INTERNATIONAL JOURNAL OF GEOMATICS AND GEOSCIENCES
Volume 5, No 2, 2014

Research article ISSN 0976 – 4380

Simulation of rainfall-runoff process using HEC-HMS model for Balijore Nala watershed, Odisha, India

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ABSTRACT

Hydrological modeling is a commonly used tool to estimate the basin's hydrological response due to precipitation. In this paper HEC-HMS model is used to simulate rainfall-runoff process in Balijore Nala Watershed of Odisha, India. To compute runoff volume, peak runoff rate, base flow and flow routing methods SCS curve number, SCS unit hydrograph, Exponential recession and Muskingum routing methods are chosen, respectively. Rainfall-runoff simulation is conducted using 24 random rainstorm events covering four year (2010 – 2013) data. Out of these, 12 events are selected for model calibration and the remaining 12 for model validation. For calibration of model the statistical tests of error functions like mean absolute relative error (MARE) and root mean square error (RMSE) between the observed and simulated data are conducted. The results indicate values of MARE of 0.20 and 0.25 for runoff depth and peak discharge, respectively. Similarly the values of RMSE between the observed and simulated data are obtained as 2.30 mm and 0.28 m^3/s for runoff depth and peak discharge, respectively. However after parameter optimization the above mentioned error functions reduce to 0.10, 0.12, 0.75 mm and 0.09 m^3/sec in sequence. The calibrated model with optimized parameter is used for model validation. The model validation was found to be satisfactory with low values of statistical error functions.

Keywords: Hydrologic modeling, rainfall-runoff simulation, Balijore Nala watershed, model calibration, model validation.

1. Introduction

The two vital natural resources required for agricultural production of any country are soil and water. The net productivity of crops depends on the proper management and utilisation of these two resources. Out of the above mentioned two resources, water is very important. To meet the industrial and urbanization demands, water is becoming a scarce resource for agricultural production in almost all places across the glove. To overcome the water related problems, extensive care should be given to the operation and management of reservoirs and watersheds. But in many cases, poor land-use planning and land management practices during rapid development have adversely impacted the surface runoff quantities and quality through the reduction of land cover, loss of plant nutrients, deterioration of river water quality and an increase of impervious surface area. A major challenge still remaining is the accurate prediction of catchment runoff responses to rainfall events (McColl and Aggett, 2006). Numerous researchers have used many methods to simulate, assess, and predict the effects of urbanization on hydrological response of the watersheds. Watershed management implies the judicious use of all land and water resources. Decision support tools can help in better development options for people to manage water, land and labor resources. One viable answer and approach to this challenge is the use of suitable hydrologic models for the efficient management of watersheds and ecosystems (Yener et al., 2012), Hydrological modeling is a commonly used tool to estimate the basin's hydrological response due to precipitation. It allows to predict the hydrologic response to various watershed management practices and to have a better understanding of the impacts of these practices (Kadam, 2011). It is evident from the extensive review of the literature that the studies on comparative assessment of watershed models for hydrologic simulations are very much limited in developing countries including India (Kumar and Bhattacharya, 2011; Putty and Prasad, 2000), There is bare necessity to undertake study on hydrologic simulation through development of a suitable watershed model. The Hydrologic Engineering Centers Hydrologic Modeling System (HEC-HMS) is a popularly used watershed model to simulate rainfall-runoff process.

Several studies have been conducted using the HEC-HMS model in different regions under different soil and climatic conditions. Chu and Stenman (2009) used HEC-HMS model for both event and continuous hydrological modeling in Monalack watershed in west Michigan. HEC-HMS model has been also used to simulate rainfall-runoff process with geo-informatics and atmospheric models for flood forecasting and early warnings in different regions of the world (Abed et al., 2005; Anderson et al., 2002; Clay et al., 2005; Hu et al., 2006; Knebl et al., 2005; ; McColl and Aggett, 2006; Yusop et al., 2007; Yener et al., 2012; Arekhi, 2012; Majidi and Shahedi, 2012; Halwatura and Najjim, 2013; Majidi and Vagharfard, 2013, Ali et al., 2011; Dzubakova, 2010). It was also used for watershed management in different parts of India (Putty and Prasad, 2000; Shrestha, 2006; Kumar and Bhattacharya, 2011; Bhatt et al., 2012; Kadam, 2011). The model was found accurate in spatially and temporally predicting watershed response in event based and continuous simulation as well as simulating various scenarios in flood forecasting and early warnings.

