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Identification of critical sub-watersheds in Hamp watershed of upper Mahanadi basin using Arc-SWAT

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ABSTRACT

Hydrologic and water quality investigations are fundamental to any watershed management programme. Surface hydrologic modelling of watershed mainly includes processes like runoff and transport of sediment as well as pollutants from the watershed. Mahanadi is one of the major inter-state east flowing perennial rivers in peninsular India. Hamp watershed of Seonath sub-basin of upper Mahanadi basin was selected for this study to estimate sediment yield, and identification of critical agricultural sub-watershed using soil and water assessment tool (SWAT) interfaced with geographic information system (GIS) *i.e.* Arc-SWAT. The study area was divided into 14 sub-watersheds considering topographical parameters derived from digital elevation model (DEM) and drainage network. Land cover, soil layers, and DEM were used to generate 207 hydrological response units (HRUs) for analysis of daily and monthly sediment yield for 2004-2008 (calibration period) and 2010-2013 (validation period). Adequately calibrated and validated Arc-SWAT model was used to estimate soil loss for identification of critical sub-watersheds of the Hamp watershed from upper Mahanadi river basin. The sediment yield and runoff estimation matched consistently well with daily and monthly measured values throughout the season. The coefficient of determination (R^2) of 0.693 and 0.96 and Nash-Sutcliffe efficiency (E_{NS}) was found to be 0.62 and 0.94 for daily and monthly sediment yield, respectively, indicating a close relationship between measured and predicted sediment yield. On the basis of average annual sediment yield of this study, sub-watersheds WS4, WS8, WS11, and WS10 were considered as critical watersheds, and the most critical sub-watershed WS4 with runoff and sediment yield of 245.97 mm and 18.18 t ha^{-1}, respectively was categorized under high priority for adoption of conservation measures to reduce soil and runoff loss.

1. INTRODUCTION

Land and water are the basic natural resources and must be conserved as effectively as possible. Water is a basic necessity for the survival of living beings and is the most precious natural resource which supports the existence of life on earth. Soil is the most fundamental, basic and natural resource on earth, which is essential for survival of human being (Chaudhary and Kumar, 2018). Hydrologic and water quality investigations are fundamental to any watershed management programme. Effective control of soil erosion requires implementation of best management practices in critical erosion prone areas. Application of physically based distributed parameter models, remote sensing (RS) technique and geographic information system (GIS) can assist planners in both identifying most vulnerable erosion prone areas and selecting appropriate management practices (Bharti, 2016). Studies have indicated that for many watersheds, a few critical areas are responsible for disproportionate amount of the pollution (Dickinson *et al.*, 1990; Dillaha, 1990; Maas *et al.*, 1985; Storm *et al.*, 1988). Against this background, it is of utmost importance to understand the behavior of different hydrological processes in any river basin for development of any watershed management plan.

Soil and water assessment tool (SWAT) is a river basin or watershed scale model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large, complex watersheds with varying soils, land use and management conditions over long periods of time. The SWAT model can be used in data scarce or ungauged catchments for identifying hydrological controlling parameters (Ndomba *et al.,* 2011). The Arc-SWAT, a Arc-GIS extension, is a graphical user interface for the distributed parameter model SWAT model (Arnold *et al.,* 1998). The Arc-SWAT has capability to run with more than 1000 numbers of hydrologic response units (HRUs) under various management schemes. The present study was carried out to prioritize the critical sub-watersheds in Hamp watershed based on soil loss or sediment-yield assessment. The Arc-SWAT model was used in the present study to estimate sediment yield for identifying critical sub-watersheds, which will be helpful in development of effective watershed management programme.

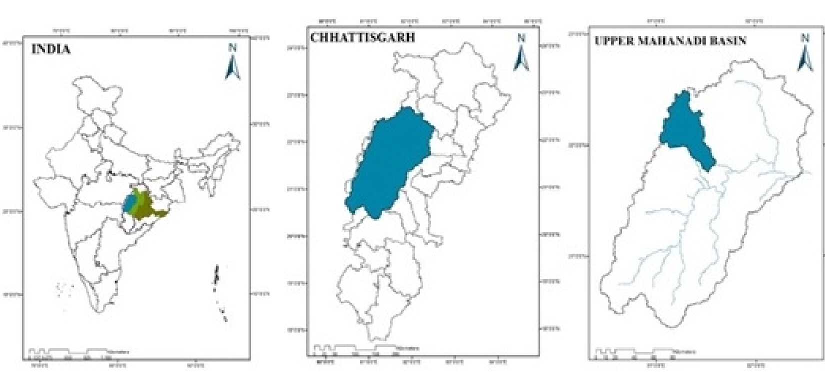
2. MATERIALS AND METHODS

Study Area

The Hamp watershed in Seonath sub-basin of upper Mahanadi basin was selected for the present study with Andhiyarkhore gauging station of Central Water Commission (CWC) as its outlet. Hamp river is the main stream of the Hamp watershed as shown in Fig. 1. It originates from Kawardha district and passes through newly formed Bemetara district and joins Seonath river at Raipur district of the state. The study area lies between 81^{0}01'E to 81^{0}36'E and 21^{0}45'N to 22^{0}30'N with an altitude ranging from 267-1193 m above the mean sea level covering a total geographical area of 2210 km^2. Hamp river is situated at the uppermost boundary of the Mahanadi basin and the area is dominated by upland farming situations promoting soil loss with poor crop productivity. Farming situation of Chhattisgarh agro-climatic zone (ACZ) is divided into four types *viz., Bhata* (Entisols), *Matasi* (Inceptisols), *Dorsa* (Alfisols) and *Kanhar* (Vertisols). *Bhata* lands are the uplands governed by slope >5%, and soil depth of less than 30 cm with soil texture of loamy fine sand to silt loam. In recent years, most soil loss from upland areas occurs as gully erosion (Römkens *et al.*, 2015). The soils having low infiltration capacity pose challenges for management of runoff and erosion (Mishra *et al.,* 2017). Hence, the Hamp watershed was selected as study watershed to estimate soil loss for identifying critical sub-watersheds to develop effective watershed management plan.

