STM JOURNALS

Research & Reviews: Journal of
Ecology

ISSN: 2278-2230
Volume 14, Issue 1, 2025
January–April
DOI (Journal): 10.37591/RRJoE

https://journals.stmjournals.com/rrjoe

Research RRJoE

Identification and Prioritization of Critical Erosion Prone and Water Potential Areas of Manandragarh Watershed Using HEC-HMS for Management

Karnika Dwivedi[1,*], M. P. Tripathi[1]

Abstract

This study was carried out at Indira Gandhi Krishi Vishwavidyalaya, Raipur (CG) on hydrological modelling and development of soil and water conservation plan for critical erosion prone and water potential sub-watersheds of Manendragarh watershed of upper Hasdeo subbasin in Chhattisgarh using Hydrological Engineering Centre-Hydrological Modelling System (HEC-HMS). The Hydrological Engineering Centre-Geo Hydrological Modelling System (HEC-Geo HMS) was utilized for developing the model setup, while the HEC-HMS model was employed to simulate monthly stream discharge and sediment concentrations within the Manendragarh watershed. After thorough validation, the HEC-HMS model was applied to identify and prioritize critical sub-watersheds prone to erosion and assess their water resource potential. Geographic Information System (GIS) tools were used to create watershed and sub-watershed boundaries, along with slopes, drainage, and soil maps. The watershed was divided into 28 sub-watersheds based on topographical and drainage characteristics derived from the Digital Elevation Model (DEM). The model was calibrated using data from six monsoon seasons (2000–2005) and validated with data from four subsequent monsoon seasons (2006–2009) to simulate monthly stream discharge and sediment yield. The calibration and validation results demonstrated a strong correlation between observed and simulated hydrographs for both variables. Based on graphical and statistical evaluation metrics, the HEC-HMS model's calibration showed that simulated monthly stream discharge and sediment yield closely matched observed values during the monsoon months of 2000–2005. Similarly, during the validation period (2006–2009), the model's simulated values aligned well with the observed data. Key parameters, including Initial Abstraction (Ia), Curve Number, Lag time (Tlag), Muskingum K and X, Erodibility factor (K), Slope length factor (LS), Cover factor (C), and Soil Conservation Practice factor (P), were calibrated to values of 20 mm, a 2% decrease for agricultural cover, a 5% decrease for forest and settlement areas, 110, 0.13 and 0.03, 0.26, 2, 0.05, and 0.5, respectively. These findings indicate that the model is effective for simulating monthly stream discharge from the Manendragarh watershed within the Hasdeo Subbasin.

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Received Date: October 23, 2024
Accepted Date: December 25, 2024
Published Date: December 31, 2024

Citation: Karnika Dwivedi, M. P. Tripathi. Identification and Prioritization of Critical Erosion Prone and Water Potential Areas of Manandragarh Watershed Using HEC-HMS for Management. Research & Reviews: Journal of Ecology. 2025; 14(1): 26–44p.

Keywords: Critical watershed, DEM, HEC-HMS, sediment yield, water potential areas

INTRODUCTION

In Chhattisgarh, 84% of the available water is utilized for agriculture and related activities, while approximately 34% of the state's geographical area (46.51 lakh hectares) is under net cultivation. Annually, around 46,000 million cubic meters of water are lost as runoff, and about 7 million hectares of land experience degradation. Developing an effective plan for soil and water conservation, along with their sustainable use, is essential for the holistic development of watersheds. This can be achieved effectively by leveraging existing computer models of watershed hydrology. Implementing management practices should ideally begin with the most critical sub-watershed, necessitating the prioritization of sub-watersheds. Watershed prioritization involves ranking sub-watersheds in order of urgency for implementing treatment and soil and water conservation measures.

Numerous studies [1–4] have demonstrated the effectiveness of Hydrological Engineering Centre-Hydrological Modelling System (HEC-HMS), RS, and Geographic Information System (GIS) techniques in characterizing and prioritizing watershed areas. While a sub-watershed may be given top priority for various reasons, the severity of land degradation is commonly used as the primary criterion. This approach of watershed prioritization is based on actual measurement of sediment yield rates which may be possible only when the less number for sub-watersheds to be prioritized and required sediment data can be obtained easily.

Hammouri and Naqa (2007) [5] have done their study on estimation of runoff and sediment from a small ungauged watershed. They also highlighted the difficulties faced by the researchers in their modelling due to their nonlinearity and scaling problems. They found that the hydrologic connectivity decreased because of infiltration and deposition of sediment and hence suggested that in these cases it became very important to use tools like models simulating these parameters to estimate runoff and soil losses from watersheds.

Kaffas and Hrissanthou (2015) [6] estimated the continuous sediment graphs by using composite mathematical model of a basin of Kosynthos river. Their main study was performed to study soil and stream bed erosion processes and to draw comparison between sediment load values and measured field values. When, in a watershed the sediment yields of different sub-watersheds do not vary appreciably, then the other methods, especially the empirical models, cannot be useful for prediction of sediment yield precisely.

Looking to the importance of HEC-HMS and its applicability, a study was carried out at Indira Gandhi Krishi Vishwavidyalaya, Raipur for identification and prioritization of critical erosion prone and water potential areas of Manandragarh watershed of Hasdeo subbasin in Chhattisgarh using HEC-HMS for management purpose. The HEC-HMS model can precisely determine the runoff and sediment yield under such situation. In this study, the identification of critical sub-watershed was done based on the simulated average annual runoff and sediment yields by HEC-HMS model for the years 2010–2018 [7]. The critical sub-watersheds were also verified by the prioritized rank done based on slope and runoff analysis of the watershed. Contribution of runoff per unit area of sub-watersheds to the total runoff was also considered for identification and prioritization of critical erosion prone and water potential sub-watersheds [8].

METHODS AND MATERIALS

The upper Hasdeo subbasin (Manendragarh watershed) was selected for the present study which lies between 23°8'N and 23°37'N latitudes and 82°8'E–82°33'E longitudes. The geographical area of Manendragarh watershed is 1023.96 km^2 which lies between 820 04' and 820 20' 16" of East longitude and 230 03' 0"–230 18' 19" of North latitude with altitude of 351–989 m above MSL. The location of study watershed in India and Chhattisgarh is shown in Figure 1. The average slope of the watershed is 12%. The Hasdeo river is the largest stream of watershed. Manendragarh is fifth order watershed.

Digital Elevation Model (DEM) is a set of databases which represents the relief of a surface between the points of known elevations. The DEM used for current study was downloaded from the website https://vertex.daac.asf.alaska.edu (Alaska Satellite Facility DAAC, 2015). The length-slope factor, slope gradient, watershed and sub-watershed boundaries, and drainage patterns were derived from the DEM, necessitating the use of highly reliable techniques and data sources for its creation.

The DEM of the Manendragarh watershed is illustrated in Figure 2. The maximum elevation of 989 m and minimum elevation of 361 m are depicted in white and dark black color, respectively in the DEM (Figure 2). Topographic maps of 1:50,000 scales were acquired from Geospatial Data Centre, Survey of India, Raipur for the preparation of base map (location of villages, towns, cities and drainage network). The soil texture map of the study area was developed using 10 km grid data obtained from NBSS and LUP, Nagpur. Additionally, shape files of the soil data were sourced from the Chhattisgarh State Watershed Management Agency, Government of Chhattisgarh, Raipur. The soil map of the study watershed is presented in Figure 3.

To prepare the land use/cover map for calibrating and validating the HEC-HMS model, two LISS-IV images dated October 23, 2009, and November 16, 2009, were utilized. Land use refers to human activities and the purposes for which land is employed, while land cover pertains to natural features like vegetation, water bodies, soil, rocks, and man-made structures resulting from environmental changes. Cloud-free LISS-IV images from 2009 were downloaded from the Earth Explorer website. The land use/cover map of the study area was created using ERDAS IMAGINE 2016 software. A supervised classification method, specifically the Maximum Likelihood Classifier (MLC) module, was applied for land use categorization. Ground Control Points (GCPs) were used to assist in the classification process. The 2009 land use/cover map of the study area is depicted in Figure 4.