A number of watershed development and management programs are now going on in Odisha, India. Reviews of literatures revels that not much work has been done on simulation of rainfall-runoff process using any watershed model including HEC-HMS model in Odisha. The objective of the present study is to simulate the rainfall-runoff process using HEC-HMS hydrological model in the Balijore Nala watershed of Odisha, India.

2. Materials and methods

2.1 Study area

The present study was undertaken in Balijore Nala watershed of Sambalpur district of Odisha, India. The latitude, longitude and altitude of the watershed area are 210 38'N - 210 40'N, 840 5' E - 840 8' E and 178.8 m above the mean sea level, respectively. Fig. 1 represents the location map of the study area. The area falls under the sub-humid climatic condition in the eastern part of the country. The area is characterised by hot summer, wet rainy and cold winter. The watershed is situated at a distance of 6 km from the National Highway. The average annual rainfall of the watershed is 1788 mm. Average maximum and minimum temperatures are 45.3 and 11.80C, respectively. Relative humidity ranges from 72 to 82% in rainy season and 38 to 70% in remaining months. Crops grown in the area are mainly rice followed by pulses like black gram and green gram and oilseeds like groundnut and sunflower. The lands are generally mono-cropped. The watershed has total area of 1551.72 ha. It covers two villages i.e. Katarbaga and Ludhapali. Total agricultural land of Katarbaga is 926.46 ha out of which up, medium and low land covers 574.37 ha, 291.25 ha and 60.84 ha, respectively. Similarly, total agricultural land of Ludhapali is 203.96 ha out of

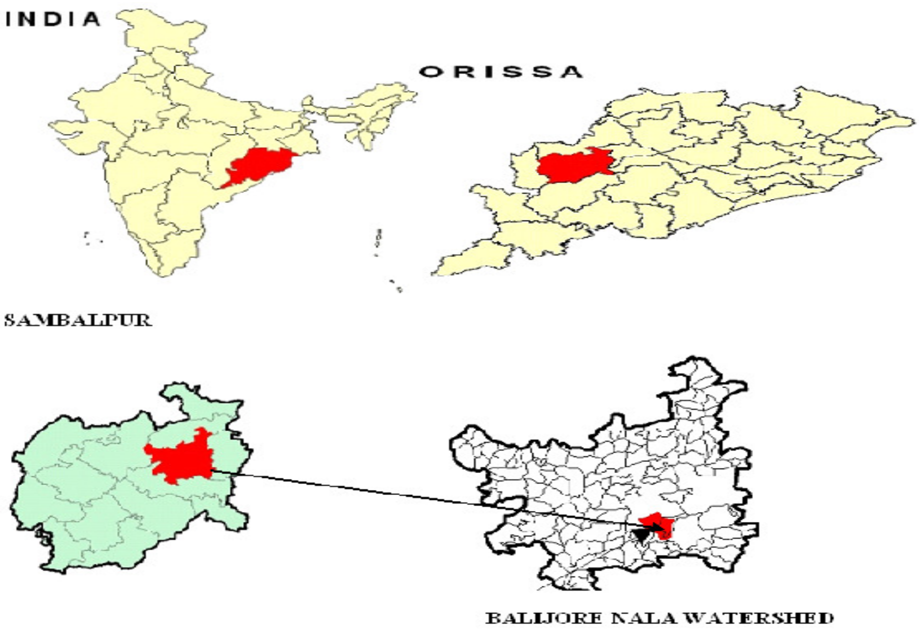

Figure 1: Location map of study area

which up, medium and low land covers 111.58 ha, 77.44 ha and 14.94 ha, respectively (Anonymous, 1997), Detail land uses of the watershed are presented in Figure. 2 (a) and (b),