Meteorological Data

Historical daily rainfall data for 31 years (1983-2013), measured at the outlet of the Hamp watershed at Andhiyarkhore gauging station of CWC, Bhubaneswar, Government of India were collected and analysed to determine the mean monthly rainfall. Maximum and minimum air temperatures recorded at the meteorological observatory of Andhiyarkhore gauging station (1983-2013) was also acquired from the CWC, Bhubaneswar. Daily rainfall data (2004-2013) were also collected from the Hydrology Data Center, Department of Water Resources, Government of Chhattisgarh for six rainfall gauging stations namely Goreghat, Hamp-Pandariya, Balod, Chhirpani, Pandariya and Saroda*,* which were lying within the Hamp watershed. Nearly more than 10 years rainfall data was available for all the gauging stations, and were used in the study. Observed data (2004-2013) on rainfall, maximum and minimum temperatures, sunshine hours, relative humidity and wind velocity were also acquired from Bilaspur meteorological observatory, which is close to the Hamp watershed. Due to non-availability of observed data for other meteorological parameters (solar radiation, wind velocity and relative humidity) for the above mentioned six rainfall gauging stations, the same was downloaded from prediction of worldwide energy resource (POWER) climatology resource for agro-climatology (https://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov). Monthly average values for 10



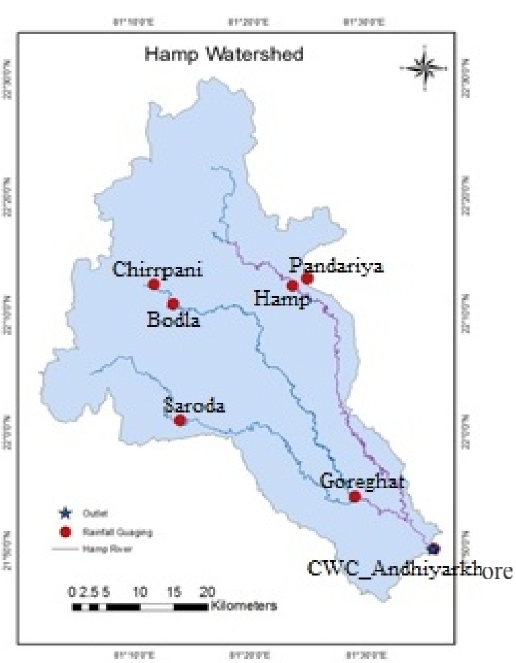


Fig. 1. Location map of the study area

years (2004-2013) for the rainfall, temperature, relative humidity, wind velocity and solar radiation for Hamp watershed are given in Table 1. The rainfall data from all the stations was averaged using thiessen polygon method, and other parameters were also averaged.

Hydrological and Sediment Data

Daily river discharge and sediment yield data (2004-2013) recorded at the outlet of the Hamp watershed, *i.e.* Andhiyarkhore gauging station was acquired from CWC Regional Office, Mahanadi and Eastern Rivers Organization, Bhubaneswar for the study. A large number of missing data were observed during the monsoon period of year 2009, and hence, it was not considered for both calibration and validation periods.

Digital Elevation Model (DEM)

In this study, Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM) of National Aeronautics and Space Administration (NASA) was used. The consultative group on international agricultural research-consortium for spatial information (CGIAR-CSI) geo-portal provides SRTM 90 m/30 m digital elevation data for most part of the globe (www.srtm.csi.cgiar.org). The SRTM data was available at 1 arc second (approximately 30 m spatial resolution) DEMs for the study area (Fig. 2). Before using the downloaded DEM, it is required to apply the geometric correction. Therefore, the SRTM-DEM was re-projected to universal transverse mercator (UTM) co-ordinate system with Datum WGS 1984 (Zone-44) with spatial resolution of 30 m.

Land Use/Land Cover (LU/LC)

The cloud free LANDSAT (TM) imagery of 20/10/2008 and 31/10/2013 of the study area was downloaded from earth explorer website (www.earthexplorer.usgs.gov) with a spatial resolution of 30 m (Fig. 3). The approximate scene size was 170 km north-south by 183 km east-west and the whole study area was covered in one scene only. The LU/LC map of the study area was generated using ERDAS-IMAGINE 2016. Most common land use classification method, the supervised classification, was used in this study. Maximum likelihood classifier (MLC) module was

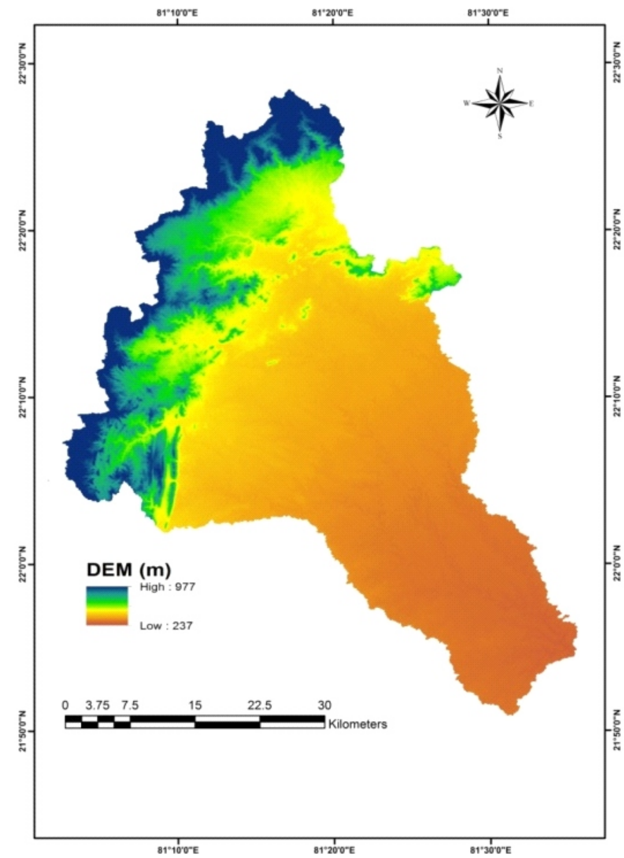


Fig. 2. 1 Arc SRTM DEM of Hamp watershed

used for classifying the land uses. The classification was carried out using ground control points (GCPs). These GCPs were taken with the help of hand held global positioning system (GPS) during field visit of the study area. Each pixel in the image data set was then categorized into the land use class it most closely resembled. The classified LU/LC classes were water body, rainfed paddy, irrigated paddy, soybean, sugarcane, maize, barren land, settlement and forest. The area covered by each class as identified by supervised classification is given in Table 2. LU/LC data of 2008 was used for the delineation of watershed and sub-watersheds.