In this research, workstation fitted with Window 7 Processor, ERDAS IMAGINE 2016 image processing program, Arc GIS version 10.4 available at the Department of Soil and Water Engineering, FAE, IGKV, Raipur was used for analysis of DEM, preparation of land use/cover and soil maps. The program has been created using Java programming Language in HEC-HMS model which can run on almost any operating system available was used for identification and prioritization of critical sub-watersheds of Manendragarh watershed. The software Arc GIS developed by ESRI (Environmental Systems Research Institute) Redlands, California, USA was used in present study for stacking different thematic layers into a sequence, and for performing various operations, such as overlaying, intersection, etc. to generate HEC-Geo HMS compatible input files. The latest version of Arc GIS 10.4 was used in this study. HEC-Geo HMS (Version 10.3) which is an extension package of Arc Map software having geospatial hydrology toolkit with few GIS experience. In this study, HEC-Geo HMS was used to obtain the river network of the study area and to delineate sub-basins using DEM. HEC-HMS (Version 4.2.1) is hydrologic modeling software developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers. It incorporates well-established hydrologic methods for simulating rainfall-runoff processes in river basins. The software HEC-HMS (v 4.2.1) [9] was downloaded from the website: http: www.hec.usace.army.mil/software/hec-hms.

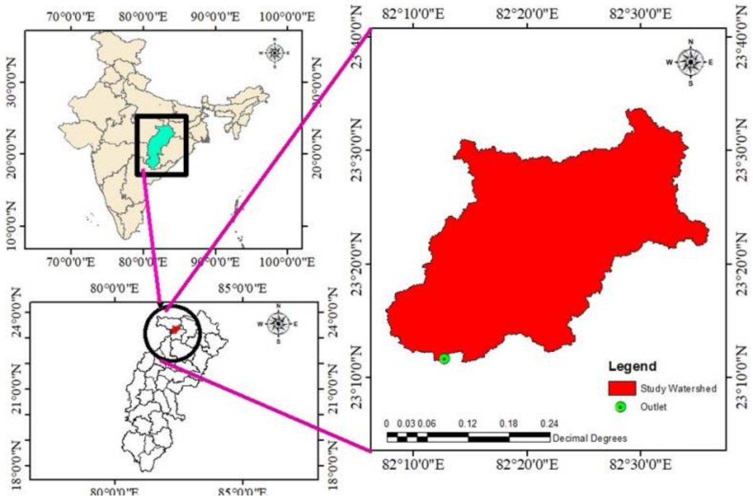

Figure 1. Location of Manendragarh watershed in Chhattisgarh, India.

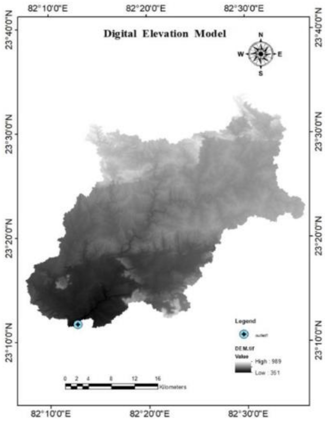

Figure 2. DEM of the Manendragarh watershed.

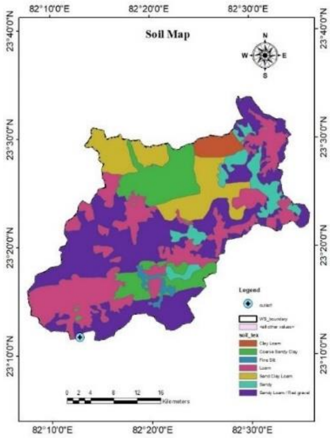

Figure 3. Soil map of the Manendragarh watershed.

Using the Spatial Analyst Tools (hydrology tool) in ArcGIS10 software, drainage channels and other parameters were extracted. The automated stream delineation method followed a series of steps, i.e., DEM, filling, accumulation flow, order stream, and network drainage. Map creation, scanning, geo-referencing, spatial data, and topology creation are the steps involved as shown in Figure 4 are extraction of drainage maps of Manendragarh watershed, Figure 5 shows the drainage map delineated for the study watershed. The entire catchment is decomposed into 28 sub-watersheds based on topography. Each stream segment was considered for delineation for this purpose; flow direction and stream link grids were used as input. The sub-watershed map of Manendragarh watershed is shown in Figure 6.

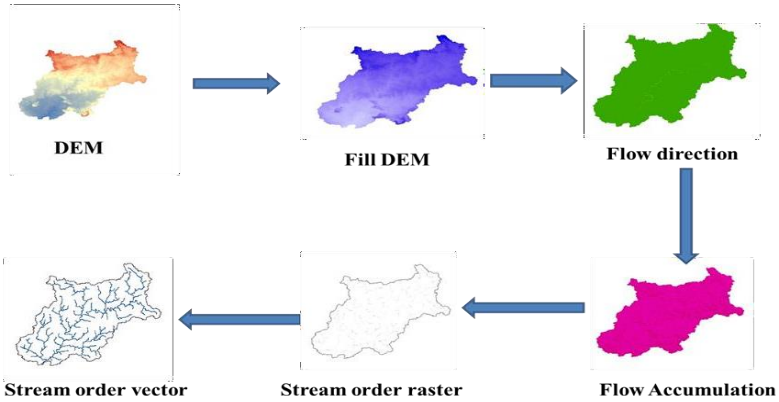

Figure 4. Steps for extraction of drainage network.

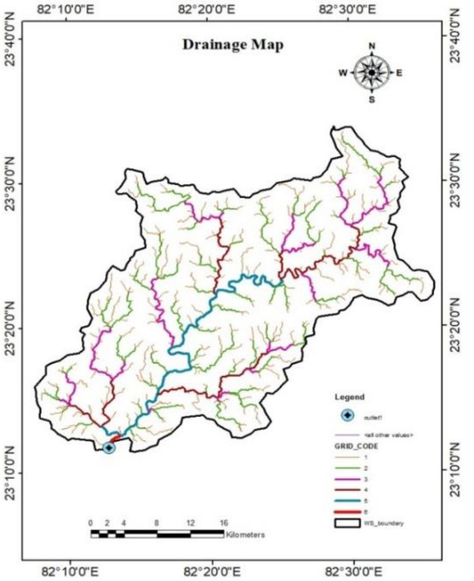

Figure 5. Drainage network and stream ordering of Manendragarh watershed.

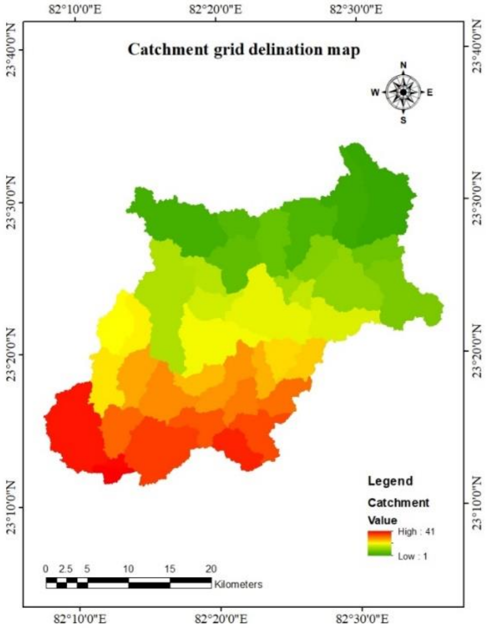

Figure 6. Sub-watersheds map of Manendragarh watershed.