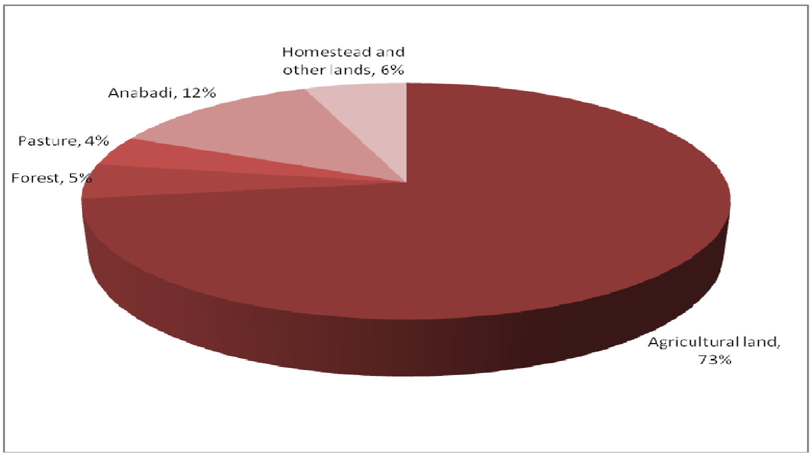

Figure 2 (a): Present land use of the watershed

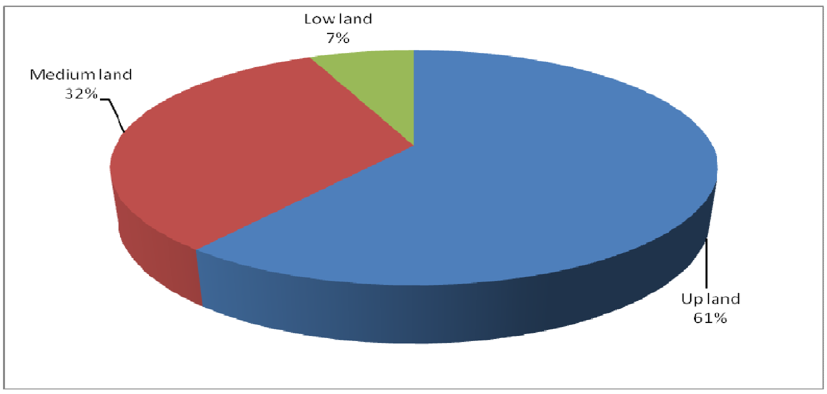

Figure 2 (b): Distribution of agricultural land in the watershed

The major soil types of the study area red (alfisols), laterite and lateritic (ultisol and oxisol) with limited patches of forest humus soil. About 41% of soils are acidic, 47% are neutral and rest are alkaline in reaction. Soil slopes in the upland are more than 6%, whereas that in medium land is about 3%. The soil texture of the study area is sandy loam with sand, silt and clay percentage of 77.8, 11.8 and 10.4, respectively. Average values of bulk density, volumetric moisture content at field capacity and permanent welting point are 1.58 gm/cc, 28% and 10%, respectively. Average pH, EC and organic carbon were 6.4, 0.08 dS/m and 0.57%, respectively (Anonymous, 1997),

The watershed comes under West Central Table Land Agroclimatic Zone of Odisha. The area is composed of undulating topography of high ridges and low vallies. The watershed is surrounded by hillocks and forest area which contributes to the internal drainage system of the project area. The general drainage pattern is dendrites. It is the principal tributary of river Ib which drains to the Hirakud reservoir. Soil erosion in the watershed is moderate to high. The forest lands are found to be severely eroded whereas the arable up lands are subjected to moderate to severe erosion. The medium lands located on the slopes are susceptible to moderate erosion whereas the low lands located mostly on the valley bottom and drainage channel are subjected to over flooding during the rainy season. The water resources in the watershed are not fully used. The scope for use of water by different sources is limited. The village Katarbaga has only 3 water harvesting structures, 68 dug wells, 6 tanks and 3 tube wells. Similarly, village Ludhapali has only one water harvesting structure, 10 dug wells, 2 tanks and 2 tube wells. Water from these sources are mainly used for domestic purposes and sometimes used as life saving supplemental irrigation during dry spells over a limited patch. The average groundwater level lies 7 to 8 m below the ground level and the scope for ground water recharge is limited. As such the best alternative to have better groundwater recharge is through constructions of water harvesting structures including farm ponds in the drainage channels (Anonymous, 1997),

Crop production in the watershed is entirely dependent on rainfall. Rainfall distribution in the area is very much erratic and uneven which causes drastic yield reduction of crops. At times, there is in-situ drought and flood which also hampers crop production. High velocity of water flowing over the sloppy land in the watershed also causes severe soil and water erosion. The problem is more aggressive in the low land where accumulation of water in the crop field during high rainfall causes submergence of crops. There is no scope of irrigation except conservation and management of excess rainfall in different soil and water conservation structures.