Table: 1
Mean monthly (2004-2013) observed meteorological data of Hamp watershed

Variables	Statistical parameters	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Rainfall	Mean	13.8	8.90	7.1	7.37	10.0	87.6	217.3	171.8	117.4	28.5	11.1	1.57
(mm)	Standard deviation	2.03	1.61	1.4	1.27	1.57	9.72	14.08	13.63	10.66	3.68	1.49	0.38
	Skewness	3.10	3.53	3.2	3.41	3.50	2.75	1.94	2.32	2.75	3.62	3.26	1.77
Maximum	Mean	26.5	30.7	35.9	39.2	40.84	34.9	29.48	28.83	29.38	29.2	27.7	26.3
Temperature (°C)	Standard deviation	3.07	4.0	4.3	4.85	4.98	5.38	1.58	1.61	1.51	1.82	1.67	2.30
Minimum	Mean	12.3	15.6	20.6	24.5	27.02	26.1	24.09	23.65	23.10	19.5	15.7	12.8
Temperature (°C)	Standard deviation	2.70	2.96	2.71	2.37	2.16	2.34	0.95	1.27	1.16	2.55	2.98	2.62
Average number of rainy days		1.13	1.34	1.57	1.87	2.23	9.38	18.29	16.45	10.56	3.05	0.95	0.43
Average wind velocity (m s^{-1})		1.76	1.94	2.19	2.51	2.88	3.35	3.04	2.68	2.11	1.56	1.44	1.54
Average solar radiation (MJ m^{-2} day^{-1})		16.8	19.8	22.7	24.5	24.20	18.6	14.40	14.23	17.25	18.8	17.1	16.2

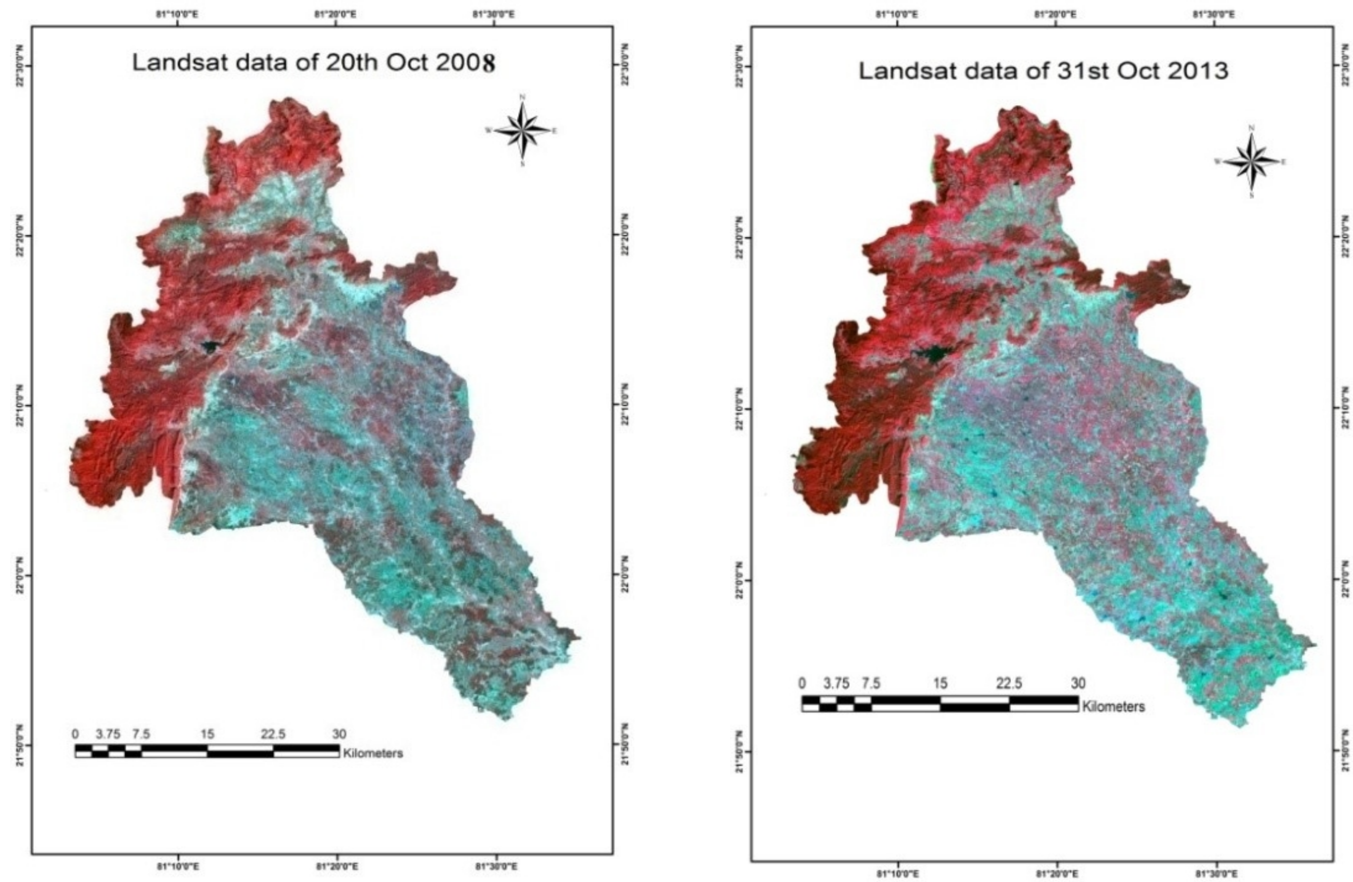


Fig. 3. Landsat satellite imageries of the study area

Soil

Soil texture map of Chhattisgarh state, which was prepared by National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur using 10 km^2 grid sampling, was used in the study. The map was further refined and re-classified based on the soil sample analysis and point data of soil health card acquired for Department of Agriculture, Government of Chhattisgarh. The soil texture found in the study area were clay, gravelly sandy loam, clay loam, silty clay, gravelly sandy clay loam, sandy clay loam and sandy loam.

Delineation of Watershed and Sub-watersheds using Arc-SWAT

Many hydrological models require a watershed to be subdivided into smaller area sub-watersheds. Each sub-watershed is assumed as homogeneous, with parameters representative of entire sub-watershed. However, the size of a sub-watershed affects the homogeneity assumption, since larger sub-watershed is more likely to have variable conditions within the sub-watershed. Runoff volume was not affected appreciably by the number and size of the sub-watersheds, whereas annual fine sediment yield produced from upland areas was very sensitive to the level of watershed sub-divisions (Bingner *et al.*, 1997). Sub-watershed classification refers to the assessment and management category assigned to a sub-watershed (Tripathi *et al.*, 2003). The Arc-SWAT uses standard methodology which is based on the eight-pour point algorithm (Jenson and Domingue, 1988) to delineate streams from DEM. With the help of the automatic watershed delineator of Arc-SWAT model, streams from the raster DEM were extracted, and based on this the sub-watersheds were delineated.

The sub-watershed delineation is performed by a process of tracing the flow direction from each grid cell until either an outlet cell or the edge of the DEM grid extent is encountered. The interface is provided with two additional setting tools *i.e.* DEM properties and threshold area in hectares used for the calculation of geomorphic parameters. The boundary of Hamp watershed and its sub-watersheds were delineated using DEM and drainage network of the study area. The delineated watershed and 14 sub-watersheds are shown in Fig. 4 and were named as WS-1 to WS-14. Watershed and sub-watershed boundaries were also delineated automatically with the help of Arc-SWAT using DEM. In this study, automatically delineated watershed having 2210 km^2 areas was decomposed into 14 sub-watersheds, and based on the similar land cover, soil layers and DEM, the watershed was classified into 207 HRUs. Afterwards, area of each sub-watersheds and length of stream reaches were calculated and stored as attributes of derived vector themes.

