

Critical Erosion Area Identification Based on Hydrological Response Unit Level for Effective Sedimentation Control in a River Basin

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Abstract Soil erosion is the worldwide most significant threat leading to land degradation and water resources deterioration. Identification and prioritization of critical erosion prone areas is an important consideration for policy makers to implement best management strategies that are more sustainable in future for long term use of these natural resources. The present study focuses to identify the specific erosion prone areas within the watershed with the help of hydrological modeling. SWAT model has been used for the identification of critical erosion areas in the Damodar catchment at two levels: watershed and hydrological response unit (HRUs). The derived spatial prioritization maps at watershed and HRUs level indicated that prioritization at watershed scale is not-sufficient methodology for prioritizing the critical soil erosion regions. The critical area identification and prioritization at HRUs level may be more efficient option to achieve the objective of soil erosion control for the policy makers. The HRUs level based analysis showed that about 67.51 % area of Damodar catchment is under critical erosion condition within which a combination of sandy loam soil with agriculture and wasteland landuse is more prone to soil erosion. The results of this study also indicate that erosion is quite sensitive to landuse and soil type within the watershed with other factor of topography and must be utilize to identify the specific patches for an effective soil erosion management rather than planning of whole watershed management which may be a cost intensive option.

Keywords SWAT · Soil erosion · Watershed · Prioritization · HRUs

1 Introduction

Soil erosion is the most significant land degradation and water resources deteriorating problem in river basins; occurring due to human activities like landuse, soil type, characteristics of rainfall and topography, and natural processes (Pimentel et al. 1995; Yang et al. 2003;

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Parsakhoo et al. 2009; Kabir et al. 2014). Problem has far-reaching to economic, political, social and environmental implications due to both on-site and off-site damages to land resources, water bodies, ecology, and nonpoint source pollution (Grepperud 1995; Wu and Chen 2012) in a river basin. Sediment generated from watersheds through erosion process is transported by runoff into depressions, streams and water bodies resulting high deposition rate (Morris and Fan 1998; Verstraeten and Poesen 1999) and deteriorating water quantity and quality. It is therefore important for soil and water conservation managers to identify the specific erosion prone areas to improve the condition by reducing the erosion and their effects on the environment.

Soil erosion occurs in places where soil is erodible, terrain slope is high, high intensity rainfall occurring on the limited vegetation covers with intensive agriculture activities (Tian et al. 2008; Beskow et al. 2009; Li et al. 2012). Identification of these erosion susceptible areas has high merit in deciding management strategies to reverse the soil erosion process (Tripathi et al. 2003). In earlier studies, measurement and modeling of sediment yield at watershed outlet, providing average useful information concerning what happens in the watershed, have been used to identify and prioritize the critical watershed/sub-watersheds (Mishra et al. 2007; Asres and Awulachew 2010; Besalatpour et al. 2012; Silva et al. 2012; Chatterjee and Krishna 2013). However, these studies do not provide any information about which specific part of the watershed is susceptible to erosion and contributing more sediment to outlet. As the watershed unit is quite a large area, erosion problem is not equally distributed everywhere in the watershed due to variation in terrain, rainfall, land use/land cover (LULC), soil properties and human activities. This approach is not very useful to the resource managers for identifying the specific part of the watershed requiring soil conservation management strategies and often leads to economic loss. To control the erosion problem effectively, resource managers require a more effective technique to demarcate the intensive erosive areas within watershed to implement the management strategy for effective and efficient management of sediment problem.

Hydrological Response Unit (HRU) is one such concept, where the identical hydrological responsive areas are grouped and accounted for runoff, soil erosion and other hydrological behavior in the watersheds. The HRUs are created on the basis of LULC, soil, and land slope condition. Within a watershed, there could be a number of well demarcated HRUs parsing different hydrological behavior depending upon LULC, soil and slope properties; representing the conditions and problems variations better within the watershed. Thus, the HRUs can give better information on critical areas within the watersheds and can be consider for management adaptation at the site specific rather than considering whole watershed. Conservation based on HRUs basis thus, will facilitate specific areas management within the prioritized watershed compared to the random area management based on watershed priority.

Distributed hydrological modeling has been in use since last decades to understand the hydrological processes and finding the solution for arising problems within the watersheds. Soil and Water Assessment Tool (SWAT) is one such widely used hydrological model (Arnold et al. 1998) in recent years, which has provision to divide the watershed in HRUs. SWAT has been used to address a variety of watershed issues such as soil erosion, sediment transport, identification of critical watersheds, climate and LULC change impacts, and best management practices (BMPs) at both watershed and catchment scales (Gassman et al. 2007; Mishra et al. 2007; Cao et al. 2009; Tuppad et al. 2010; Mukhtar et al. 2014). In previous studies identification and prioritization was performed at watershed/sub-watershed level (Pai et al. 2011; Besalatpour et al. 2012) and none has used the HRUs approach, which may be more advantageous for resource managers. Keeping in view the challenges and requirement, the primary objective of this study has been formulated to elaborate the HRUs based identification of erosion prone specific areas within the watershed. The method will be more effective in

managing the resources for sustainability in the present and future context of changing conditions. The study is performed by- i) calibrating and validating the SWAT model for Damodar catchment, ii) identifying the critically eroding watersheds of catchment, iii) identifying the specific erosion portions within the watershed on the HRUs basis, and iv) identifying the impact of LULC and soil types on sediment yield. The method can be used in other areas for effectively demarcating the erosion prone areas within the watershed for better management of soil and water resources.