Land Use/Cover (LULC): The cloud free LISS- IV imagery of the years 2009 were downloaded from Earth Explorer website. The land use/cover map of the study area was developed using ERDAS IMAGINE 2016. The study employed the widely used supervised classification method, utilizing the MLC module to categorize land uses. The classification was carried out using GCPs. The land use/cover map of the year 2009 is shown in Figure 7. The classified land use/cover classes were deep water body, shallow water body, barren land, current fallow, settlement, lowland paddy, upland crops, midland crops and forest. The area covered by each class as identified by supervised classification was found to be 34.39 km^2, 37.27 km^2, 133 km^2, 49.28 km^2, 130.34 km^2, 86.42 km^2, 96.23 km^2, 53.15 km^2, 47.27 km^2, 192.28 km^2, and 110.18 km^2 respectively under deep water body, shallow water body, dense forest, settlement, sand dune, low land crop, barren land, fallow land, mid land crop, open forest, and upland crop.

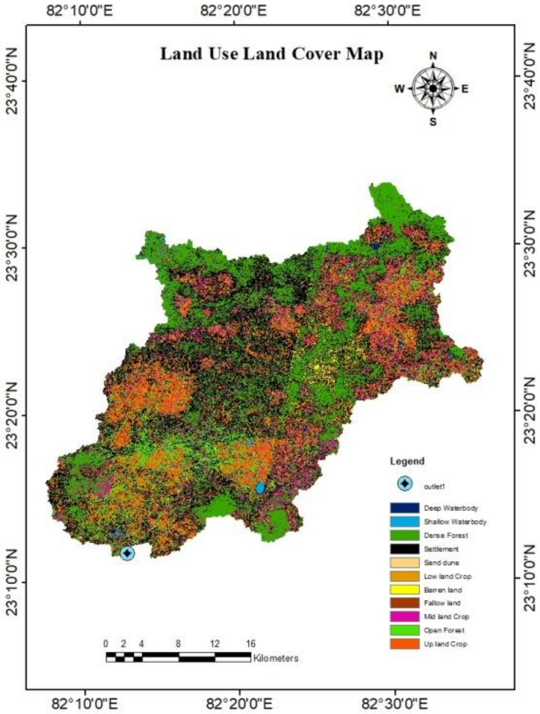

Figure 7. Land use/cover map of the Manendragarh watershed

Curve Number (CN) Generation

Curve Number (CN) is used in loss module of HEC-HMS model. The CN) module was initially derived by combining the LULC and soil maps. It was then refined in HEC-HMS through a trial-and-error approach. Several steps were undertaken to generate CN grids for the study area using LULC and Hydrological Soil Group (HSG) maps. First, vectorization of both the LULC and HSG maps was carried out, followed by a union operation to create polygons representing unique combinations of the two maps in ArcGIS. Next, CN values were assigned to these unique polygons through a query operation in ArcGIS, leading to the creation of a CN grid map. The CN for each sub-watershed was subsequently determined, and the resulting CN grid map is shown in Figure 8.

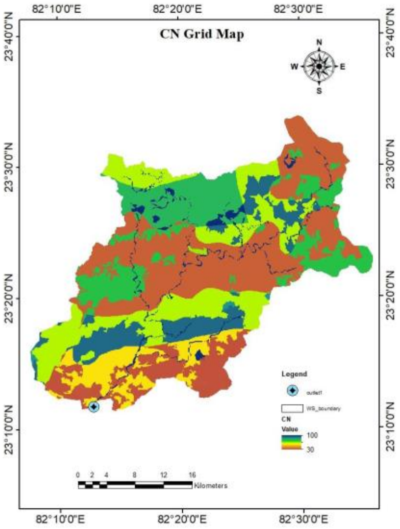

Figure 8. CN grid map of Manendragarh watershed.

SELECTION OF MODELLING METHODS

The methods chosen for various components of the runoff process, including runoff volume, direct runoff, base flow, and channel routing, in event-based hydrological modeling are summarized in Table 1. These methods were selected based on their applicability, limitations, data availability, suitability for similar hydrological conditions, reliability, stability, widespread acceptance, and recommendations from researchers. A detailed description of each method, along with its applications and limitations, is provided following the Table 1.

Table 1. Selected methods for runoff components in event based hydrological modeling.

Hydrological Element	Calculation Type	Method
Subbasin	Runoff volume	SCS curve number (CN)
	Direct runoff	SCS Unit hydrograph method
	Base flow	Exponential recession method
Reach	Routing	Muskingum method
Sediment	Subbasin	Modified USLE
	Reach	Volume Ratio

HEC-HMS Hydrological Model

HEC-HMS is a hydrological simulation software developed by the U.S. Army Corps of Engineers (USACE, 2010). It is a semi-distributed, physics-based model designed to simulate rainfall-runoff processes across diverse geographic areas, ranging from large river basins used for water supply to flood hydrology and runoff in smaller urban and natural river basins. For this study, HEC-Geo HMS Version 10.3 and HEC-HMS Version 4.2.1 were employed.

SCS CN Method

It is a simple, predictable and stable method used for estimating excess precipitation as a function of cumulative precipitation, soil cover, land use, and antecedent moisture [10]. The equation is as follows.

$$\mathrm{P_e} = \frac{(P-I_a)^2}{(P-I_a+s)} \tag{1}$$

where Pe represents the accumulated precipitation excess at time t, while P is the total rainfall depth at time t. Ia denotes the initial abstraction, which refers to the initial loss due to interception, evaporation, detention, and infiltration before runoff begins. S represents the potential maximum retention, or the watershed’s capacity to absorb and retain storm precipitation. Based on the analysis of results from various small experimental watersheds, the SCS established an empirical relationship between Ia and S as follows:

$$\mathrm{Ia} = 0.2\mathrm{S}. \tag{2}$$

Therefore, the cumulative excess precipitation at time t is:

$$P_e = \frac{(P-0.2S)^2}{(P-0.8S)} \text{ subject to P } \geq 0.2S \text{ otherwise } P_e = 0. \tag{3}$$

The CN value ranges from a minimum of zero to a maximum of one hundred, although it can be zero for permeable impervious surfaces. The incremental excess for a given time interval is calculated as the difference between the accumulated excess at the start and end of the period. The maximum potential retention (S) and watershed characteristics are linked by an intermediate parameter known as the CN. This index represents a combination of the HSG, land treatment classes, and antecedent moisture conditions.

SCS Unit Hydrograph Method

The Soil Conservation Service (SCS) introduced a parametric unit hydrograph (UH) model in HEC-HMS. This dimensionless UH is defined as the ratio of the UH discharge (Ut) to the peak discharge (Up) of the UH, for any given fraction of time (t) relative to the peak time (Tp).

Exponential Recession Method for Base Flow

The Exponential Recession Model in HEC-HMS is used to represent the base flow of a watershed, describing the drainage from natural storage within the watershed. It establishes a relationship between Qt (the base flow at any given time t) and an initial base flow value. The model employs a simple finite difference approximation of the continuity equation, like the modified plus model.

$$Q_t = Q_0^{Rt} \tag{4}$$

where Q0 = represents the initial base flow at time t = 0, which is a user-specified value (Figure 9), and Rt is the exponential decay constant. In HEC-HMS, k is defined as the ratio of the base flow at time t to the base flow one day earlier. The initial base flow value, Q0, serves as the model's starting condition.

In HEC-HMS, the base flow model is applied both at the beginning of a storm event simulation and later as the delayed subsurface flow reaches the watershed channels, as illustrated in Figure 10. A user-defined threshold flow determines the point at which the recession model (Eq. (4)) begins to define the total flow.