SWAT Model

Arc-SWAT is a semi-distributed parameter model that operates on a daily or sub-daily time step basis. The first step in the calibration and validation process in Arc-SWAT is the determination of the most sensitive parameters for a given watershed or sub-watershed (Arnold *et al.,* 2012). The hydrology model is based on the water balance equation:

$$SW_t = SW + \sum_{i=1}^{t} (R_i - Q_i - ET_i - P_i - QR_i) \qquad ...(1)$$

Where, SW is the soil water content minus the 15-bar water content, t is time in days, and R, Q, ET, P, and QR are

Table: 2
Pixel based land use/cover classification along with accuracy assessment of Landsat satellite False Color Composite (FCC) data

Land use classes	Pixel Based classification								% Area Change
	2008				2013				
	Area (ha)	% Area	Producers Accuracy	Users Accuracy	Area (ha)	% Area	Producers Accuracy	Users Accuracy	
Water	886.5	0.4	100%	100%	986.5	0.45	100%	100%	0.05
Forest-mixed	55401.0	25.07	88%	84%	51401.0	23.26	90%	80%	-1.81
Sugarcane	16257.4	7.36	76%	93%	22356.3	10.12	79%	86%	2.76
Rice- irrigated	21179.5	9.58	79%	95%	21978.9	9.95	79%	77%	0.36
Soybean	26658.0	12.06	97%	97%	33917.7	15.35	91%	97%	3.29
Barren	6953.2	3.15	50%	100%	4833.7	2.19	77%	70%	-0.96
Settlement	21787.2	9.86	100%	50%	22737.5	10.29	93%	98%	0.43
Rice - rainfed	31932.3	14.45	77%	91%	24942.8	11.29	91%	87%	-3.16
Maize	39949.2	18.08	86%	86%	37849.6	17.13	89%	80%	-0.95
Total	221004.3	100			221004.3	100			0
Overall Classification accuracy	90.81%				89.71%				
Overall Kappa Statistics	0.87				0.885				

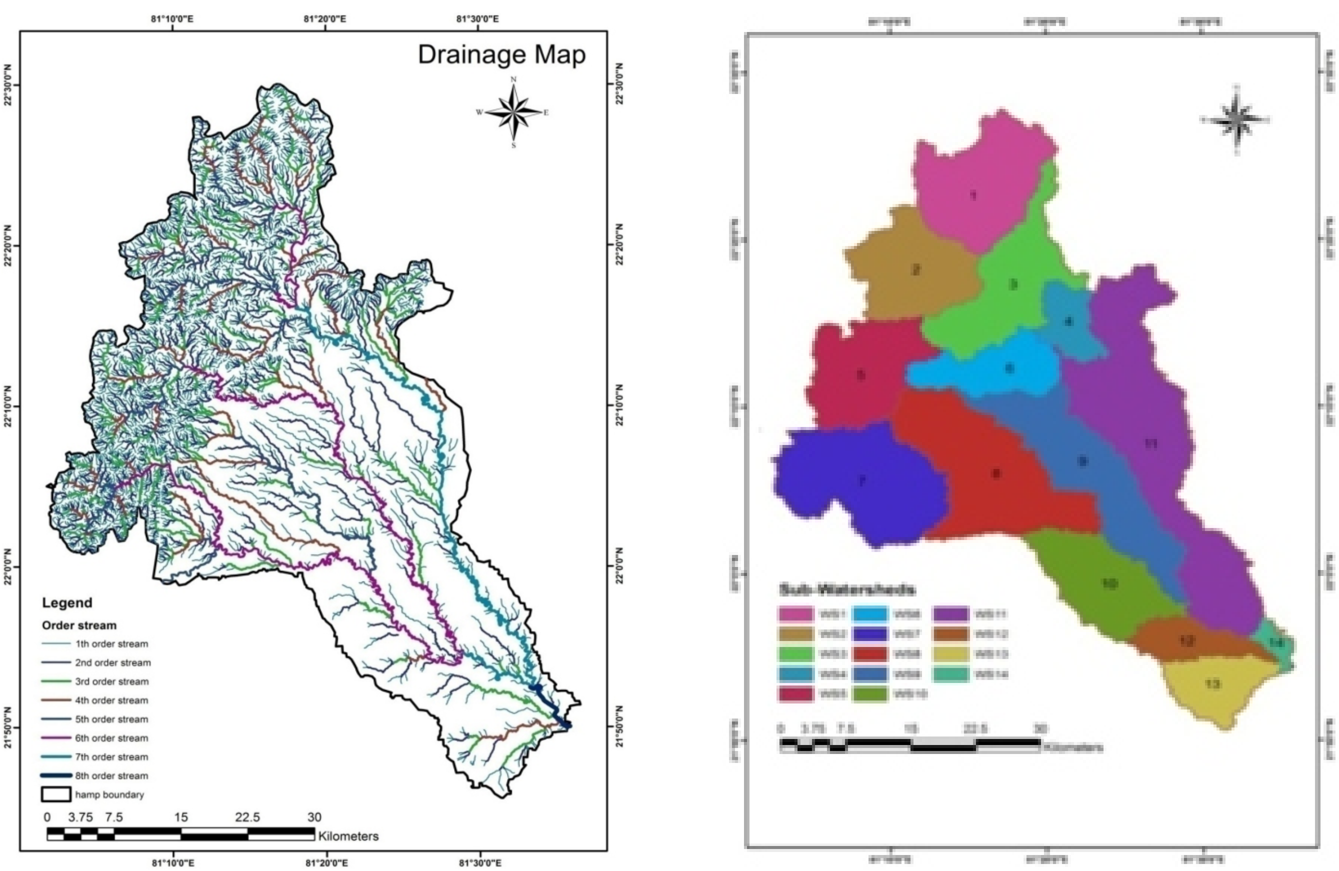


Fig. 4. Hamp drainage network and sub-watersheds delineation map

the daily amounts of precipitation, runoff, evapo-transpiration (ET), percolation, and return flow, respectively; all units are in mm. Since the model maintains a continuous water balance, complex basins are subdivided to reflect differences in ET for various crops and soils. Thus, runoff is predicted separately for each sub-area and routed to obtain the total runoff for the basin. This increases accuracy and gives a much better physical description of the water balance. SWAT predicts surface runoff for daily rainfall by using the soil conservation service (SCS) curve number (CN) method. Sediment yield was computed for each sub-basin with the modified universal soil loss equation (MUSLE).

Sensitivity analysis was performed using the SUFI-2 algorithm of SWAT-CUP (Patil *et al.,* 2019). The parameter producing the highest average percentage change in the objective function value is ranked as most sensitive. SWAT-CUP uses the SWAT input files and runs the SWAT simulations by modifying the given parameters. Sensitivity analysis was conducted using a combined method of latin hypercube (LH) sampling and one-factor-at-a-time (OAT). Each variable was varied within the prescribed range keeping others constant. The output of model simulated runoff and sediment yield were analyzed to determine their variation with respect to their respective counterpart observers values. From sensitivity analysis it was possible to decide which variables need to be precisely estimated to make accurate predictions of the runoff and sediment yields.