2 Materials and Methods

2.1 Study Area

Damodar catchment, a part of the lower Ganges river, located in the upper reaches of the Damodar river basin in the Jharkhand state of India (Fig. 1) has been selected for the study. Catchment is a part of the Damodar Valley Corporation (DVC), a river valley project located in the eastern region (West Bengal and Jharkhand states) of India, started in 1948 with multifaceted objectives of flood control, irrigation development and hydropower generation. To meet these objectives, DVC has constructed three major reservoirs in the catchment (Konar, Panchet and Tenughat). The catchment area of about 10,878 km² is bounded between 23° 34' to 24° 09' N latitude and 84° 42' to 86° 46' E longitudes with elevation variation from 122 to 1340 m above mean sea level. The soils of the study area classified into three texture groups- sandy loam, sandy clay loam, and loamy sand. The slope of the catchment varies between minimum of 0.5 % to a maximum of 62.3 % with average slope of 2.7 %. The catchment comes under sub-tropical climate and receives 70 to 80 % of its annual rainfall (~1250 mm) during the monsoon months (June to September). In the catchment, the daily temperature varies from a minimum of 3 °C to a maximum of 40 °C with relative humidity variation from 40 to 95 %. Landuse within the study area is mostly agriculture, forest, and wasteland with major crops grown in the area are rice, groundnut, maize in monsoon season, and wheat, mustard and some vegetables in winter season. The settlements are mostly of low density and principal population centers within the towns of Dhanbad, Bokaro, Ramgarh, Hazaribagh and Sindri.

Within few years after the construction of reservoirs, high sedimentation rate has been realized because of accelerating soil erosion from the catchment. In order to perpetuate the benefits by prolonging the life of the reservoirs, soil and water conservation program in the catchment embarked upon. A survey carried by DVC revealed that about 66 % of Upper Damodar catchment lies under high erosion category (Misra 1999). Consequently, investigations have been carried out on individual watershed basis to understand soil erosion problems for prioritization of critical areas (watersheds) and management strategies to reverse the erosion process for improving water quantity and quality (Jain and Kothiyari 2000; Tripathi et al. 2003; Singh et al. 2006; Mishra et al. 2007; Pandey et al. 2007; Ghosh and Banerjee 2012) in the catchment. However, these studies only identified the watersheds which are contributing more sediment and said nothing about the specific areas within watershed where treatment measures should be adapted. Also, so far no study has been carried out on the whole Damodar catchment, therefore this study emphasizes on the catchment along with watersheds and HRUs for identification and prioritization of critical erosion prone specific areas to initiate the suitable management options. HRUs are created by overlaying the LULC, soil and slope maps, and thereafter defining a combined threshold of 10 % of the landuse and 5 % of soil area as HRU. With this approach 2975 number of HRUs were created in the Damodar catchment.