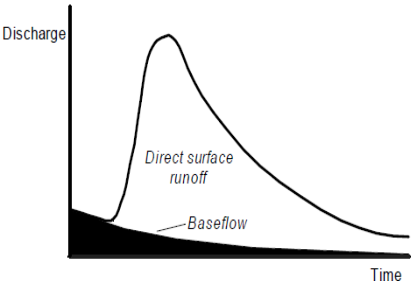

Figure 9. Initial base flow recession.

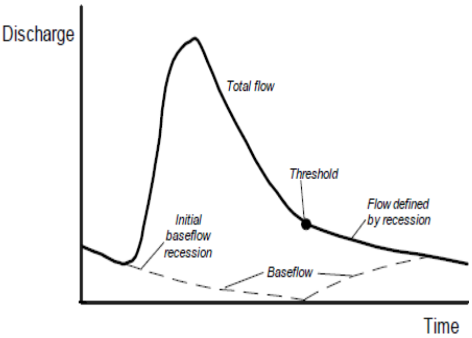

Figure 10. Base flow model illustration.

Estimation of Base Flow Model Parameters

The parameters of the exponential recession model include the initial base flow (Qo), recession constant (Rc), and threshold flow (Qt). The initial base flow (Qo) is typically estimated through field inspection. For analyzing hypothetical storm runoff, it is advisable to select an initial flow that represents the average flow likely to occur at the beginning of the storm runoff event. The recession constant (Rc) is determined from observed flow hydrographs and depends on the source of the base flow. The threshold flow (Qt) is the flow value at which the recession model begins to define total flow, marking the transition point for the base flow dynamics [11]. Typical values for different flow constants are provided in Table 2. When k = 1.00, the base flow contribution remains constant, meaning Qt = Q0. However, for natural watersheds, the value of k must be less than 1.00. The threshold flow (Qt) is estimated from the observed flow hydrograph, specifically at the point where the recession limb is best approximated by a straight line. This threshold flow is critical for accurately representing the transition between base flow and direct runoff in the model.

Table 2. Typical recession constant values.

Flow Component	**Recession Constant, Daily**
Groundwater	0.950
Interflow	0.8–0.9
Surface runoff	0.3–0.8

Modified Universal Soil Loss Equation (MUSLE)

Modified Universal Soil Loss Equation (MUSLE) [12] method is a good integration for the methods in HEC-HMS due to its runoff energy factor concept (Pak et al., 2008). HEC-HMS sediment calculation using MUSLE requires soil erodibility (K), topography (LS), cover management (C), practice factor (P), and gradation curve. The MUSLE is given by

$$Sed = 11.8\left(q_{surf} + q_{peak}\right)^{0.56} K.LS.C.P \tag{5}$$

where, Sed, Qsurf, and qpeak are the sediment yield for a given event, the surface runoff volume, and the peak runoff rate, respectively.

MUSKINGUM Model for Channel Routing

It uses a straightforward finite difference approximation of the continuity equation, similar to the modified plus model. The model is:

$$\frac{(I_{t-1}+I_t)}{2} + \frac{(O_{t-1}O_t)}{2} + \frac{(S_t - S_{t-1})}{\Delta t} \tag{6}$$

where I = inflow rate (m3/s), O = outflow rate (m3/s) and S = storage (m3).

Catchment Grid Delineation

The entire catchment is decomposed into 28 sub-watersheds. Each stream segment was considered for delineation and for this purpose flow direction and stream link grids were used as input. The drainage map and sub-watershed map are presented in Figures 5 and 6, respectively. During Catchment Polygon Processing, a vector layer (polygon subbasin layer) for each subbasin is generated using the catchment grid.

$$S_t = KQ_t\,(It - Q_t) = K[X\,It + (1 - X)Q_t\,] \tag{7}$$

where K= Travel time of the flood wave through routing reach; and X= Dimensionless weight (0 ≤ X ≤ 0.5). If Equation (6) is substituted into Equation (7) and the result is rearranged to isolate the unknown values at time t, the result is:

$$O_t = \left(\frac{\Delta t - 2KX}{2K(1-X)+\Delta t}\right) I_t + \left(\frac{\Delta t + 2KX}{2K(1-X)+\Delta t}\right) I_{t-1} \left(\frac{2K(1-X)-\Delta t}{2K(1-X)+\Delta t}\right) O_{t-1} \tag{8}$$

HEC-HMS solves Equation (8) recursively to compute ordinates of the outflow hydrograph given the inflow hydrograph ordinates (It for all t), an initial condition (Ot = 0), and the parameters, K and X.

Estimating the Muskingum Model Parameters

If observed inflow and outflow hydrographs are available, parameter K can be determined by calculating the interval between corresponding points on the inflow and outflow hydrographs. Once K is known, parameter X can be estimated through trial and error. The value of X ranges from 0 to 0.5. Experience suggests that for channels with gentle slopes and over-bank flow, X tends to approach 0.0. For steeper streams with well-defined channels that do not experience over-bank flow, X will be closer to 0.5. Most natural channels have an X value somewhere between these two extremes. X is estimated as [13].

SELECTION OF HEC-HMS ROUTING METHODS

Each routing model incorporated in HEC-HMS solves the momentum and continuity equations, but it simplifies or omits certain terms of these equations to provide a solution. To choose the most suitable routing model, the following assumptions are typically considered:

a. *Backwater effects:* The Muskingum models cannot account for the influences of backwater on the flood wave, because this is based on uniform-flow assumptions. This method is not suitable for a river basin model while this method is suitable for small watershed runoff where backwater effect is negligible.
b. *Floodplain storage:* The Muskingum model can be calibrated to match the peak flow and timing of a specific flood magnitude.
c. *Configuration of flow networks:* In a dendritic stream system, if the tributary flows or the main channel flows do not cause significant backwater at the confluence of the two streams, any of the hydraulic or hydrological routing methods can be applied.
d. Interaction of channel slope and hydrograph characteristics.
e. Occurrence of subcritical and supercritical flow.
f. Availability of data for calibration.

Identification and Prioritization of Critical Sub-watersheds

It is crucial to begin management efforts with the most critical sub-watershed, which necessitates prioritizing the available sub-watersheds. Watershed prioritization involves ranking the critical sub-watersheds based on the order in which they should be addressed for treatment and soil and water conservation measures. A specific sub-watershed may be given top priority for various reasons, but typically, the severity of land degradation is used as the primary criterion. This approach of watershed prioritization is based on actual measurement of sediment yield rates which may be possible only when the less number for sub-watersheds to be prioritized and required sediment data can be obtained easily. When, in a watershed the sediment yields of different sub-watersheds do not vary appreciably, then the other methods, especially the empirical models, cannot be useful for prediction of sediment yield precisely. But the HEC-HMS model can precisely determine the sediment yield under such situation.

In this study, the identification of critical sub-watershed was done based on the simulated average annual sediment yields by HEC-HMS model for the years 2010–2018.

Priorities were established by ranking each critical sub-watershed based on its susceptibility to erosion and average annual soil loss, as outlined in Table 3 [14]. The critical sub-watersheds were also verified by the prioritized rank done based on slope and runoff analysis of the watershed. Contribution of runoff per unit area of sub-watersheds to the total runoff was also considered for identification and prioritization of critical erosion prone and water potential sub-watersheds. Runoff contribution per unit area of each sub-watershed to the total runoff of the watershed was also considered for identification of critical erosion prone and water potential area. Contribution of runoff from 0 to 1 m3/s considered as low, 1.1–6 m^3/s as medium and more than 6.1 m^3/s as high water potential zone.

Table 3. Area under different classes of soil erosion by water in India.

