	0.76	0.69	0.54	0.58
CNCOEF	0.87	0.82	0.64	0.68	CNCOEF	0.81	0.71	0.59	0.62

these three sub-basins in the study region. In calibration, NS value increases up to 0.54 for Adityapur, 0.56 for Jamshedpur (Fig. 6), and 0.68 for Ghatshila (Fig. 7) catchment.

These are the best combination of parameters with the highest NS values. While validating the model, no parameters are changed. Instead of this we keep all parameters the

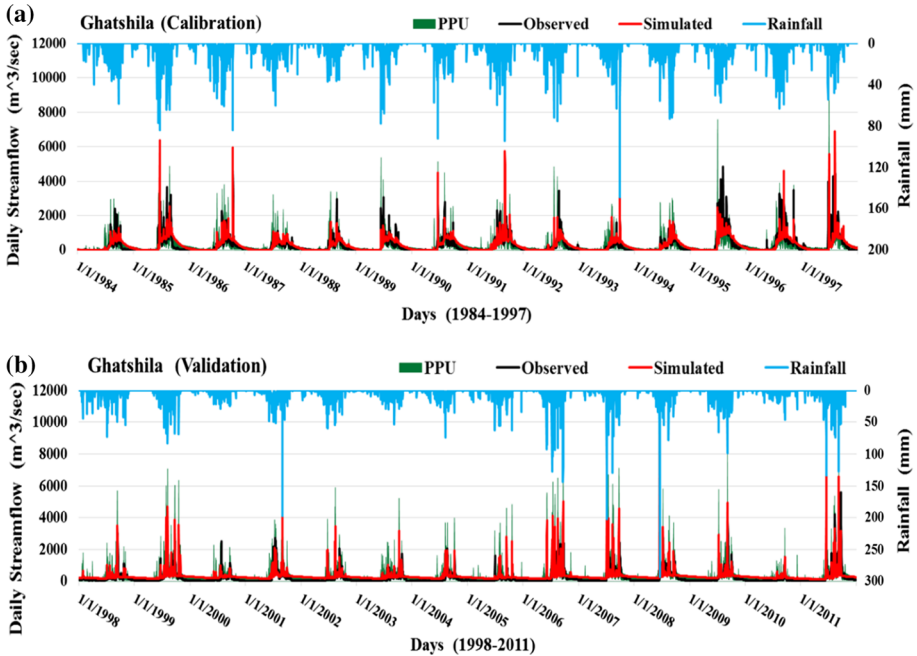


Fig. 5 Observed and simulated daily stream flow hydrographs including rainfall of Ghatshila during **a** calibration and **b** validation periods

same as obtained by the calibration. In validation, NSE for Adityapur, Jamshedpur, and Ghatshila is 0.48, 0.53, and 0.62, respectively. The validation results for all the three basins are presented in Figs. 5, 6 and 7. Among these stations, Ghatshila has a quite satisfactory NSE for daily stream flow data. In the basin, the location of Ghatshila is in the lower portion of the basin.

4.4 Runoff of response during extreme events

Extreme rainfall events are identified for the three gauging stations, but extreme rainfall events comprising of “very heavy” and “exceptionally heavy” events are identified for Ghatshila and Jamshedpur stations. Extreme heavy rainfall events occur when rainfall is $> 124.4 \text{ mm day}^{-1}$. Efficiency of the model is checked for the extreme events in the recent ten years (i.e., 2002–2011). Five events are identified in these recent 10 years. The highest rainfall in terms of intensity occurred in June 2008 (viz., $293.08 \text{ mm day}^{-1}$). The lowest amount of rainfall (among extreme rain events) occurred in September 2011 ($126.93 \text{ mm day}^{-1}$). In case of extreme rainfall events, there is a strong possibility of having intense runoff. Saturation excess runoff and infiltration excess runoff are the two main types of runoff. Sorland and Sorteberg (2015) found that intense rainfall from the extreme events causes saturation excess runoff. In this study, among rainfall events which are identified on the basis of criteria defined by IMD (Pattanaik and Kumar 2014), five events were selected for Ghatshila and Jamshedpur sub-basins. No extreme rainfall events are identified over Adityapur catchment. To accomplish this work we have selected 10-day period for each event of Ghatshila and Jamshedpur sub-basins. Details are given in