3. Data acquisition

The daily continuous recording rainfall and other meteorological data of the watershed for the year 2010, 2011, 2012 and 2013 were collected from the agro-met observatory center, Agriculture Department, Sambalpur which is located near to the watershed. The daily continuous recording runoff data of the watershed measured using automatic water level stage record was also collected for the year 2010, 2011, 2012 and 2013 from the source where rainfall data are collected. The maps like topographical, soil type, land slope, land use/pattern, drainage network, watershed boundary etc. for the watershed were extracted using Survey of India maps and GIS model which is used to create the basin model input for HEC-HMS. The software used for the present study is HEC-HMS (v3.5.0) downloaded from USACE website http:www.hec.usace.army.mil/software/hec-hms.

3.1 HEC-HMS hydrological model

HEC-HMS is hydrologic modeling software developed by the US Army Corps of Engineers-Hydrologic Engineering Center (HEC), It is the physically based and conceptual semi distributed model designed to simulate the rainfall-runoff processes in a wide range of geographic areas such as large river basin water supply and flood hydrology to small urban and natural watershed runoff. The system encompasses losses, runoff transform, open-channel routing, analysis of meteorological data, rainfall-runoff simulation and parameter estimation. HEC-HMS uses separate models to represent each component of the runoff process, including models that compute runoff volume, models of direct runoff, and models of base flow. Each model run combines a basin model, meteorological model and control specifications with run options to obtain results.

Following methods were selected for each component of runoff process such as runoff depth, direct runoff, base-flow and channel routing in event based hydrological modeling. These methods are selected on the basis of applicability and limitations of each method, availability of data, suitability for same hydrologic condition, well established, stable, widely acceptable, researcher recommendation etc.

3.2 SCS Curve Number (CN) method

In SCS-CN method, accumulated precipitation excess is estimated as a function of cumulative precipitation, soil cover, land use, and antecedent moisture and is:

$$P_e = \frac{(P-I_a)^2}{(P-I_a+S)} \quad (1)$$

Where, P_e = Accumulated precipitation excess at time t; P = Accumulated rainfall depth at time t; I_a = Initial abstraction and S = Potential maximum retention.

I_a and S are calculated from following equations:

$$I_a = 0.2S \quad (2)$$

$$S = \frac{(25400-254CN)}{CN} \quad (3)$$

For a watershed that consists of several soil types and land uses, a composite CN is calculated as suggested by Panigrahi (2013),

3.3 SCS unit hydrograph method

SCS unit hydrograph is applied for estimating direct runoff. The basin lag time (T_{lag}) is the parameter of SCS UH model which is 0.6 times the time of concentration (T_c), Value of Tc is computed as suggested by Panigrahi (2013),

3.4 Exponential recession method

It is used to represent watershed base flow. It is given by:

$$Q_t = Q_o^{Rt} \quad (4)$$

Where, Q_0 = Initial base flow at time t = 0, Q_t = Threshold flow at time t, and R = Exponential decay constant.

Initial base flow (Q_o) is estimated by field inspection. The recession constant (R) is estimated from observed flow hydrograph which depends upon the source of base flow. The threshold flow (Q_t) is estimated from observed flows hydrograph, wherein the flow at which recession limb approximated well by a straight line (USACE –HEC, 2008),

3.5 Muskingum method

Muskingum method for channel routing is chosen. In this method X and K parameters must be evaluated. Theoretically, K parameter is time of passing of a wave in reach length and X parameter is constant coefficient that its value varies between 0 - 0.5. Therefore parameters can be estimated with the help of observed inflow and outflow hydrographs. Parameter K estimated as the interval between similar points on the inflow and outflow hydrographs. Once K is estimated, X can be estimated by trial and error (USACE –HEC, 2008),

3.6 Calibration and validation of the model

The successful application of the hydrologic watershed model depends upon how well the model is calibrated which in turn depends on the technical capability of the hydrological model as well as the quality of the input data. HEC-HMS watershed model is calibrated for the event based simulation. The objective of the model calibration is to match observed simulated runoff volumes, runoff peaks and timing of hydrographs with the observed ones.