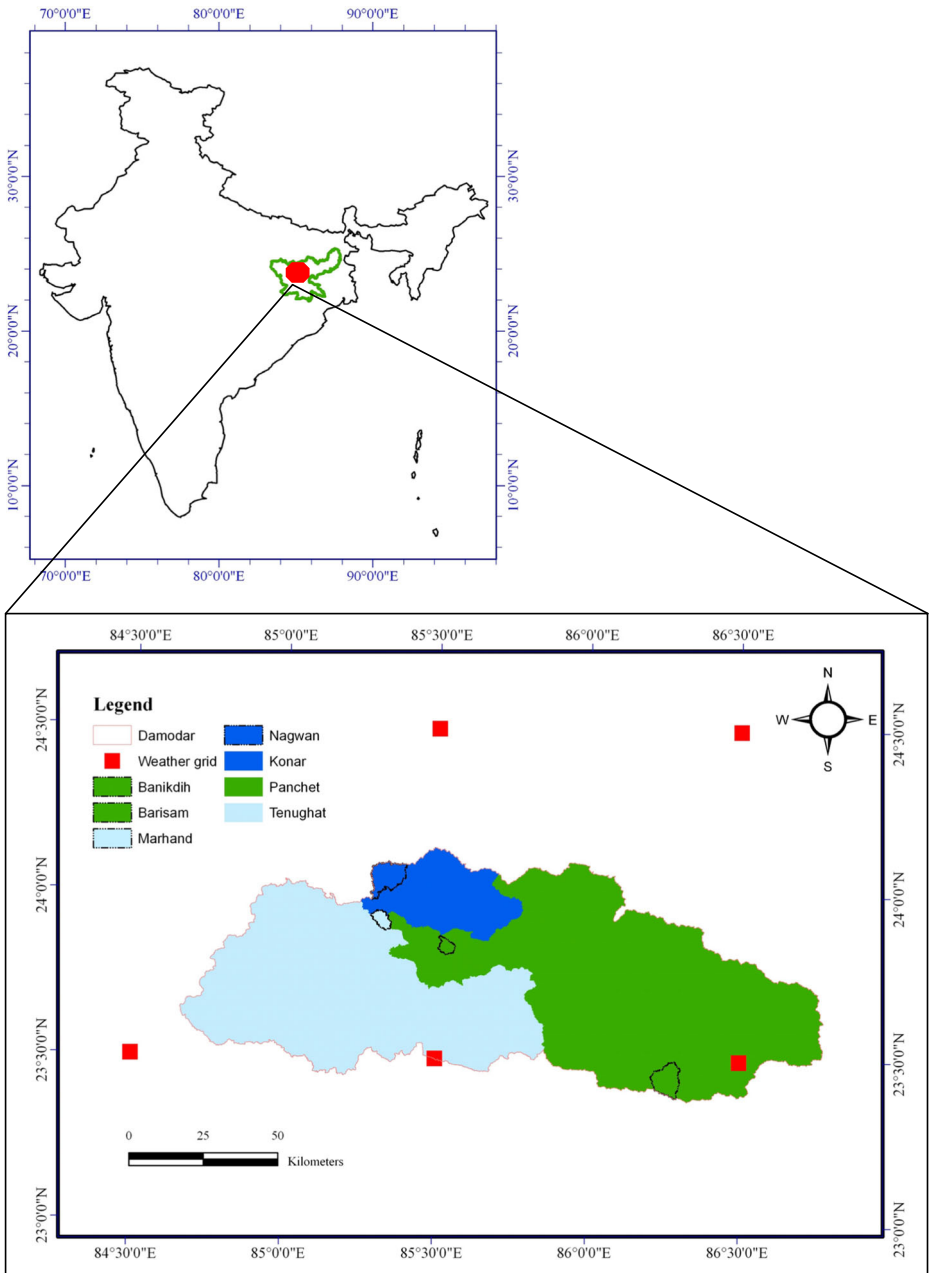


Fig. 1 Location map of study area: Damodar catchment

2.2 Input Data

The input data for driving SWAT model include weather, topography, soil properties, LULC and land management information. The topography of the catchment was characterized using

Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM) having resolution of 30 m to delineate the watersheds within the Damodar catchment. The minimum threshold value of 400 ha is used to generate the stream network and predefined watershed boundary map of catchment is overlaid on the delineated stream network. The outlet locations are assigned manually to delineate watersheds that resemble predefined watersheds in terms of area coverage and periphery. With this approach, 411 watersheds were delineated against previously manually delineated 472 watersheds by the DVC. Differences in number of watersheds occur because many of the first-order streams were not extracted using the ASTER DEM.

The soil map and soil properties data of the study area were collected from the National Bureau of Soil Survey and Land Use Planning (NBSS&LP) Kolkata, India. The soils of the study area are classified into three texture groups- sandy loam (80.17 %), sandy clay loam (9.53 %), and loamy sand (10.3 %). The LULC of the catchment is classified in five landuse classes namely- agriculture (34.78 %), forest (31.32 %), wasteland (23.63 %), urban (4.99 %), and water (5.29 %) using Enhanced Thematic Mapper Plus (ETM+) remote sensing images of landsat-7 of 2000 (Row/path: 141/44, 140/43; date: 14.10.2000, 22.11.2000) and 2001 (Row/Path: 141/43, 140/44, 139/44; date: 25.01.2001, 02.11.2001, 26.11.2001).

The girded daily ($1 \times 1^\circ$) rainfall, minimum and maximum temperature (1990 to 2006) were collected from India Meteorological Department (IMD), Pune, India. The monthly monsoon season runoff and sediment yield data for four watersheds (Banikdih and Barsim for Panchet sub-catchment, Nagwan for Konar sub-catchment, and Mahrand for Tenughat sub-catchment) were collected from the Soil Conservation Department (SCD), DVC Hazaribagh, Jharkhand, India for a period of 5 years (1997 to 2001). The area of Nagwan, Mahrand, Banikdih and Barsim are, respectively, 94.43, 26.78, 80.06 and 21.79 km². More than 70 % of the annual rainfall confined during the monsoon period (June to September), results in high amount of runoff and sediment yield from the catchment. Gauging of runoff and sediment yield is done only in monsoon season as there is no flow or less flow in other months of the year. The watersheds boundary and treatment maps prepared by DVC were collected along with the details of conservation measures performed in watersheds of the catchment.

2.3 Distributed Hydrologic Modeling: SWAT Model

The physically-based, distributed, daily time step, agro-hydrological model SWAT (Arnold et al. 1998); developed by United States Department of Agriculture, Agriculture Research Service (USDA-ARS); has been used to simulated hydrological process at watershed level. The SWAT modeling system is embedded within geographical information system and can integrate various spatial environmental data including soil, LULC, climate and topographical features. The model divides the basin\catchment into a number of watersheds based on topography factor. Then each watershed is further divided into number of HRUs based on unique combination of soil, landuse and slope. HRU is the smallest component of SWAT model which is used for computing the hydrologic and other process in the watershed.

The hydrological processes simulated for each HRU are based on well known water balance equation in which surface runoff is predicted for the daily rainfall by using Soil Conservation Service (SCS) Curve Number (CN) method, and peak runoff rate is estimated by using a modified rational method. The sediment yield (ton/ha) is estimated for each HRU using

the modified universal soil loss equation developed by Williams and Berndt (1977). Finally the HRUs output of hydrological processes and sediment yield are area weighted for the watershed. The model has three methods to simulate potential evapotranspiration (PET): Hargreaves, Priestley-Taylor and Penman-Monteith methods. Hargreaves method of ET estimation was opted in this study because of two reasons- i) availability of daily temperature data, and ii) recommendations given by Kannan et al. (2007) in which they showed that the combination of CN method with Hargreaves methods of ET estimation gives good results than any other combination. For details about the model, one can refer SWAT user manual (Neitsch et al. 2005).

2.4 Model Calibration and Validation

Calibration and validation of model was performed for the period of 1997–1999 and 2000–2001, respectively, with 2 year of warm up period in each phase. Sensitivity analysis was performed for 30 parameters identified in the literature to have a potential influence on flow and sediment yield from Barisam, Banikdih, Mahrand, and Nagwan watersheds. It has been found, that the rank of sensitive parameters are different for watersheds in the catchment which is shown in Table 1. After sensitivity analysis, calibration and validation of the model was done at monthly time steps due to the availability of data at monthly time. Table 1 lists the calibrated parameters, their prescribed range of minimum and maximum values with calibrated values. After calibration, model was validated without making any change in input parameter except for meteorological data for four watersheds to simulate monthly runoff and sediment yield at watershed level for the monsoon season. The numerical and graphical performance criteria were used to evaluation model performance during calibration and validation period.