The model was calibrated during the monsoon season (June to October) for the years 2004-2008, including three years of warm-up period (2001-2003) using daily values of the observed rainfall, runoff and sediment yield. The model was validated during the monsoon season (June to October) for the years 2010-2013. Annual sediment losses were simulated for each sub-watershed of Hamp watershed using adequately tested calibrated and validated Arc-SWAT model for identification and prioritization of critical sub-watersheds.

Criteria for Model Evaluation

Several types of statistics provide useful numerical measures of the degree of agreement between models simulated and recorded quantities. The numerical criteria as described in Table 3 is used in the study.

In this study, criterion suggested by Moriasi *et al.* (2007) has been adopted to analyze the performance of the SWAT model as shown in Table 4.

3. RESULTS AND DISCUSSION

Regression analysis was performed between the observed and pre-calibrated monthly runoff values. Statistical indicators such as the coefficient of determination, nash-sutcliffe coefficient and percent bias were used to test the results of model simulation. The overall deviation between the observed and pre-calibrated simulated discharge was found to be 43.94% which is quite high and makes essential for the model to be calibrated.

Sensitivity Analysis of Model Parameters

The sensitivity analysis ranking of SWAT parameters are mentioned in Table 5. It was found that the parameter SCS-CN was found highly sensitive to runoff and conservation practices factor of universal soil loss equation's (USLE_P) to sediment yield.

Parameter Used for Model Calibration

The calibration procedure involves rigorous manual adjustment, through the manual calibration tool for the Arc-SWAT model parameters until acceptable simulation was achieved. The default model value and calibrated values used in the Arc-SWAT model are presented in Table 6.

Table: 3
Details of criteria for model evaluation

S.No.	Criteria for Model Evaluation	Equation	Source
1.	Coefficient of determination (R^2)	$R^2 = \left\{ \frac{\sum_{i=1}^{N}\left(Y_i^{obs} - Y_{mean}^{obs}\right)\left(Y_i^{sim} - Y_{mean}^{sim}\right)}{[\sum_{i=1}^{N}(Y_i^{obs} - Y_{mean}^{obs})]0.5\ [\sum_{i=1}^{N}(Y_i^{sim} - Y_{mean}^{sim})2]0.5} \right\}^2$	Willmott, 1981; Legates and McCabe, 1999
2.	Nash-Sutcliffe efficiency (E_{NS})	$E_{NS} = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_{mean}^{obs}\right)^2} \right]$	Nash and Sutcliffe, 1970
3.	Percent bias (PBIAS)	$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) \times 100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)} \right]$	Gupta *et al.,* 1999

Table: 4
General performance ratings for recommended statistics

Performance rating	ENS	PBIAS (%) for Runoff	PBIAS (%) for Sediment
Unsatisfactory	E_{NS}< 0.50	PBIAS > + 25	PBIAS > + 55
Satisfactory	0.50 <E_{NS}< 0.65	+ 15 < PBIAS <+ 25	+30< PBIAS <+55
Good	0.65<E_{NS}< 0.75	+ 10 < PBIAS <+ 15	+ 15< PBIAS <+30
Very good	0.75 <E_{NS}< 1.00	PBIAS <+ 10	PBIAS <+ 15

Table: 5
SWAT parameters with rank according to sensitivity analysis

Rank	Name	Description	Lower Bound	Upper Bound	Process
1.	CN	SCS runoff CN for moisture condition II	25	98	Runoff
2.	RCHRG_DP	Deep aquifer percolation fraction (-)	0	1	Groundwater
3.	ESCO	Soil evaporation compensation factor (-)	0	1	Flow
4.	SOL_AWC	Available water capacity of the soil layer (mm mm^{-1} soil)	-25	25	Soil
5.	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	-1000	1000	Groundwater
6.	EPCO	Plant evaporation compensation factor (-)	0	1	Evaporation
7.	GW_ REVAP	Groundwater-revap coefficient (-)	0	1	Flow
8.	CH_K2	Hydraulic conductivity in main channel (mm hrs^{-1})	1	150	Channel
9.	CH_N2	Manning coefficient for main channel (-)	0	1	Channel
10.	OV_N	Manning "n" value for overland flow	0.01	0.6	Runoff
11.	ALPHA_BF	Base flow alpha factor (days)	0	1	Groundwater
12.	GW_ DELAY	Groundwater delay (days)	-30	90	Groundwater
13.	SOL_Z	Soil depth (mm)	-25	25	Soil
14.	SURLAG	Surface runoff lag time (days)	0.05	24	Runoff
15.	CANMX	Maximum canopy storage (mm)	0	10	Soil
16.	BLAI	Maximum potential leaf area index (-)	0	1	Crop
17.	CH_K1	hydraulic conductivity for tributary (mm hr^{-1})	0	1	Soil
18.	USLE_P	Support practice factor	0	1	Sediment
19.	CH_COV	channel cover factor	0	1	Sediment
20.	CH_EROD	Channel erodibility factor (-)	0	1	Sediment
21.	SPEXP	Exponent parameter for calculating sediment restrained in channel sediment routing	1	1.5	Basin
22.	BIOMIX	Biological mixing efficiency (-)	0	1	Management
23.	SOL_ALB	Soil albedo (-)	-25	25	Evaporation

Table: 6
Initial and calibrated parameter values

S.No.	Parameter	Default values	Calibrated values
1.	CN	72-91	68.4-86.5 for agricultural cover
		60-73	55.5-67.5 for forest
		59-72	54.6-66.6 for settlements
2.	RCHRG_DP	0.05	0.46
3.	ESCO	0.95	0.50
4.	SOL_AWC	0-0.23	0-0.253
5.	GWQMN	0	60
6.	EPCO	1	0.75
7.	GWREVAP	0.02	0.15
8.	CH_K2	0	25
9.	CH_N2	0.014	0.025
10.	Alpha bf	0.0482	0.193
11.	GW Delay	31	15
12.	USLE_P	0.01-1	0.65
13.	CH_COV	0-1	0.71
14.	CH_EROD	0-1	0.61

Calibration of the Model for Daily Runoff Simulation

The time series of the observed and simulated daily runoff values of Hamp watershed for the calibration period were compared graphically by using scatter plots alongwith 1:1 line and is presented in Fig. 5. It is observed that the simulated runoff follows the trend of the observed runoff. But still the daily simulation is complex phenomenon and is difficult to match with the observed data. The daily rainfall and runoff pattern fluctuates on every single day making it difficult to derive the simulation based on daily events. Further, efficiency of model for simulating runoff was tested by statistical analysis and the results were observed during calibration (E_{NS} = 0.725, PBIAS = -5.864, R^2 = 0.749) for the period of 2004 to 2008 (Table 7).