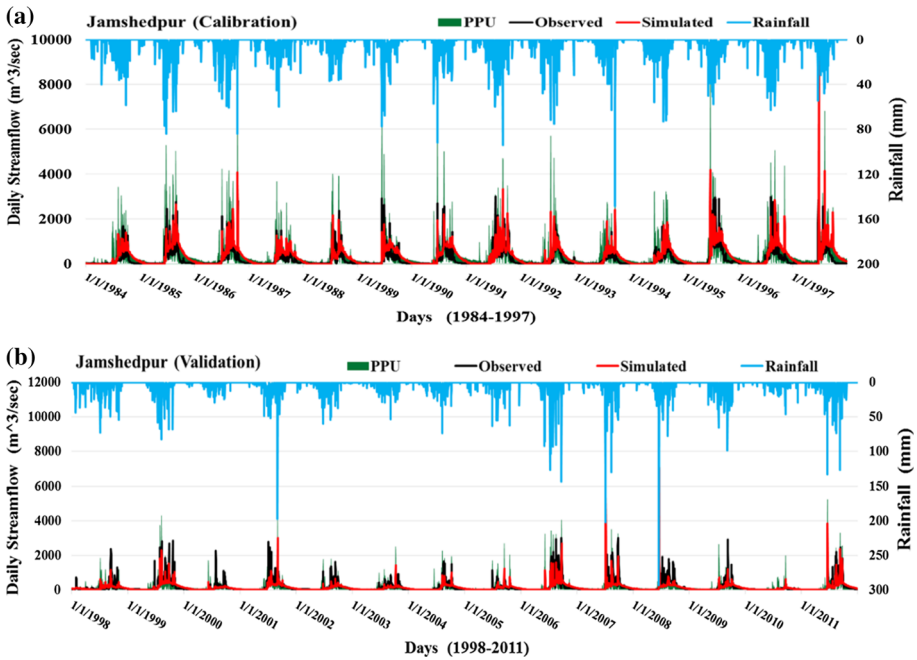


Fig. 6 Observed and simulated daily stream flow hydrographs including rainfall of Jamshedpur during **a** calibration and **b** validation periods

Table 7. These events come under the validation period of the data used in the simulation. The observed and simulated flow values are plotted against each other to show the goodness of fit. Two recent extreme rainfall events for Jamshedpur and Ghatshila are shown in Fig. 8. In these events, extreme rainfall occurred on June 19 and September 9, 2011, over Jamshedpur and Ghatshila, respectively, followed by a runoff on the next date of the rain event. To evaluate the model performance NSE is calculated and found to be 0.97 for Jamshedpur and 0.95 for Ghatshila. Comparison of simulated and observed daily flow during extreme event showed NSE values of 0.89 and 0.96 for Jamshedpur and Ghatshila, respectively, suggesting quite a satisfactory model performance. It may be noted that the high value of NSE is because of smaller number of extreme rainfall events considered in the present study.

It may be noted that there are differences in the observed and simulated flows, especially for Ghatshila and Jamshedpur which are not very far apart. River stream flow characteristics depend on the dams, reservoirs, and barrages constructed on the river. Between Jamshedpur and Haldia, there are several barrages and irrigation canals on the Subarnarekha River. The most important among them is the Galudih barrage downstream of Jamshedpur and upstream of Haldia. Therefore, stream flow at Haldia depends on the amount and timing of water release from these reservoirs. In the present study, the role of such dams/barrages, etc., has not been included. The water reaching Haldia from Jamshedpur is based on the natural flow in the river without any intervention. The differences in the observed stream flow between Ghatshila and Jamshedpur are due to the role of such interventions. It is seen that the differences are especially large in the month of June when the barrage authorities try to retain or fill the barrage for irrigation purpose.