Soil Erosion Classes	**Slight**	**Moderate**	**High**	**Very High**	**Severe**	**Very Severe**
Soil erosion range (t/ha/yr)	0–5	5–10	10–20	20–40	40–80	>80
Area (km^2)	801,350	1,405,640	805,030	160,050	83,300	31,895

RESULTS AND DISCUSSION

Model Calibration

Calibration of HEC-HMS model was done with manual adjustment of various parameters by performing various trial and error runs to achieve acceptable simulation results for the Manendragarh watershed. The values of parameters, such as Ia, CN, Lag time (Tlag), Muskingum K and X, Erodibility factor (K), Slope length factor (LS), Cover factor (C) and Conservation practice factor (P) were chosen within their prescribed ranges for the adjustment. The optimized corresponding values of the different parameters after calibration were found to be 20.0, 2% decrease for agricultural cover and 5% decrease for forest and settlements, 110, 0.13, 0.03, 0.26, 2, 0.05, and 0.5, respectively. The calibrated and model input values of different parameters are presented in Table 4. These values have close agreement with the values of other studies carried out in upper Mahanadi basin using SWAT model [15, 16].

Table 4. Calibrated values of different parameters for study watershed.

Methods/Technique	Parameters	Input Value	Calibrated Values
Loss Rate Parameter	Initial Abstraction (Ia), mm	23.4	20.0
	Curve Number (CN)	Varies	2% decrease in agricultural cover and5% decrease for forest and settlements
Transform Parameter	Lag time (Tlag), min	110	110
Routing Method Constants	Muskingum (K), hr	0.23	0.13
	Muskingum (X)	0.27	0.03
Sediment method	K	0.07	0.26
	LS	1.6	2
	C	0.45	0.05
	P	1	0.5
	Threshold (m^3/s)	1	1

Simulation of Monthly Stream Discharge

In this study HEC-HMS model was calibrated for monthly simulation of stream discharge at the outlet of the Manendragarh watershed during monsoon season (June to October) for the years 2000–2005. The graphical comparison of observed and simulated monthly stream discharge is shown in Figure 11. It showed that the trend was similar between observed and simulated monthly stream discharge in all the months during calibration period. Further the efficiency of model for simulating monthly stream discharge was carried out by evaluating the results by regression analysis as shown in Figure 12. The uniform distribution of observed and simulated values of monthly stream discharge showed that model simulation results are very good. The values of r2, PBIAS, and ENS were found to be 0.930, 1.702, and 0.920 (Table 5). Results of Student's t-test revealed that monthly values of means observed (803.63 m^3/s) and simulated (828.57 m^3/s) sediment yields were found to be similar at 95% confidence level (Table 5). Similar results have been reported by the previous researchers for simulation of daily and monthly sediment yield using HEC-HMS [17].

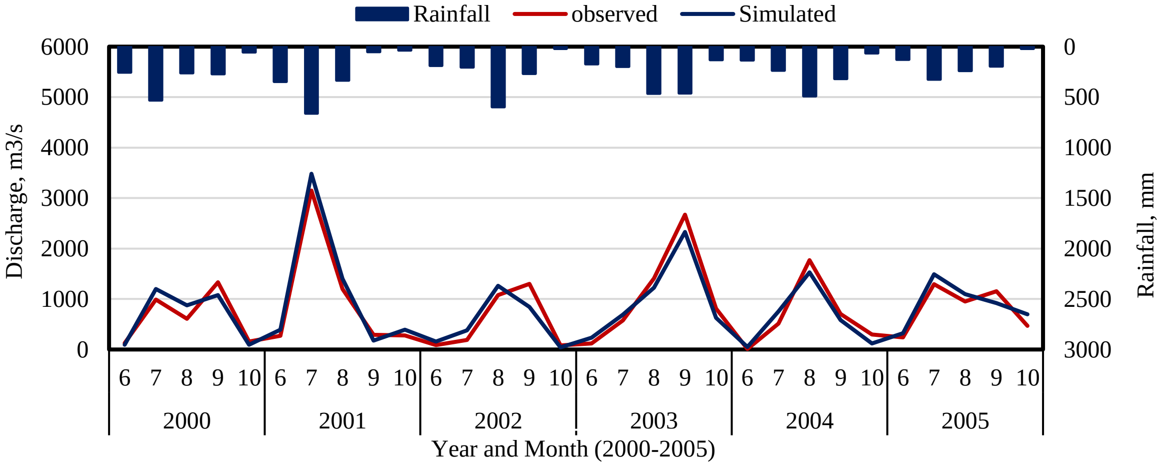

Figure 11. Graphical comparison of simulated and observed monthly discharge (calibration run).

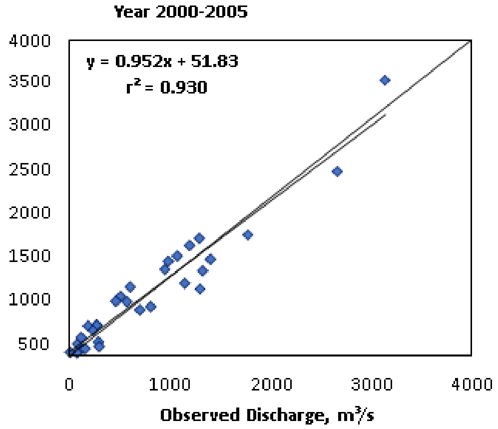

Figure 12. Scattergram of monthly discharge (Calibration run 2000–2005).

Table 5. Descriptive statistics for monthly discharge (m^3/s) for calibrationrun.

Statistical Parameters	**2000–2005**	
	Observed	Simulated
Mean	803.63	828.57
Maximum	3148.71	3261.54
Std Dev	755.04	731.11
Count	30	30
r^2	0.930	
ENS	0.920	
t-critical	2.045	
t-statistical	–0.230	
PBIAS	1.702	

Simulation of Monthly Sediment Yield

Monthly sediment yield simulation was done by the model for the monsoon months of 6 years (from 2000 to 2005). The comparison of observed and simulated values of monthly sediment yield is depicted in Figure 13, which showed that trends of sediment yields were very similar. Time to peaks and quantum were also matching with each other. Results of Student's t-test revealed that monthly values of observed (1.129 t/ha) and simulated (1.076 t/ha) sediment yields were found to be similar at 95% confidence level (Table 6). Overall deviation (9.49%) based on BIAS value indicated that the simulated monthly sediment yield compared well with observed sediment yield.

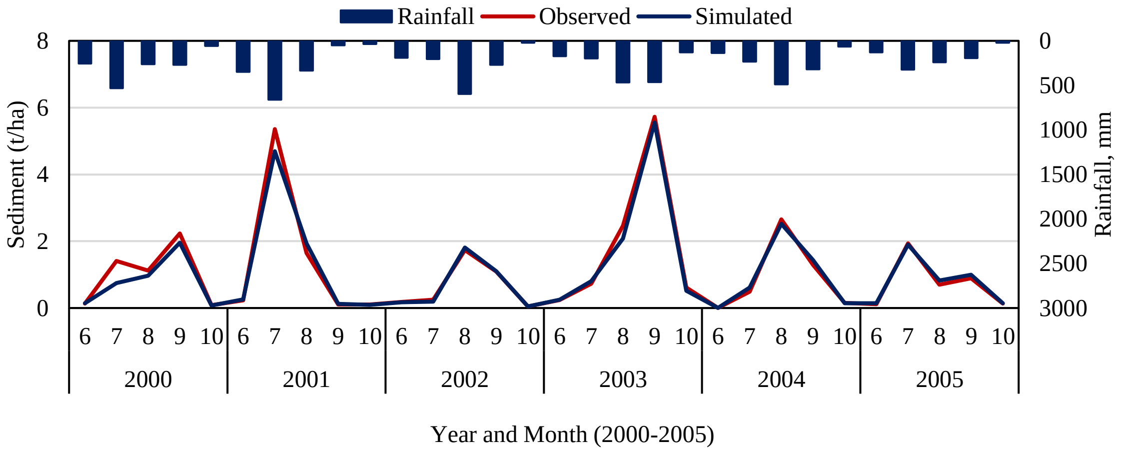

Figure 13. Graphical comparison of simulated and observed monthly sediment yield (calibration run).