Validation of the Model for Daily Runoff Simulation

The year-wise 1:1 scatter plots of validation results for the daily runoff is shown in Fig. 5. The graphs show that the magnitude and temporal variation of simulated daily runoff matched closely with the observed runoff values for the entire monsoon season for the period 2010-2013 (Table 7). Timings of occurrence of the peaks for both observed and simulated runoff matched well. Points are somewhat evenly distributed about the 1:1 line, except for the events corresponding to higher magnitude of runoff.

Calibration of the Model for Monthly Runoff Simulation

The time series of the observed and simulated monthly runoff values of Hamp watershed for the calibration period were compared as 1:1 scatter plots and are presented in Fig. 6. It was observed that the simulated runoff follows the plot of the observed runoff. Further, efficiency of model for simulating runoff was tested by statistical analysis and the results were observed during calibration (E_{NS} = 0.942, PBIAS = 1.147, R^2 = 0.943) for the period of 2004 to 2008 (Table 8). The magnitude of the simulated monthly runoff was found

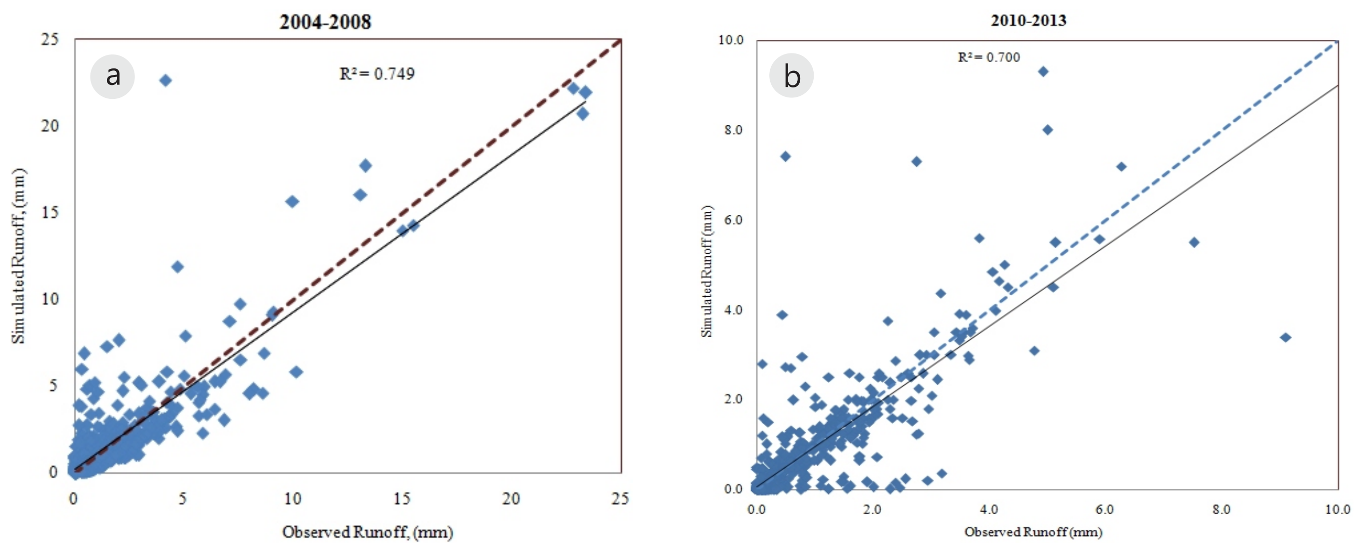


Fig. 5. Scatter plot of simulated and observed daily runoff (mm) during (a) calibration period and (b) validation period

Table: 7
Model performance during calibration period (2004-2008) and validation period (2010-2013) in simulating daily runoff

Year	Observed			Simulated			Calibration/validation		
	Mean	Max	Std Dev	Mean	Max	Std Dev	E_{NS}	PBIAS	R^2
2004-2008	1.256	23.394	2.277	1.329	22.630	2.389	0.725 (Good)	-5.864 (Very Good)	0.749
2010-2013	0.842	1.283	14.127	0.823	1.372	15.30	0.646 (Satisfactory)	2.206 (Very Good)	0.700

higher than that of observed runoff for most of the months as is reflected by the positive value of PBIAS. Generally it was found that during the initial phase of initiation of monsoon rains, the observed runoff was less than the simulated runoff. This may be due to the fact that significant portion of the rainfall is stored in the bunded paddy fields. R^2 and E_{NS} showed good relationship between the observed and simulated monthly runoff data during the whole calibration period explaining acceptable and minimum deviation between the monthly observed and simulated values.

Validation of the Model for Monthly Runoff Simulation

The results of the monthly runoff validation alongwith comparison of simulated and measured monthly runoff are shown in Table 8. The model validation with a high R^2 value (0.923) indicated a close relationship between measured and simulated runoff which is also satisfied by E_{NS} value of 0.914 and PBIAS value of 5.80.

Calibration of the Model for Daily Sediment Simulation

The time series of the observed and simulated daily

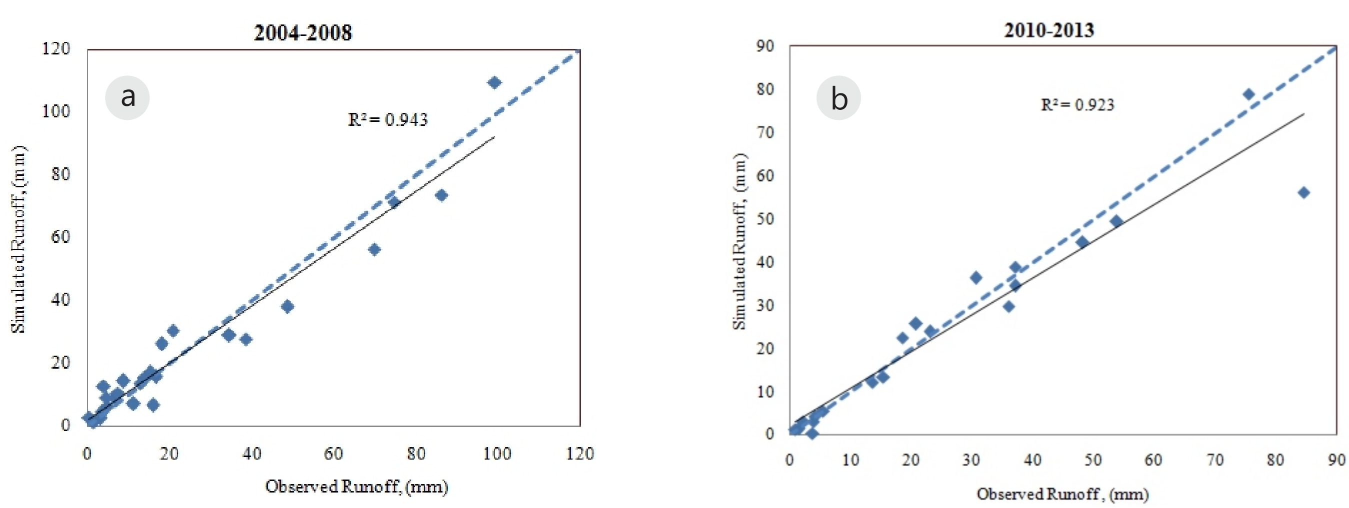


Fig. 6. Scatter plot of simulated and observed monthly runoff (mm) during (a) calibration period and (b) validation period