The available hydro-meteorological data is split up in two parts for model calibration and model validation. Out of selected 24 events, 12 events were selected for model calibration and rest 12 for model validation. The events used for model calibration and model validation are mentioned in Tables 2 and 4, respectively.

The rainfall runoff data recorded in the Balijore Nala watershed have been used to calibrate and validate the model. The parameter values required for calibration were calculated and given as initial values at the time of calibration to the selected model. These parameters have also been optimized using the optimization tools available in HEC-HMS. The values of initial and optimized parameters are given in Table 1.

Table 1: Calculated initial and optimized parameters for the watershed

Sr. No.	Parameter	Initial Value	Optimized Value
1	Initial abstraction (I_a), mm	17.23	13.10
2	Curve Number (CN)	63.15	65.90
4	Lag time (T_{lag}), min	18.51	17.90
5	Initial discharge (Q), m^3/sec	0.0774	0.069
6	Recession constant (R_c)	0.746	0.627
7	Threshold flow (Q_t), m^3/sec	0.0564	0.055
8	Muskingum (K), Hr	0.378	0.292
9	Muskingum (X)	0.287	0.301

Different parameters of the observed direct surface runoff hydrographs like the values of runoff depth and peak discharge were compared with that of the simulated runoff hydrographs (both before optimization and after optimization trial) for individual calibration events and are presented in Table 2.

Table 2: Comparison of simulated and observed runoff depth and peak discharge (model calibration part)

Event	Runoff depth (mm)			Peak discharge (m^3/s)		
	Simulated		Observed	Simulated		Observed
	Before optimization	After optimization		Before optimization	After optimization	
9/7/10	10.05	12.66	13.88	0.76	1.08	1.18
15/7/10	8.03	10.45	9.65	0.68	0.98	0.80
27/7/10	14.17	13.95	12.70	1.01	1.03	1.17
10/8/10	9.55	11.18	12.86	0.88	1.08	1.03
18/8/10	8.09	7.64	7.05	0.78	1.00	0.94
24/8/10	6.35	5.05	5.38	0.55	0.70	0.68
15/07/11	11.79	14.14	15.1	0.88	1.09	1.19
19/07/11	6.85	6.05	6.16	0.46	0.34	0.38
22/07/11	12.46	14.83	14.70	0.78	0.83	0.89
02/08/11	21.99	24.70	25.98	1.19	1.31	1.44
13/08/11	5.67	5.08	5.18	0.42	0.30	0.33
20/08/11	3.47	3.38	3.30	0.39	0.36	0.34

3.7 Statistical test of error function

Following statistical tests of error function were performed to study the suitable performance of the model calibration and validation. Values of these error function with optimized and non-optimizes values are shown in Table 3.

Table 3: Error function computed for calibration and validation

RMSE				MARE			
Runoff depth (mm)		Peak discharge (m^3/s)		Runoff depth		Peak discharge	
a)Calibration							
Before optimization	After optimization	Before optimization	After optimization	Before optimization	After optimization	Before optimization	After optimization
2.30	0.75	0.28	0.09	0.20	0.10	0.25	0.12
(b) Validation							
---	0.70	---	0.09	---	0.05	---	0.06

Root Mean Square Error (RMSE) of peak discharge = $\sqrt{\frac{\sum_{i=1}^{n}(Qoi-Qci)^2}{n}}$ (5)

Mean Absolute Relative Error (MARE) peak discharge= $\frac{\sum_{i=1}^{n}\left|\frac{(Qoi-Qci)}{Qoi}\right|}{n}$ (6)

Root Mean Square Error (RMSE) of runoff depth = $\sqrt{\frac{\sum_{i=1}^{n}(Roi-Rci)^2}{n}}$ (7)

Mean Absolute Relative Error (MARE) of runoff depth = $\frac{\sum_{i=1}^{n}\left|\frac{(Roi-Rci)}{Qoi}\right|}{n}$ (8)

Where, Roi = Observed runoff depth, Rci = Computed runoff depth; Qoi = Observed peak discharge and Qci = Computed peak discharge. Variation of the observed and simulated runoff hydrographs (both before optimization trial and after optimization trial) for 1st event (9th July, 2010) and 4th event (10th August, 2010) as example are shown in Figures 3 and 4, respectively.