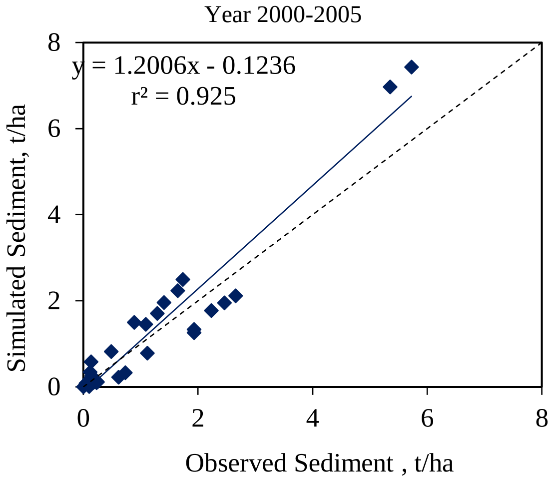

Figure 14. Scattergram of monthly sediment yield (calibration run 2000–2005).

Result of regression analysis indicated that the values of observed and simulated monthly sediment yield are distributed uniformly along the 1:1 line (Figure 14). The values of r2 and ENS were found to be 0.925 and 0.840, respectively also indicated the close agreement between observed and simulated values of monthly sediment yield. Similar results have been reported by the previous researchers for simulation of daily and monthly sediment yield using HEC-HMS [18].

Table 6. Descriptive statistics of monthly sediment yield (t/ha) for calibration run.

Statistical Parameters	**2000–2005**	
	Observed	**Simulated**
Mean	1.129	1.076
Maximum	5.726	5.552
Std Dev	1.434	1.331
Count	30	30
r^2	0.925	
ENS	0.840	
t-critical	2.045	
t-statistical	1.389	
PBIAS	9.490	

MODEL VALIDATION

Simulated Monthly Stream Discharge

The observed and simulated monthly stream discharge was also analyzed for evaluating the model validation performance for the study watershed. The graphical comparison of monthly discharge of the monsoon months of the year 2006–2009 is shown in Figure 15, whereas scattergram along with regression and 1:1 line is shown in Figure 16. The descriptive statistics for the monthly validation performance of the model are given in Table 7. Data depicted in Figure 15 clearly showed that simulated monthly peaks were close to observed stream discharge peaks for most of the months. Moreover, distribution of observed and simulated monthly discharge were found to be uniform along 1:1 line with coefficient of determination (r2 = 0.920) very close to 1. Results of statistical analysis indicated that the model was slightly over simulating monthly discharge as the deviation was found to be 1.702% (Table 7). Also, the difference between measured and simulated means of monthly discharge was found to be almost same as t-calculated (2.093) is lower than t-critical (0.340) at 95%

confidence level. The high value of ENS (0.940) indicates comparatively better performance of the model for simulation of monthly stream discharge (Table 7).

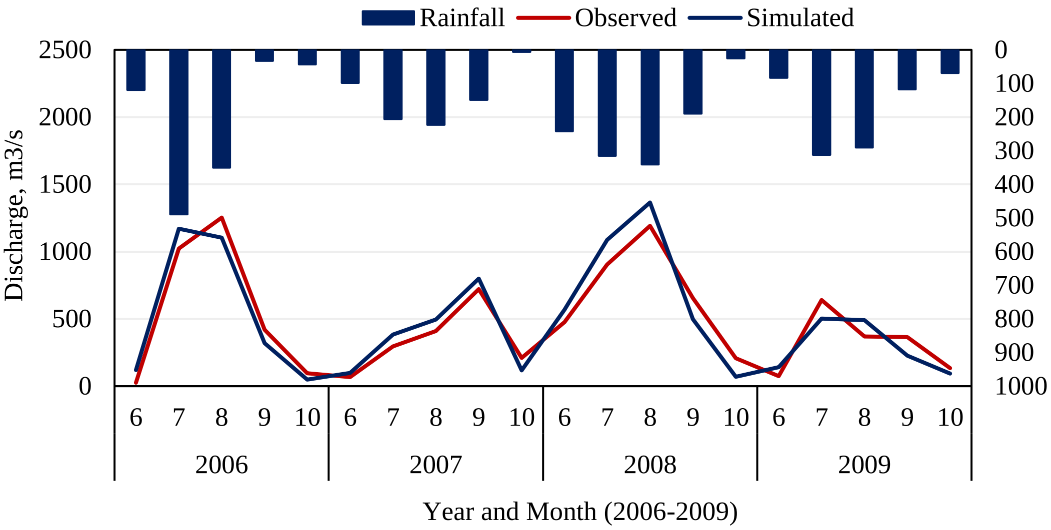

Figure 15. Graphical comparison of monthly discharge of monsoon season (validation run).

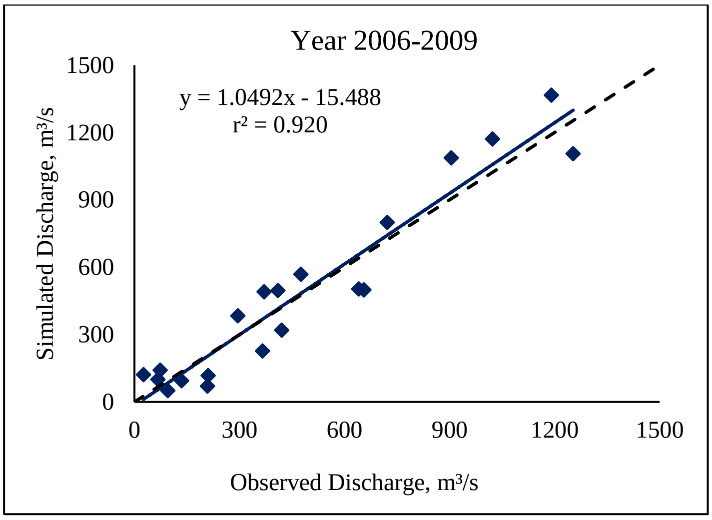

Figure 16. Scattergram of monthly discharge (Validation run 2006–2009).

Table 7. Descriptive statistics of monthly discharge (m^3/s) for validation run.

Statistical parameters	**2006–2009**	
	Observed	**Simulated**
Mean	476.933	480.84
Maximum	1253.05	1244.96
Std Dev	378.15	389.66
Count	20	20
r^2	0.920	
ENS	0.940	
t-Crit	2.093	
t-Stat	0.340	
PBIAS	–1.702	

Simulation of Monthly Sediment Yield

Monthly measured and simulated sediment yields were compared graphically for validation period and shown in Figure 17. The monthly simulated sediment yield was plotted against the measured values, with their distribution along the 1:1 line shown in Figure 18. The predicted sediment yields were evenly distributed along the 1:1 line, both for lower and higher observed sediment yield values. Regression analysis was also performed between the observed and simulated sediment yield values and the best-fit line was drawn as shown in Figure 18. The r2 value of 0.731 indicated good relationship between the measured and simulated monthly sediment yield for the study watershed.

The descriptive statistics for both measured and simulated monthly sediment yields are given in Table 8. The similarity between means of observed and simulated sediment yield was examined by using Student's t-test. The difference between means was not significantly different at 95% confidence level (t-critical = 2.43 > t-statistical = 2.09). The high value of ENS (0.920) indicated that the model was predicting sediment yield accurately for the monsoon months of the year 2006–2009. However, the maximum sediment yield predicted by the model was slightly higher than the observed maximum sediment yield. The value of PBIAS clearly indicates that the HEC-HMS model is over predicting monthly sediment yield by 7.44% which can be well accepted as per model evaluation criteria.