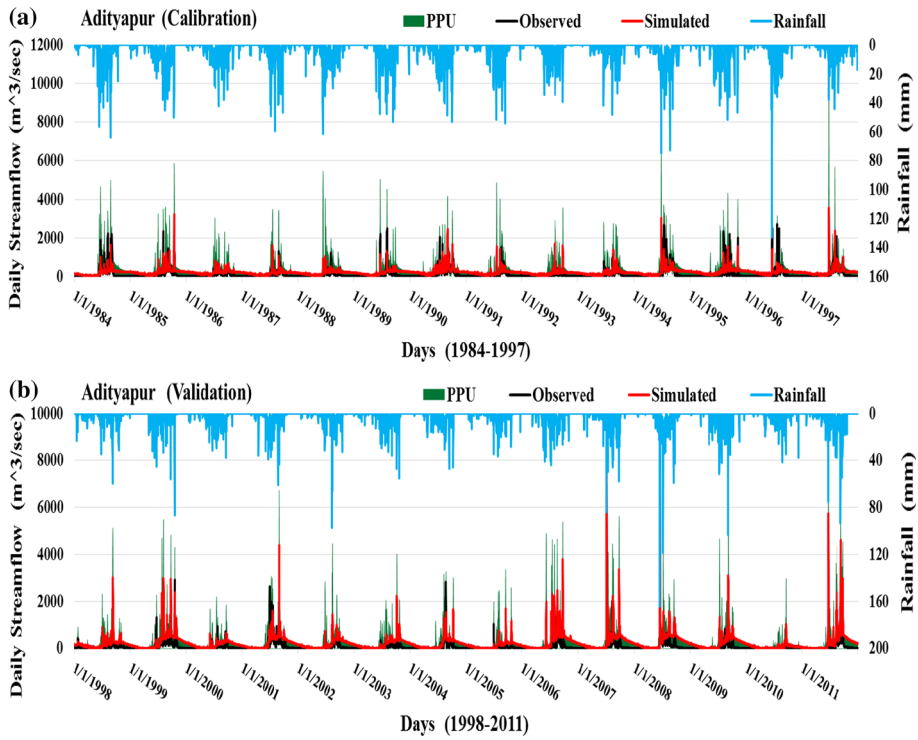


Fig. 7 Observed and simulated daily stream flow hydrographs including rainfall of Adityapur during **a** calibration and **b** validation periods

Table 7 Statistics of the runoff response during extreme events of Jamshedpur and Ghatshila sub-basins

Date of extreme heavy rain	10-day period	Rainfall (mm day ⁻¹)	NSE for Jamshedpur	NSE for Ghatshila	Average NSE for Jamshedpur	Average NSE for Ghatshila
August 30, 2001	22–31 August	197.07	0.97	0.96	0.898	0.962
August 12, 2007	11–20 August	129.58	0.63	0.97		
June 18, 2008	15–24 June	293.08	0.93	0.95		
June 19, 2011	15–24 June	133.16	0.99	0.98		
September 9, 2011	5–14 September	126.93	0.97	0.95		

Moreover, the simulated results for the extreme cases are during validation period. In the cases of June 16–17 and 22, 2011, the model simulates almost no stream flow even when there is large amount of precipitation. While the model utilizes some amount of precipitation for making the soil saturated, evaporation, and ground water recharge (it being the beginning of monsoon season after long hot and dry spell), the model is unable to generate enough runoff for enhanced stream flow. In order to overcome this deficiency in the model, more number of sensitivity testes are required, which are being carried out. However, the results of such studies are beyond the scope of the present paper.