Table 1 Calibrated hydrological parameters of SWAT Model for four watersheds (Nagwan, Banikdih, Barisam and Mahrand) of the Damodar Catchment

Parameter	Prescribed range		Barisam	Banikdih	Mahrand	Nagwan
	Minimum	Maximum				
OV_N	0.01	0.5	0.15	0.07	0.20	0.10
CH_N1	0.01	0.5	0.15	0.21	0.18	0.09
CH_K1	0	100	2.15	6.70	2.50	2.00
CH_N2	0.01	0.5	0.15	0.19	0.01	0.04
CH_K2	0	100	1.00	1.00	1.00	3.00
SURLAG	1	4	1.00	1.00	1.00	1.00
CN2	35	98	49–79	73–81	48–67	49–67
ALPHA_BF	0	1	0.5	0.5	0.5	0.5
CH_EROD	0	1	0.5	0.5	0.5	0.5
CH_COV	0	1	0.5	0.5	0.5	0.5
SPCON	0.0001	0.01	0.009	0.009	0.009	0.009
SPEXP	1	2	1.13	1.13	1.13	1.13
USLE_P	0	1	0.8	0.6	0.8	0.6
ALPHA_GW	0	1	0.3	0.3	0.3	0.3
EPCO	0	1	0.6	0.6	0.6	0.6
ESCO	0	1	0.5	0.5	0.5	0.5

The numerical performance criteria include percent bias (PBAIS), correlation coefficient (r) and Nash-Sutcliffe efficiency (NSE) as shown in Eqs. 1, 2 and 3:

$$PBIAS = \frac{\sum_{i=1}^n (Y_{obs,i} - Y_{sim,i})}{\sum_{i=1}^n Y_{obs,i}} \times 100 \quad (1)$$

$$r = \frac{\sum_{i=1}^n (Y_{obs,i} - Y_{obs}^-) (Y_{sim,i} - Y_{sim}^-)}{\sqrt{\sum_{i=1}^n (Y_{obs,i} - Y_{obs}^-)^2 \sum_{i=1}^n (Y_{sim,i} - Y_{sim}^-)^2}} \quad (2)$$

$$NSE = 1 - \frac{\sum_{i=1}^n (Y_{obs,i} - Y_{sim,i})^2}{\sum_{i=1}^n (Y_{obs,i} - Y_{obs}^-)^2} \quad (3)$$

Where, $Y_{obs,i}$ and $Y_{sim,i}$ are the observed and simulated hydrologic variables; whereas Y_{obs}^- and Y_{sim}^- are the average of observed and simulated hydrologic variables.

2.5 Identification and Prioritization of Critical Erosion Areas of Damodar Catchment

The calibrated model has been applied for the identification of critical watersheds and HRUs of the Damodar catchment. Simulated average annual sediment yield for period (1997–2001) was determined for all watersheds and then classified into three erosion classes, i.e., slight (0–5 t/ha/yr), moderate (5–20 t/ha/yr) and high (>20 t/ha/yr) following the criteria proposed by DVC. The spatial distribution of critical watersheds was compared with DVC prioritized watersheds. The above classification of watershed into three erosion classes was done mainly to compare spatial distribution between DVC erosion classes and SWAT model derived erosion classes to test the model capability. Since there is difference in number of watersheds between SWAT delineated and DVC reported, we compared the area under different soil erosion classes identified by DVC with the SWAT analysed erosion classes with help of ArcGIS software to compare the accuracy of SWAT model.

Identification and prioritization of watershed gave fundamental idea about the watersheds. However, it does not give detail analysis about critical erosion areas within the watershed and the cause behind the high soil erosion from the watersheds. Since, the analysis is done on the average condition, we cannot say that whole watershed is contributing erosion at high rate. Therefore, this analysis is done on HRUs basis to capture real erosion sites within the watersheds of Damodar catchment. To capture significantly detailed distribution of the seriously eroded sites within the watersheds, we adopted HRUs- level sediment yield to identify critical erosion prone sites. For that, identification and prioritization of critical watersheds was done again on the basis of criteria suggested by Singh et al. (1992) for

Indian condition (0–5 t/ha/yr slight, 5–10 t/ha/yr moderate, 10–20 t/ha/yr high, 20–40 t/ha/yr very high, 40–80 t/ha/yr severe and above 80 t/ha/yr very severe) and then HRUs based prioritization has been followed.

3 Results and Discussion

3.1 Model Calibration and Validation

SWAT model was calibrated (1997–1999) and validated (2000–2001) at the outlets of four watersheds (Nagwan, Mahrand, Barisam and Banikdih) using monthly runoff and sediment yield for monsoon period. Figure 2 shows the graphical presentation of calibration and validation results. The results indicate a close agreement between the observed and simulated monthly runoff and sediment yield during the calibration and validation periods. The specific results for calibration and validation are discussed as below.

3.1.1 Runoff

The Fig. 2 shows that the magnitude and temporal variation of simulated runoff follows the trend of observed runoff for the monsoon seasons at the outlets of four watersheds during calibration period. However, it is observed from the graphical comparisons that, some peaks are slightly over and under-predicted by the model. The model results reveal that at the beginning of the monsoon season i.e., June, the model under predicts the runoff for the watersheds which may happen due to low initial soil moisture and higher infiltration condition, but overall model performance was found satisfactory as indicated by close agreement between observed and simulated values of runoff for four watersheds. During the validation period, temporal variations are very well simulated by the model corresponding to rainfall conditions in four watersheds. However, some peak runoff events do not match well in all four watersheds and showing slight over estimated peaks by the model during the month of high rainfall. The differences between observed and model estimated runoff may be due to the differences in real world and model presented status of initial soil and water conditions during the validation period.