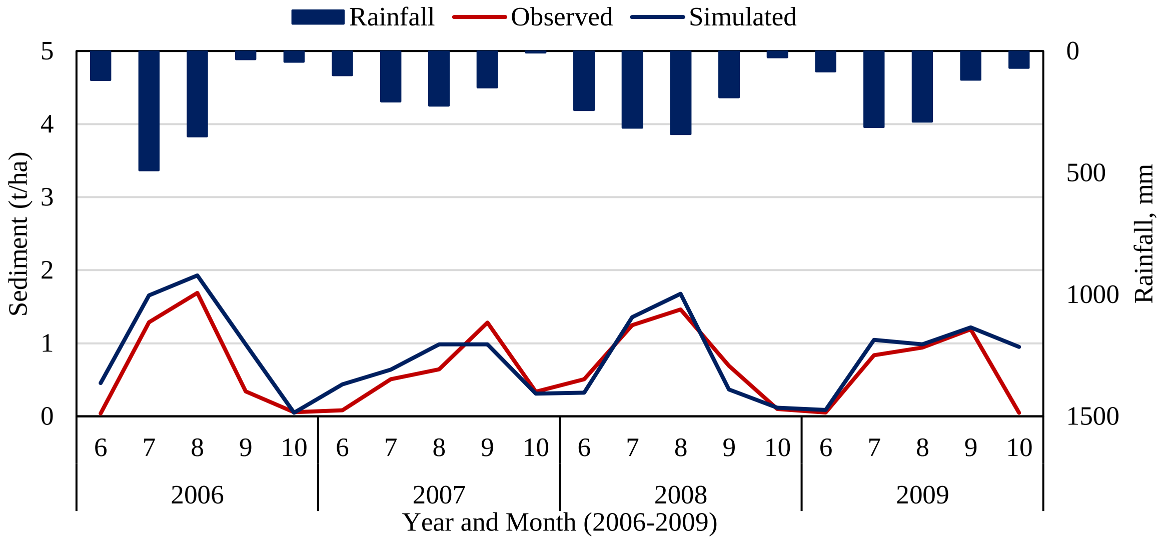

Figure 17. Graphical comparison of monthly sediment yield for the monsoon season (validation run).

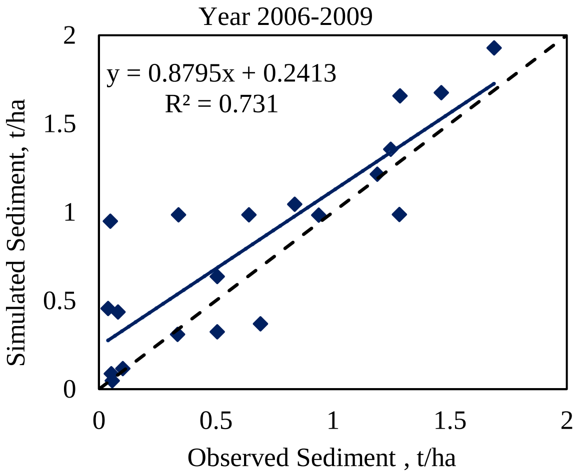

Figure 18. Scattergram of monthly sediment yield (Validation run 2006–2009).

Table 8. Descriptive statistics of monthly sediment yield (t/ha) for validation run.

Statistical Parameters	**2006–2009**	
	Observed	**Simulated**
Mean	0.67	0.83
Maximum	1.69	1.93
Std Dev	0.54	0.56
Count	20	20
r^2	0.731	
E_{NS}	0.920	
t Critical	2.43	
t Stat	2.09	
PBIAS	–7.44	

The calibrated values of CN were found to be 2% less for agricultural cover and 5% less from actual values for calibrated forest and settlements. Calibrated values for other parameters, such as Time lag, C, Practice factor, Muskingum K and X, K, and topographic factors were found as 110, 0.05, 0.5, 0.13, and 0.03, 0.26, and 2.0, respectively. The calibrated values of CN were found to be 2% less for agricultural cover and 5% less from actual values for calibrated forest and settlements. Calibrated values for other parameters, such as time lag, cover factor, Practice factor, Muskingum K and X, K, and topographic factor were found as 110, 0.05, 0.5, 0.13 and 0.03, 0.26, and 2.0, respectively.

Identification and Prioritization of Sub-watersheds

The HEC–HMS model was calibrated and validated successfully for the simulation of stream discharge and sediment yield on daily and for monthly basis for Manendragarh watershed. After successful verification of HEC-HMS model, it was applied for identification of the critical erosion prone and water potential areas (sub-watershed) of Manendragarh watershed. Since HEC-HMS was calibrated and validated adequately for simulating the daily, monthly and seasonal stream discharge and sediment yield at the outlet of the Manendragarh watershed, the watershed was divided into 28 sub-watersheds. Based on the result of model testing it can be assumed that the stream flow (runoff) and sediment yield values simulated by the model for each sub-watershed were also satisfactory and the quantum of these parameters are equal to actual values. Based on this assumption it can be used for further study especially for identification of critical erosion prone and most water potential sub-watersheds of Manendragarh watershed of Hasdeo subbasin in Chhattisgarh. Therefore, models were run for multiple years from 2009 to 2018 using daily rainfall data. The output of the model was utilized for identification of critical erosion prone and water potential sub-watersheds and thereafter for prioritization of critical sub-watershed for effective planning and management. The model simulated runoff and sediment yield of each sub-watershed of Manendragarh watershed along with slope and area are given in Table 9. Based on average values of these parameters obtained through long term (2011–2018) simulation runs of the model, prioritization, and ranking of the sub-watersheds was done for management purpose.

The sub-watersheds were divided into four erosion classes based on sediment yield based on Table 3. In this study different soil erosion classes were utilized for categorization of sub-watersheds as suggested by [14]. These erosion classes were considered based on the annual soil loss rate of the country, such as slightly low (SL), medium (M), high (H), and very high (VH) category. Ten sub-watersheds, i.e., SW6, SW8, SW5, SW18, SW4, SW10, SW3, SW1, SW2, and SW9 fall under slightly low category which do not require any type of management since soil loss was found to be within the permissible limit, i.e., 11.20 t/ha/year (Mannings, 1981). The sub-watersheds SW26, SW7, SW21, SW16, SW23, SW28, SW20, and SW25 fall under moderate category and, therefore, require least management. The sub-watersheds SW15, SW22, SW6, SW27, SW12, SW24, and SW17 fall under high erosion class and need management to bring down the soil loss within the average annual soil loss of the country, i.e., 16.35 t/ha/year [11].

The sub-watersheds SW19, SW13, and SW14 fall under very high erosion class category and considered as critical erosion prone and water potential sub-watersheds and hence, given top priority for the management. Runoff contribution per unit area of each sub-watershed to the total runoff of the watershed was also considered for identification of critical erosion prone and water potential area. Contribution of runoff from 0 to 1 m^3/s was considered as low, 1.1–6 m^3/s as medium and more than 6.1 m^3/s as high water potential zone. The sub-watershed (SW14) was found to be the most critical therefore, it was assigned first rank as runoff and sediment yield in this sub-watershed was found to be the highest. The values of different parameters along with their priority rank of each sub-watershed are provided in Table 9. Identified critical sub-watersheds map of the Manendragarh watershed is shown in Figure 19.

Table 9. Model output for identification of the critical watersheds (2010–2018).