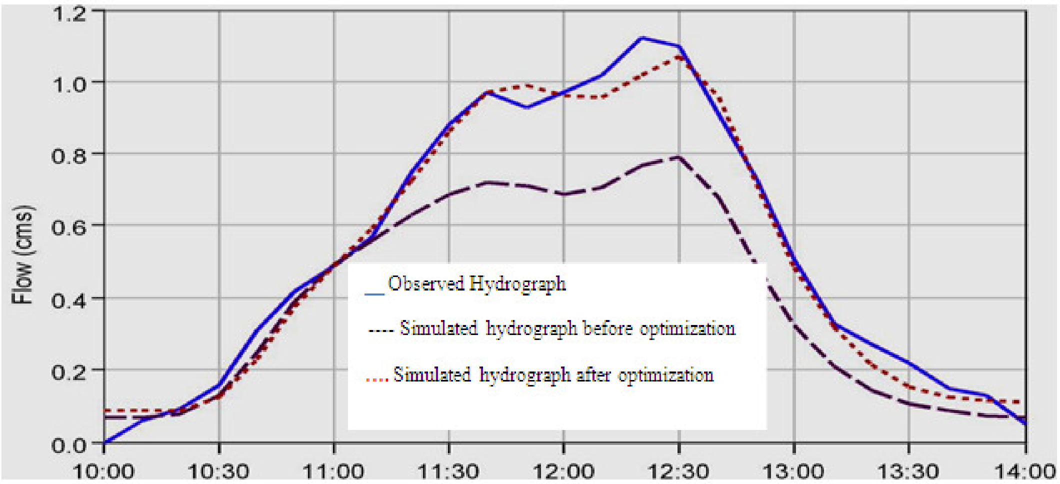

Figure 3: Comparison of runoff hydrograph for 1st event (9th July, 2010)

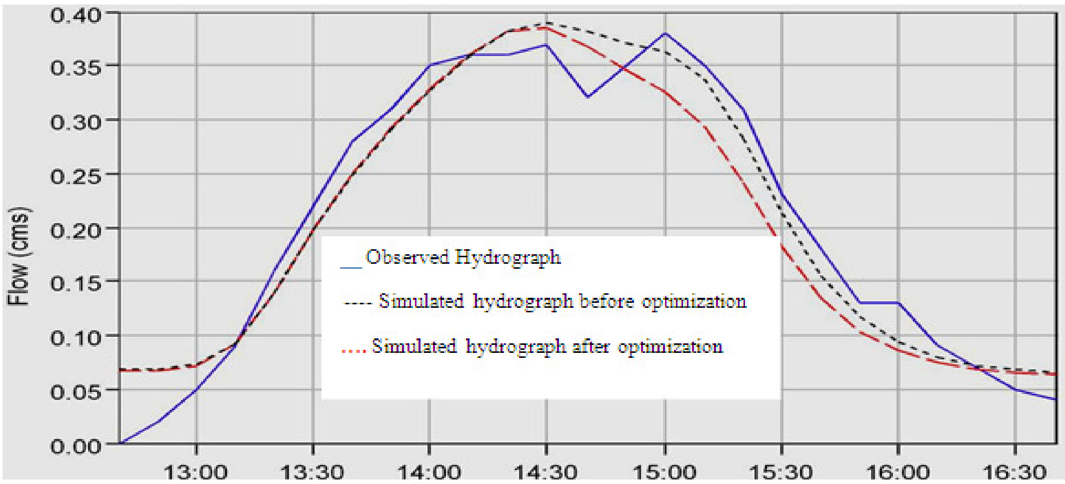

Figure 4: Comparison of runoff hydrograph for 4th event (10th August, 2010)