The statistical analysis of calibration and validation results, for monthly runoff (Nagwan, Mahrand, Barisam and Banikdih) is presented in Table 2. The correlation coefficient (r) variation from 0.83 to 0.95 during calibration and validation period for the four watersheds shows a quite strong agreement between the measured and simulated runoff during the monsoon season. On the other side, NSE variation from 0.74 to 0.89 during calibration and validation period shows better agreement between the measured and simulated runoff. The higher values of r and NSE indicate that the model is well simulating the pattern and the magnitude of the runoff during the calibration and validation periods. At the same time, low value of PBIAS (varying from -13.65 to 9.76 % during calibration and validation period) indicates that the model is simulating runoff within the acceptable level of accuracy during the calibration and validation period for the four watersheds.

3.1.2 Sediment Yield

Results show that the simulated sediment yield follows the trend of the observed sediment yield during the monsoon season of calibration period except for few months as observed from the Fig. 2. Slight over and under prediction is observed during some of the monsoon months

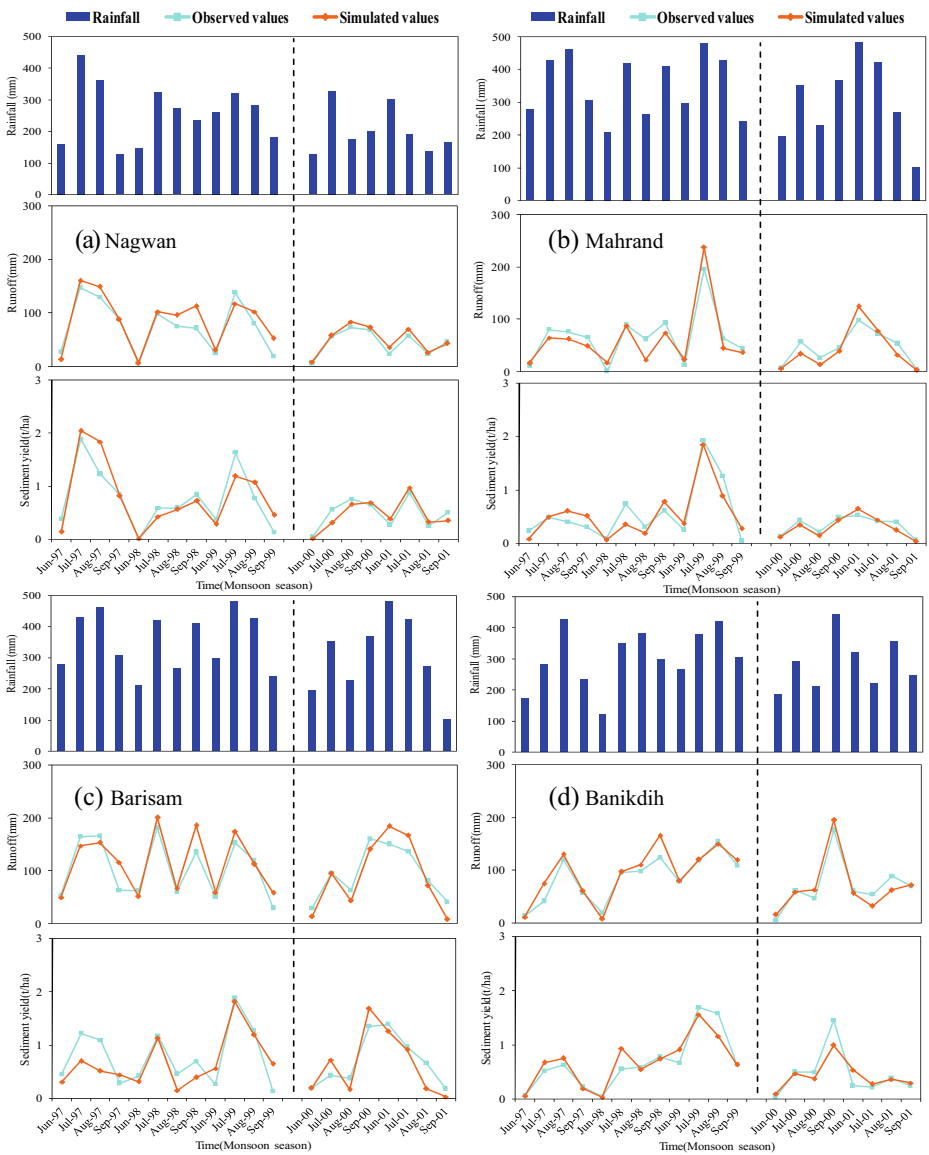


Fig. 2 Comparison between observed and SWAT simulated monthly runoff and sediment yield during calibration (1997–1999) and validation period (1999–2001) for (a) Nagwan, (b) Mahrand, (c) Barisam, and (d) Banikdih watersheds

which may be attributed to the rainfall characteristics and the approach of SWAT model for sediment estimation based on the total rainwater quantity rather than the intensity in the specific period. The slight difference may also be attributed to conservation measures adopted during the years in the four watersheds. The sediment yield has direct relationship with runoff and hence it has been observed that sediment yield also follows the trend of simulated runoff as observed from the Fig. 2. During the validation period it has been observed in the four watersheds that the trend of simulated sediment yield follows well to the measured sediment

Table 2 Statistical analysis between observed and simulated monthly runoff and sediment yield for four watersheds during calibration and validation period

Runoff						
Name	PBIAS (%)		r		NSE	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
Nagwan	-13.65	-12.32	0.87	0.95	0.80	0.87
Mahrand	7.63	9.76	0.88	0.87	0.82	0.74
Barisam	-10.87	4.26	0.83	0.92	0.77	0.76
Banikdih	-9.63	1.01	0.91	0.91	0.84	0.89
Sediment yield						
Nagwan	-3.09	5.67	0.80	0.81	0.75	0.77
Mahrand	3.0	9.99	0.84	0.74	0.84	0.74
Barisam	12.73	7.15	0.66	0.81	0.62	0.69
Banikdih	-2.79	4.28	0.85	0.86	0.85	0.76

yield for the months of monsoon season for the year 2000 and 2001. Overall graphical comparison indicates that model is simulating the sediment yield trend quite well with slight variations in simulating the peaks during the monsoon months in the four watersheds.