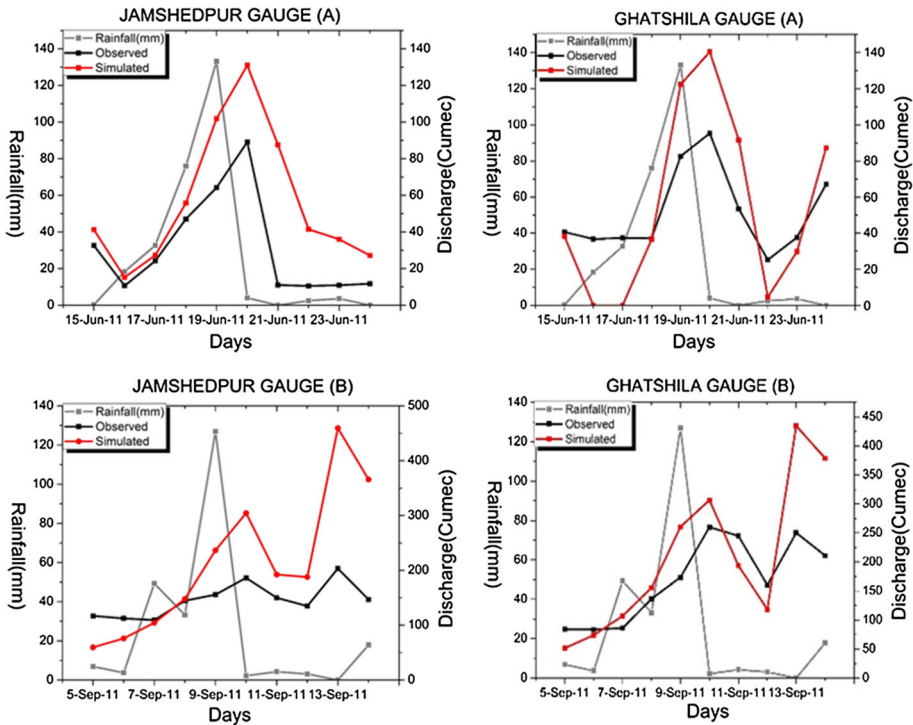


Fig. 8 Runoff response in extreme events over Jamshedpur and Ghatshila sub-basins

5 Conclusions

The present study comprises the application of hydrological model to simulate the hydrological response of three sub-basins (viz., Adityapur, Jamshedpur, and Ghatshila) in the Subarnarekha basin during extreme rainfall events. The hydrological model selected for modeling stream flows in the Subarnarekha basin is the soil and water assessment tool (SWAT). The basin is divided into 32 sub-basins with their own climate data and channel characteristics.

For all of these sub-basins 297 hydrological response units (HRUs) are then defined, which are areas with similar land use, soil, and slope characteristics. The performance of the model is rated to be satisfactory with NSE and R^2 values of 0.68 and 0.64, respectively, for Ghatshila during model calibration and of 0.62 and 0.59, respectively, during model validation. The satisfactory performance of model is achieved by experimenting four processes, which govern basin parameters, in which governing factors are the first routing method and also the curve number method for runoff estimation.

This calibrated and validated model is subsequently applied for analyzing the estimated runoff impact during extreme rainfall events. Five events were selected for Ghatshila and Jamshedpur sub-basins. In the evaluation of runoff, the performance of model is very good with NSE values of 0.89 for Jamshedpur and 0.96 for Ghatshila. The analysis yields crucial information about the response of watershed for extreme rainfall events of the river basin regardless of various assumptions and limitations of the model. In many cases, extreme rainfall events result in floods, and well-calibrated and well-validated SWAT model for

extreme rainfall will be helpful in flood inundation modeling as simulated stream flow is input for the flood inundation modeling. The present study is also useful to hydrology community as a detailed study on the sensitivity parameters has been carried out here. Analysis of the miscellaneous events furnishes a range of results that can significantly assist in water resources planning and management in the middle Subarnarekha basin. The findings of the present study can also be useful in forecasting runoff response during extreme rainfall events.

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