Table: 8
Model performance during calibration period (2004-2008) and validation period (2010-2013) in simulating monthly runoff

Year	Observed			Simulated			Calibration/validation		
	Mean	Max	Std Dev	Mean	Max	Std Dev	E_{NS}	PBIAS	R^2
2004- 2008	24.770	99.248	28.64	24.46	109.62	26.77	0.942 (Very Good)	1.147 (Very Good)	0.943
2010-2013	25.75	84.51	24.65	24.26	78.94	21.87	0.914 (Very Good)	5.80 (Very Good)	0.923

sediment yield values for the calibration period were compared by drawing scatter plots along with 1:1 line (Fig. 7). It is seen that simulated sediment yield follows the trend of observed sediment yield. The results of performance criteria (Table 9) also indicated a close relationship between observed and simulated sediment yields with E_{NS}, PBIAS, R^2 values of 0.620, -24.232, and 0.693, respectively. The overall prediction of the daily sediment yield during calibration period was in acceptable range.

Validation of the Model for Daily Sediment Simulation

Table 9 displays the overall statistical indicators for the whole validation period (2010-2013). PBIAS, E_{NS} and R^2 are found within the acceptable range during the validation period verifying the same for daily sediment prediction. The simulated sediment yield values were distributed evenly about the 1:1 line for lower as well as higher values of observed sediment yield (Fig. 7).

Calibration of the Model for Monthly Sediment Simulation

It is evident from the Fig. 8 that the simulated sediment yield closely follows the trend of observed sediment yield. Performance criteria (Table 10) showed a close relationship between observed and simulated sediment yields during calibration (E_{NS} = 0.94, PBIAS = -19.724, R^2 = 0.963). The overall prediction of the monthly sediment yield during the whole calibration period was in very good agreement with its observed values.

Validation of the Model for Monthly Sediment Yield

The time of peak sediment yield in case of predicted graph matched consistently well with the measured sediment graph throughout the season. However, the model-predicted values were sometimes higher and sometimes lower than the observed values during the validation period (Fig. 8). A high R^2 value of 0.950 indicates a close relationship between measured and simulated monthly sediment yields (Table 9). The E_{NS} value of 0.941 indicated a very good agreement between observed and simulated sediment. The marginal deviation of PBIAS (-9.633%) of simulated sediment yield from observed sediment yield indicated that the model was predicting sediment yield quite well. However, the model slightly over-predicted few events of sediment yield.

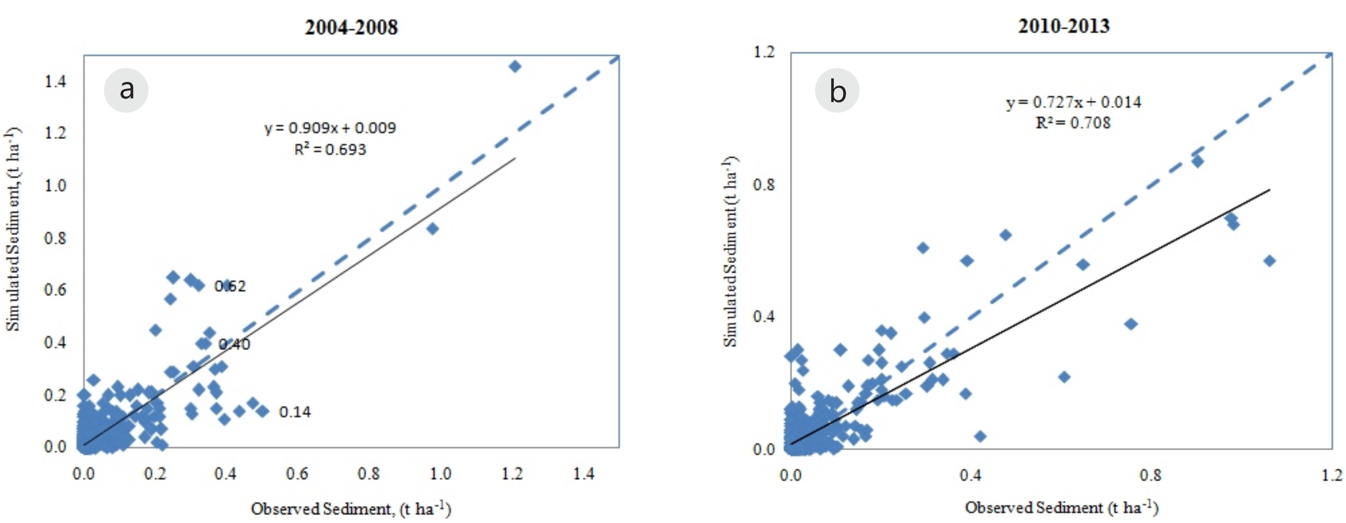


Fig. 7. Scatter plot of simulated and observed daily runoff (mm) during (a) calibration period and (b) validation period

Table: 9
Model performance during calibration period (2004-2008) and validation period (2010-2013) in simulating daily sediment yield

Year	Observed			Simulated			Calibration/validation		
	Mean	Max	Std Dev	Mean	Max	Std Dev	E_{NS}	PBIAS	R^2
2004-2008	0.027	1.205	0.087	0.034	1.460	0.095	0.620 (Satisfactory)	-24.232 (Good)	0.693
2010-2013	0.036	1.060	0.108	0.041	0.870	0.094	0.706 (Good)	-13.092 (Very Good)	0.708

Identification and Prioritization of Critical Sub-watersheds

Identification and prioritization of critical sub-watersheds based on actual sediment yield rates may be possible only when sediment data is available. The model was run for four consecutive years (2010-2013) and annual watershed yield including runoff and sediment yield were considered for each sub-watershed and are given in Table 11. The ranges of erosion rates and their classes suggested by Singh *et al.* (1992) were used to identify and prioritize the critical sub-watersheds. Out of the fourteen sub-watersheds, the WS-3, WS-6, WS-9, WS-12, WS-13, and WS-14 fell under moderate soil loss group of soil erosion classes (5 t $ha^{-1}yr^{-1}$ to 10 t $ha^{-1}yr^{-1}$). The WS-4, WS-8, WS-10 and WS-11 fell under high soil loss group of soil erosion classes (10 t $ha^{-1}yr^{-1}$ to 20 t $ha^{-1}yr^{-1}$), whereas other sub-watersheds fell under slight erosion classes.