The statistical analysis of calibration and validation results of sediment yield at the outlets of four watersheds (Nagwan, Mahrand, Barisam and Banikdih) is presented in Table 2. The results indicate a close agreement between observed and simulated sediment yield from watersheds as indicated by quite high values of *r* (varying from 0.66 to 0.86 during calibration and validation period) and NSE (varying from 0.62 to 0.85 during calibration and validation period) for all the four watersheds. In all cases, PBIAS is less than 15 % during the calibration and validation period (varying from -3.9 to 12.73 %), which indicate that the model simulates sediment yield reasonably well in the four watersheds. Based on review study performed by Moriasi et al. (2007), the results are well within the acceptable range of accuracy. The graphical and statistical comparison of results also indicates that the model is quite well calibrated and validated for the monsoon months for the four watersheds and can be used for further study in the catchment.

3.2 Identified Critical Watersheds of Damodar Catchment

After successful calibration and validation of SWAT model for four watersheds coming within different reservoir sub-catchments, the calibrated model parameters value of these watersheds were assigned to other un-gauged watersheds within the same reservoir sub-catchment (Nagwan for Konar sub-catchment, Barisam and Banikdih for Panchet sub-catchment and Mahrand for Tenughat sub-catchment). After up-scaling of parameter, the model was run for the period 1997–2001 and the simulated average annual sediment yield from the individual watershed and HRUs has been considered in prioritizing the critical erosion prone areas in catchment.

The critical watersheds were identified first on the basis of average annual sediment yield obtained from the model output for the period of 1997–2001 and compared with available data on critical watersheds for Damodar catchment from SCD, DVC. Model delineated 411 watersheds against manually delineated 472 watersheds by SCD, DVC. Out of 411 watersheds

delineated with the help of model, 277 watersheds fall under high, 84 watersheds under moderate and 50 watersheds under slight soil erosion class and on the other side, SCD data shows that, 317, 94 and 61 watersheds fall under high, moderate and slight soil erosion classes, respectively. Figure 3a, b show ground truth data information provided by SCD, DVC and model priority map based on model simulation results. It is observed that the spatial distribution of different classes performed using SWAT model result match well with manually defined erosion classes. Because of difference in number of watersheds of SWAT model and DVC, we are unable to match the accuracy of the SWAT model on watersheds basis. To solve this problem; we compared the area under different classes instead of watersheds with the help of GIS tools. From the analysis, it has been found that there is 80.60 % match between SWAT model priority and DVC priority, with 19.40 % area having mismatching. After this, identification and prioritization of the watersheds was done again using criteria suggested by Singh et al. (1992) for Indian condition. From the analysis, it has been found that 50, 84, 169, 61, 30 and 17 watersheds fall under slight, moderate, high, very high, severe and very severe classes and the spatial distribution of these is shown in Fig. 4a.

3.3 Critical Area of Soil Erosion in Damodar Catchment

The approach of prioritizing watersheds based on actual sediment yield rates may be taken as one possible criteria when the number of watersheds are more; but this gives only basic ideas about watershed with average condition within the watershed. Since every part of the watershed is not contributing same amount of sediment yield to the stream, there are only some portions of watershed which contribute high sediment yield (depending on soil, slope and landuse condition) due to which watershed falls under critical zone or even vice-versa. Identification of these specific areas within the watershed will help in deciding specific and cost effective management options (biological or engineering) to reduce the sediment transport problem. To identify these critical zones in Damodar catchment, HRUs based identification of critical erosion area was done. Damodar catchment was divided into 2975 HRUs on the basis of soil, slope and landuse. From the HRU analysis it has been found that 1017, 522, 508, 499, 281 and 148 numbers of HRUs fall under slight, moderate, high, very high, severe and very severe soil erosion classes, respectively. Figure 4b shows the spatial distribution of soil erosion classes based on HRUs in the Damodar catchment. Comparison between Fig. 4a and b shows difference between prioritization at watershed and HRUs level. From these figures, it is observed that there is much spatial difference between prioritization at watershed and HRUs level which suggests that the prioritization at HRUs could be more useful to conservation planners and managers as compared to prioritization at watershed level. From the analysis of HRUs prioritization, it is observed that about 67.51 % area of Damodar catchment is under high and above erosion classes. The analysis suggested that the identification and prioritization of critical area prone to soil erosion should be done at HRUs level as compared to watershed level, which will help soil and water conservation managers to decide the proper strategies for erosion prone area.