S. N.	**WS Code**	**Area (km^2)**	**Slope (%)**	**CN**	**Runoff (mm)**	**Sediment (t/ha/yr)**	**Soil Erosion Class**	**Water Potential Zone**	**Priority (Ranking)**
1	SW6	26.47	10.76	80	566.20	1.67	SL	I	28
2	SW8	18.20	5.86	75	589.15	1.99	SL	I	27
3	SW5	41.45	9.94	80	702.16	2.10	SL	I	26
4	SW18	22.88	9.04	62	605.16	2.28	SL	I	25
5	SW4	34.74	10.57	80	638.17	2.94	SL	I	24
6	SW10	53.76	6.05	70	630.16	3.60	SL	II	23
7	SW3	56.13	11.04	78	647.64	3.87	SL	II	22
8	SW1	52.01	11.15	65	730.29	4.45	SL	II	21
9	SW2	36.05	12.13	65	637.29	4.64	SL	I	20
10	SW9	69.23	9.35	64	716.16	4.80	SL	II	19
11	SW26	17.48	16.97	43	630.28	6.20	M	I	18
12	SW7	58.93	5.71	70	773.94	6.26	M	II	17
13	SW21	15.19	5.65	74	634.85	6.59	M	I	16
14	SW16	24.84	8.56	74	703.96	7.45	M	I	15
15	SW23	18.23	12.72	64	645.27	8.64	M	I	14
16	SW28	31.42	7.59	63	711.82	8.73	M	I	13
17	SW20	28.71	8.92	70	685.26	9.36	M	I	12
18	SW25	23.04	12.91	50	643.27	9.50	M	I	11
19	SW15	36.64	7.16	63	690.25	10.99	H	I	10
20	SW22	29.14	9.60	72	680.17	12.59	H	I	9
21	SW11	30.49	8.54	66	780.23	12.97	H	I	8
22	SW27	56.04	8.67	42	805.26	13.32	H	II	7
23	SW12	27.32	6.06	66	741.39	13.99	H	I	6
24	SW24	48.29	9.89	40	760.33	14.99	H	II	5
25	SW17	30.08	10.12	73	722.16	17.68	H	I	4
26	SW19	39.66	9.48	64	840.18	20.36	VH	II	3
27	SW13	54.67	7.75	65	810.24	22.53	VH	II	2
28	SW14	44.05	9.21	64	925.17	27.65	VH	II	1

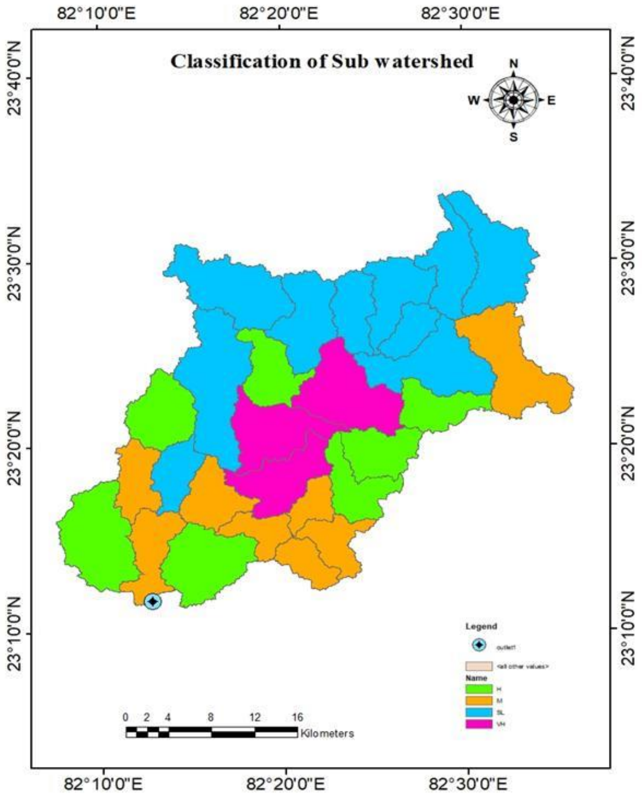

Figure 19. Identified critical sub-watersheds map of the Manendragarh watershed.

CONCLUSIONS

Sub-watersheds W620, W730, W580, W800, W590, W770, and W660 of Manendragarh watershed falls under high erosion class whereas, sub-watersheds W790, W500, W720, W640, W750, W820, W710, and W780 falls under moderate soil loss classes. The sub-watersheds which fall under low soil erosion classes are W480, W510, W470, W690, W450, W570, W440, W420, W430, and W550 whereas the Sub-watersheds W700, W600, and W610 fall under very high erosion class based on annual runoff and sediment yield. The sub-watershed SW610, which produced the highest annual runoff and sediment yield, was selected for developing an optimal water management plan aimed at reducing both runoff and soil loss to within permissible limits. This sub-watershed, with its highest runoff and sediment yield, serves as a priority area for implementing effective water management strategies.

REFERENCES

1. Agrawal N, Verma MK, Tripathi MP. Hydrological modelling of Chhokranala watershed using weather generator with SWAT model. Indian J Soil Conserv. 2011;39(2):89–94.
2. Barik DK, Singh AD. Estimation of runoff and sediment yield from a small ungauged watershed using GIS and HEC-HMS. Int J Civil Eng Technol. 2017;8(6):517–527.
3. Chow VT, Maidment DR, Mays LW. Applied Hydrology, McGraw- Hill Book Company; 1988.
4. Chu X, Steinman A. Event and continuous hydrologic modelling with HEC-HMS. J Irrig Drain Eng. 2009;135(1):119–124.
5. Hammouri N, Naqa AE. Hydrological modelling of ungauged wadis in arid environments using GIS: a case study of Wadi Madoneh in Jordan, Revista Mexicana de Ciencias Geológicas, 2007;24 (2):185–196.
6. Kaffas K, Hrissanthou V. Estimate of continuous sediment graphs in a basin, using a composite mathematical model. Environ Process. 2015;2:361–378.

7. Kumar and Bhattacharjya, 2011. Distributed rainfall runoff modelling. Int J Earth Sci Eng. 2011;04(06):270–275.
8. Linsley RK, Kohler MA, Paulhus JLH. Hydrology for Engineers. New York: McGraw-Hill; 1982.
9. Majidi A, Shahedi K. Simulation of rainfall-runoff process using Green-Ampt method and HEC-HMS model (Case study: Abnama watershed, Iran). Int J Hydraul Eng. 2012;1(1):5–9.
10. Mannering JV. The use of soil tolerances as strategy for soil conservation. In: Soil Conservation Problem and Prospect. Chichester: R.P.C. Morgan John Wiley & Sons; 1981. pp. 337–349.
11. Narayana VVD. Soil and water conservation research in India. New Delhi: Indian Council of Agricultural Research; 1993.
12. Pilgrim DH, Cordery I. Flood runoff. In: Maidment DR, editors. Handbook of Hydrology. New York: McGraw-Hill Inc.; 1992. pp. 9.1–9.42.
13. Singh VP. Computer models of water resources. Publications, P.O.B. 260026, Highlands Ranch, Colorado 80126-0026, USA; 1995.
14. Singh G, Babu R, Narain P, Bhushan LS, Abrol IP. Soil erosion rates in India. J Soil Water Conserv. 1992;47(1):97–99.
15. Tiwari P, Tripathi MP. Calibration and validation of ArcSWAT model for estimation of surface runoff and sediment yield from Dhangaon watershed. J Agric Issues. 2014;19(2):23–34.
16. USACE. (2015). Hydrologic modelling system HEC-HMS, User’s Manual version 4.2 USACE, 2010). Available at http: www.hec.usace.army.mil/software/hec-hms
17. Verma AK, Jha MK, Mahana RK. Evaluation of HEC-HMS and WEPP for simulating watershed runoff using remote sensing and geographical information system. Paddy and Water Environ. 2009;8(2):131–144. doi: 10.1007/s10333-009-0192-8.
18. Williams JR, Berndt HD. Determining the universal soil loss equation’s length slope factor for watershed soil erosion: Prediction and control. Soil Cons Soc Am.1976:217–225.