4. Results and discussion

4.1 Model calibration

The calculated initial parameter values (Table 1) were first used in the HEC-HMS model for calibration and different parameter like runoff depth and peak discharge were simulated. These parameters were compared with the observed value (Table 2), It is found out that there are large differences between the observed and simulated values of all parameters for all 12 events used for calibration. The percentage of variation for the runoff depth varied from 0.48 to 22.9 with a mean value of 16.2. Similarly the percentage variation of peak discharge between the observed and simulated values (simulated with initial values) was found to range from 10.4 to 28.8 with a mean value of 18.05. The initial calculated parameters were then optimized using the optimization tool available in HEC-HMS model and the different optimized parameters are shown in Table 1. With the help of these optimized parameters the hydrograph parameters like the runoff depth and peak discharge were again simulated (Table 2), It is observed that the optimized values gave close values of the different hydrograph parameters with the observed one. The mean percentage variation of the runoff depth and peak discharge between the observed and simulated (simulated after optimization) values were found to get reduced to 2.66 % and 2.97 %, respectively. Since the optimized values gave values of different hydrograph parameters which are very close to the observed values, we considered hence optimized values of initial parameters (last column of Table 1) for calibration of HEC-HMS model. The variations of observed and simulated (both optimized and unoptimized/initial parameter) runoff hydrograph were also studied for all the events under study. Figures 3 and 4 represent the variation for 2 calibrated events i.e. event 1 (9^{th} July, 2010) and event 4 (10^{th} August, 2010), respectively. From these two figures it is observed that the optimized parameter in HEC-HMS model gave values of different runoff hydrograph parameter close to the observed ones than when unoptimized (before optimization) parameters are considered. Similar trends were noted for all other events used for calibration.

The statistical test of error functions (Eq. 5 to 8) gave values of MARE of 0.20 mm and 0.25 m^3/s for runoff depth and peak discharge, respectively. Similarly the values of RMSE between the observed and simulated data are obtained as 2.30 mm and 0.28 m^3/s for runoff depth and peak discharge, respectively. However after optimized values are considered, these values got reduced to 0.10 mm, 0.12 m^3/sec, 0.75 mm and 0.09 m^3/sec in sequence (Table 3), Thus, the various statistical tests also reveal that the optimized value should be considered in HEC-HMS model to simulate the runoff hydrographs.

4.2 Model validation

A calibrated model should be validated before it is recommended for use. For validation, the simulated data as predicted by the model must be computed with the observed data and statistical tests of error functions must be carried on. If the values of error functions are very small then the model is validated. For validation of model, 12 events were considered. These 12 randomly selected events are mentioned in Table 4. The values of different runoff hydrograph like runoff depth and peak discharge were simulated by the calibrated model with inclusion of optimized parameters and are presented in Table 4. It is observed that the simulated values of these parameters are close to the observed values for all the events (Table 4). The mean percentage of variation between the observed and simulated values of runoff depth and peak discharge is calculated to be 4.79 and 4.99, respectively. Figures 5 to 6 shows

Table 4: Comparison of simulated and observed runoff depth and peak discharge (model validation part)

Events	Runoff depth (mm)		Peak discharge (m³/s)	
	Simulated	Observed	Simulated	Observed
28/08/2011	73.03	77.74	2.95	3.03
09/09/2011	34.13	36.04	2.31	2.42
15/09/2011	8.20	7.39	0.53	0.59
19/09/2011	13.02	12.71	1.02	1.10
17/05/2012	10.71	10.06	0.69	0.62
13/06/2012	6.81	7.10	0.41	0.48
29/08/2012	26.90	27.65	1.46	1.39
03/10/2012	4.92	4.61	0.44	0.51
09/06/2013	8.60	8.40	0.54	0.51
15/07/2013	14.98	15.14	0.98	1.10
26/09/2013	10.50	10.88	0.83	0.89
19/11/2013	6.80	6.98	0.69	0.65