To elaborate the specific difference between the two methods, we also analysed the area coming under different soil erosion conditions. Table 3 shows statistical analysis of HRUs and watersheds prioritized area under different soil erosion classes (based on Singh et al. 1992) in the catchment. From the analysis, it has been found that there is difference in the area of HRUs and watersheds prioritization under different erosion classes and major difference is seen under slight and high erosion class. Prioritization based on watershed shows less area under slight erosion class (1555 km²) and large area under high erosion class (4555 km²), which has been found opposite to that of prioritization based on HRUs level. From the HRUs analysis, it is

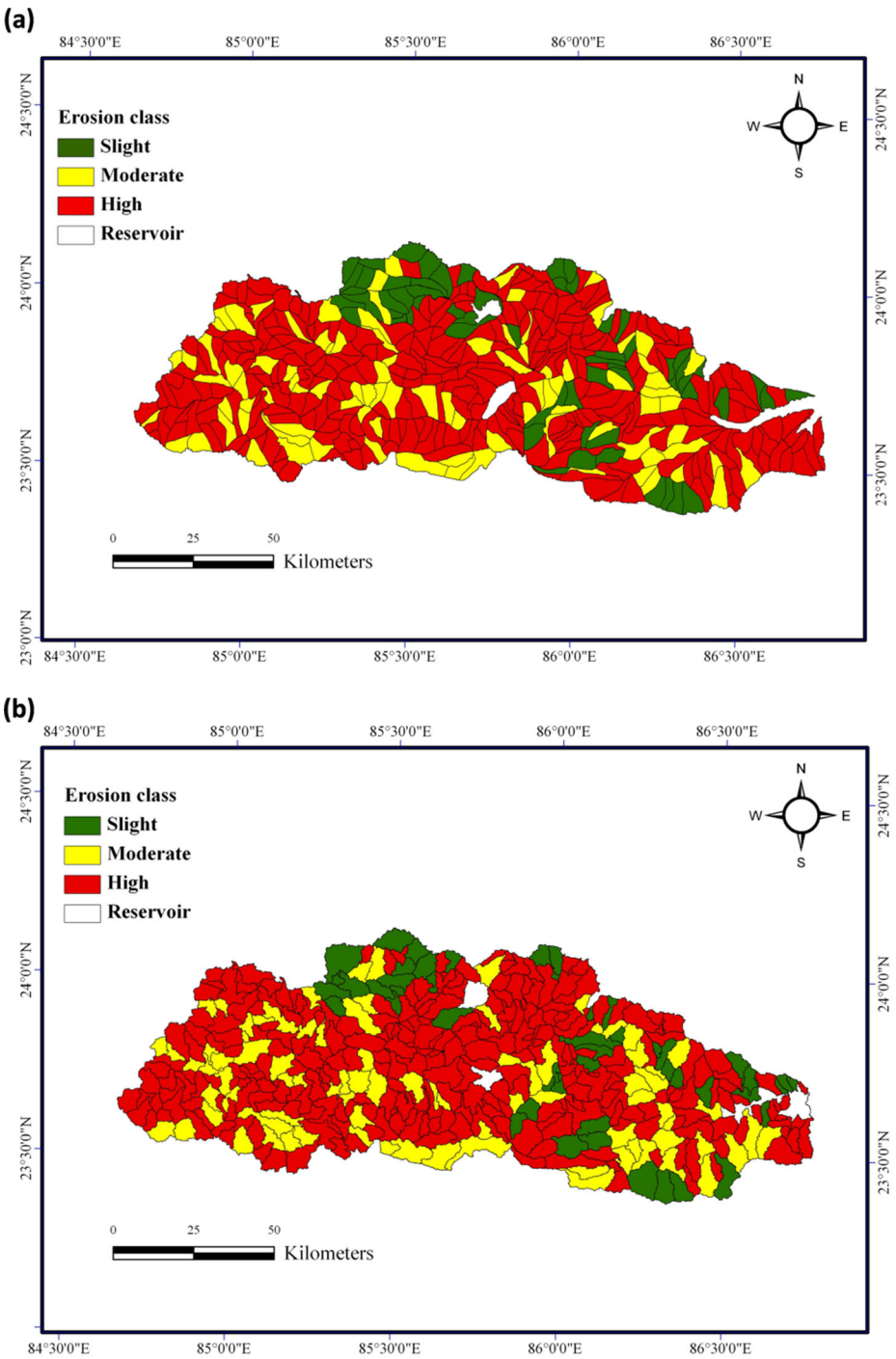


Fig. 3 Spatial distribution of prioritized watersheds of Damodar catchment by (a) DVC and (b) SWAT simulation