None of the sub-watersheds fell under very high, severe or very severe erosion classes. Though nearly 30% area is having extremely undulating topography with steep slopes, still due to the nearly level topography of the remaining area, average slope is gentle slope. The study watershed might have got stabilized as contour and graded bunds and settlements already exist in the watershed. However, the sub-watershed WS-4 resulted in maximum sediment yield, which is also more than average soil loss of 16.35 t $ha^{-1}yr^{-1}$ (Narayana, 1993). This may be due to high average surface slope of 9.1% with undulating topography. Sub-watersheds WS-8 and WS-11 exceeded the prescribed permissible upper limit of 11.2 t $ha^{-1}yr^{-1}$ (Mannering, 1981) whereas WS-10 is very near to the permissible limit.

There are certain limitations of present study that the model does not simulate detailed event based flood and sediment routing. Precipitation causes considerable errors in runoff estimation, if less numbers of rain gauging stations are used to represent an entire watershed. Even the missing data or non availability of long term continuous data was the major limitation of the study.

4. CONCLUSIONS

Arc-SWAT was successfully calibrated and validated for Hamp watershed of upper Mahanadi river basin, with close accuracy, and could be successfully utilized to analyse the effect of various management practices on runoff and sediment yield from the sub-watersheds. The monthly simulation was found to be in close agreement with the observed data sets, which was reflected by the high values of statistical indicators, whereas the daily simulation could not be found to be so high. The sediment yield and runoff estimation matched consistently well with the daily and monthly measured values throughout the season. The coefficient of determination (R^2) of 0.693 and 0.96 for daily and monthly sediment yield, respectively, indicated a close relationship between measured and predicted sediment yield. The nash-sutcliffe efficiency (E_{NS}) was found to be 0.62 and 0.94 for daily and monthly sediment yield, respectively and 0.914 for monthly runoff estimation. Arc-SWAT was successfully calibrated and validated for Hamp watershed and was setup for hydrological studies. The critical sub-watersheds were identified on the basis of average sediment yield and runoff during the period of 2010 to 2013. Out of the 14 sub-watersheds, the WS-3, WS-6, WS-9, WS-12, WS-13, and

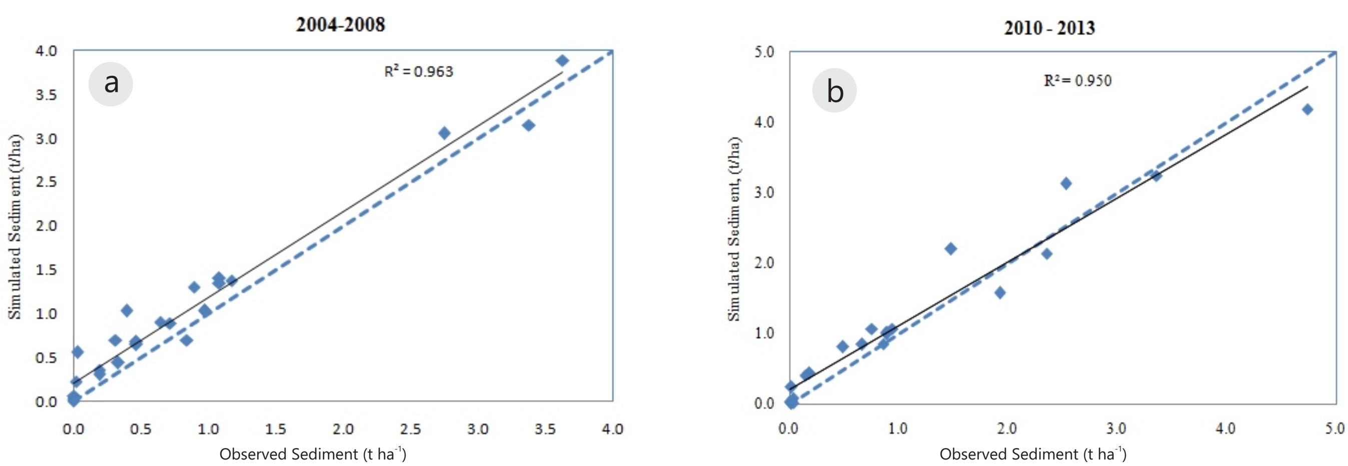


Fig. 8. Scatter plot of simulated and observed monthly sediment yield (t ha^{-1}) during (a) calibration period and (b) validation period

Table: 10
Model performance during calibration period (2004-2008) and validation period (2010-2013) in monthly sediment yield

Year	Observed			Simulated			Calibration/validation		
	Mean	Max	Std Dev	Mean	Max	Std Dev	E_{NS}	PBIAS	R^2
2004-2008	0.825	3.631	1.004	0.988	3.890	0.989	0.940 (Very Good)	-19.724 (Good)	0.963
2010-2013	1.113	4.737	1.282	1.220	4.190	1.190	0.941 (Very Good)	-9.633 (Very Good)	0.950

Table: 11
Model output for identification of the critical sub-watersheds (2010-2013)

SWS	Area (km^2)	Rainfall (mm)	Runoff (mm)	Sediment Yield (t $ha^{-1}yr^{-1}$)	Soil erosion class	Priority
1.	184.88	1110	77	1.67	Slight	11
2.	149.48	1110	61	0.99	Slight	13
3.	176.53	1110	157	6.82	Moderate	8
4.	54.05	1001	246	18.18	High	1
5.	150.78	586	16	1.10	Slight	12
6.	96.77	530	32	8.44	Moderate	6
7.	227.13	575	11	0.84	Slight	14
8.	254.73	980	137	15.55	High	2
9.	207.63	980	134	9.42	Moderate	5
10.	139.72	654	58	10.17	High	4
11.	411.92	1000	263	14.73	High	3
12.	62.56	654	72	6.61	Moderate	9
13.	77.60	923	231	7.07	Moderate	7
14.	16.26	926	204	5.41	Moderate	10

WS-14 fell under moderate soil loss group of soil erosion classes (5 t $ha^{-1}yr^{-1}$ to 10 t $ha^{-1}yr^{-1}$). The WS-4, WS-8, WS-10, and WS-11 fell under high soil loss group of soil erosion classes (10 t $ha^{-1}yr^{-1}$ to 20 t $ha^{-1}yr^{-1}$), whereas other sub-watersheds fell under slight erosion classes. The sub-watershed WS-4 resulted in maximum sediment yield (18.18 t $ha^{-1}yr^{-1}$). On the basis of average annual sediment yield of this study, sub-watersheds WS-4, WS-8, WS-11, and WS-10 were considered as critical watersheds and categorized under high priority for adoption of conservation measures to reduce soil loss and runoff.

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