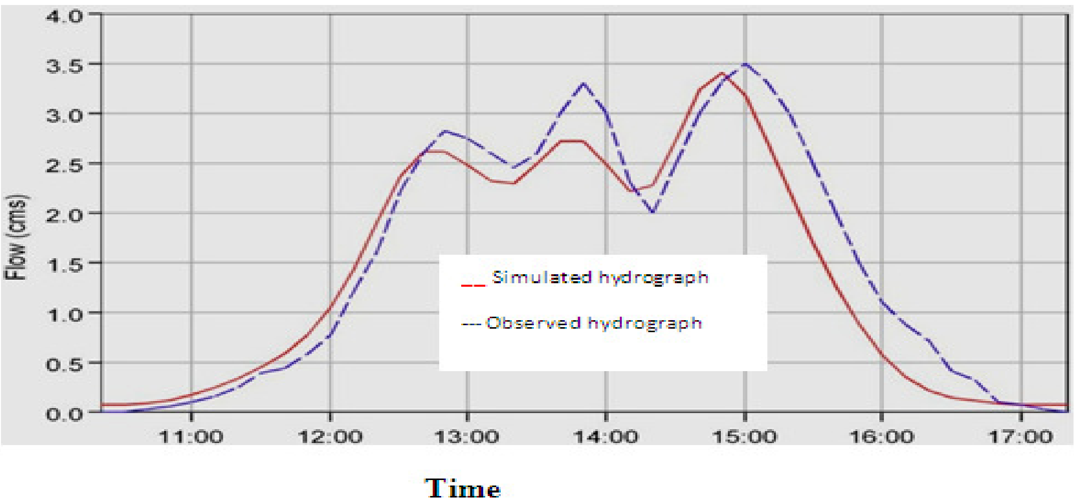

Figure 5: Comparison of runoff hydrograph for 13th event (28th August, 2011)

the comparison of observed and simulated hydrograph for event 13 (28th August 2011) and event 18 (13th June, 2012) as example. These figures reveal that the simulated runoff hydrograph is close to the observed one for all the events. Various error functions are computed as discussed earlier and are given in Table 3. The values of RMSE for runoff depth and peak discharge are estimated to be 0.70 mm and 0.09 m^3/s, respectively. Values of MARE for runoff depth and peak discharge are worked out to be 0.05 and 0.06, respectively. Thus, the statistical tests of error functions also justify the validation of the model for simulation of runoff hydrograph in the study watershed.

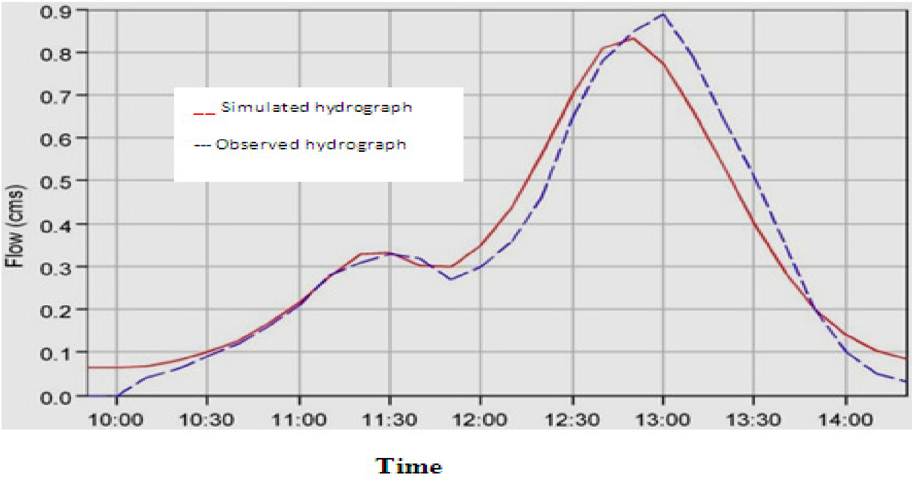

Figure 6: Comparison of runoff hydrograph for 18th event (13th June, 2012)

5. Conclusions

HEC-HMS model is used for simulation of runoff hydrograph in Balijore Nala watershed of Sambalpur district of Odisha, India. The initial calibration parameter was derived with the help of geomorphologic characteristics. By obtaining optimization technique, final validation parameter were derived and considered as global values for the model. The HEC-HMS model used for rainfall-runoff simulation in the selected watershed shows RMSE as 0.09 m^3/sec and MARE as 0.06 for peak discharge and RMSE as 0.70 mm and MARE as 0.05 for runoff depth. These obtained square functions in the validated model indicate satisfactory performance of HEC-HMS model in simulation runoff hydrograph. Despite difficulties, limitations and uncertainties associated with obtaining observations and measured parameters, this study ended-up with optimistic results for the simulation of rainfall-runoff process and hence the HEC-HMS model may be used to simulate rainfall-runoff process in the Balijore Nala watershed. The model can help to save time and money in obtaining the runoff data rather than measurement of runoff in the watershed. Moreover, it may help to simulate runoff in un-gauged watershed where there is no gauging station to measure runoff

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