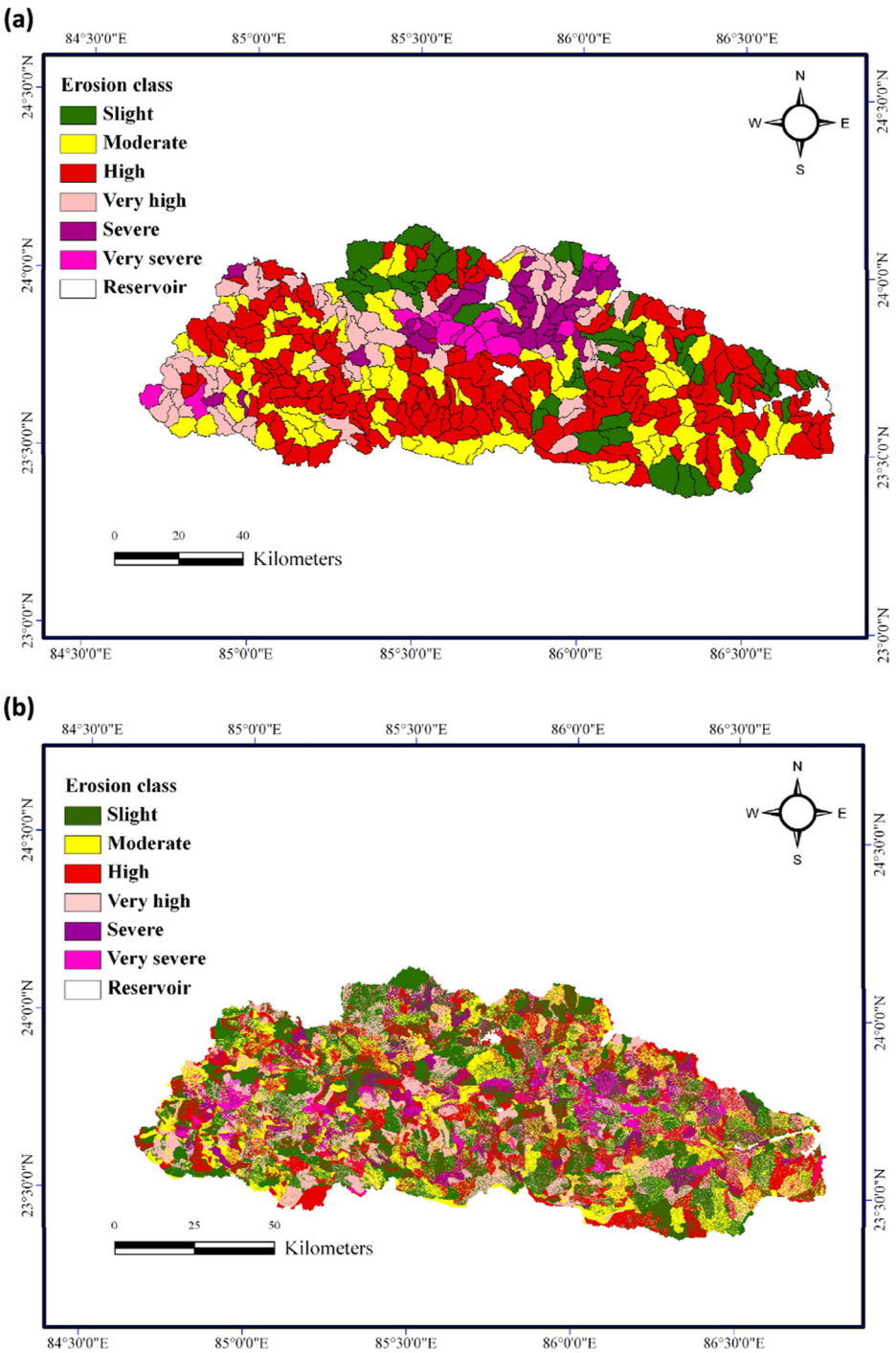


Fig. 4 Spatial distribution of prioritized specific areas using SWAT model for Damodar catchment following (a) watershed approach and (b) HRUs approach

Table 3 Watershed and HRUs based prioritization statistics for damodar catchment (value outside bracket are for HRUs and within bracket are for watersheds)

Erosion class	No of HRUs (watersheds)	Area (km ²)	Minimum sediment yield (t/ha/year)	Maximum sediment yield (t/ha/year)	Average sediment yield (t/ha/year)
Slight	1017 (50)	4167.93 (1555.15)	0.01 (0.90)	4.99 (4.98)	1.82 (3.88)
Moderate	522 (84)	2194.44 (2570.91)	5.00 (5.02)	9.99 (9.99)	7.36 (7.23)
High	508 (169)	2157.43 (4555.35)	10.01 (10.00)	19.99 (19.40)	14.42 (12.91)
Very high	499 (61)	1935.28 (1531.39)	20.05 (20.20)	39.84 (38.78)	28.28 (27.34)
Severe	281 (50)	914.37 (714.35)	40.00 (40.23)	79.93 (75.52)	55.78 (51.47)
Very severe	148 (17)	481.67 (437.07)	80.11 (84.83)	510.46 (248.37)	141.34 (132.40)

observed that the area under slight, very high, severe and very severe erosion class is more compared to prioritization based on watersheds and less under moderate and high erosion classes. It is evident from the analysis that average annual minimum and maximum sediment yield for six erosion classes are comparable for both HRUs and watershed prioritization, except for very severe erosion class. When comparing HRUs based analysis with watershed based analysis, the average annual sediment yield is more under HRUs based prioritization for all soil erosion classes except slight erosion class. This is happening because in watershed based analysis, the more area coming under moderate and high erosion classes normalizes the sediment yield estimates and thus resulting to show less area under particularly high erosion classes. Over all HRUs based prioritization gives better details about the most erosion prone area within the catchment rather than watershed based prioritization.

3.4 Soil Erosion Relation with Different Landuse and Soil Type

HRUs are the unique combination of landuse and soil type which have varying effect on erosion. With this understanding we have also analysed the individual and combined effects of landuse and soil type on sediment yield. Figure 5a shows the area of different soil erosion classes respective of landuse in catchment and indicates that agriculture is major contributor to soil erosion in the catchment. The agriculture comprises of 34.78 % area of the Damodar catchment out of which 70.29 % comes under high and above erosion category. The area under forest and waste land are 31.32 and 23.63 %, out of which respectively 55.09 and 84.09 % area comes under high and above erosion classes. This may be because of illegal mining activities in the catchment. Overall 67.52 % area of the catchment is under threat of soil erosion. Since the catchment is very important for both agriculture and mining sector, management should be done in these areas to control soil erosion for the best use of catchment in the future.

The Damodar catchment has three types of soils- sandy loam (80.17 %), sandy clay loam (9.53 %), and loamy sand (10.3 %). Figure 5b shows the area of different soils under different soil erosion classes. It is observed from the figure that maximum area lies under high and above soil erosion classes which constitutes about 67.52 % area of different soils. Sandy loam and sandy clay loam soils are the major contributor to the soil erosion in the catchment as shown in Fig. 5b and this may be due the high content of sand in the soil, which is easily erodible. Figure 6 shows the area of different soil erosion classes (Y-axis) under the combination of different landuse and soil type (X-axis). From the Fig. 6, it is observed that sandy loam soil is more prone to soil erosion in the catchment in combination with all types of land uses. The agriculture, forest and wasteland contribute more soil erosion in combination with sandy loam soil because this soil consists of more than 75 % of sand and covers large portion of the

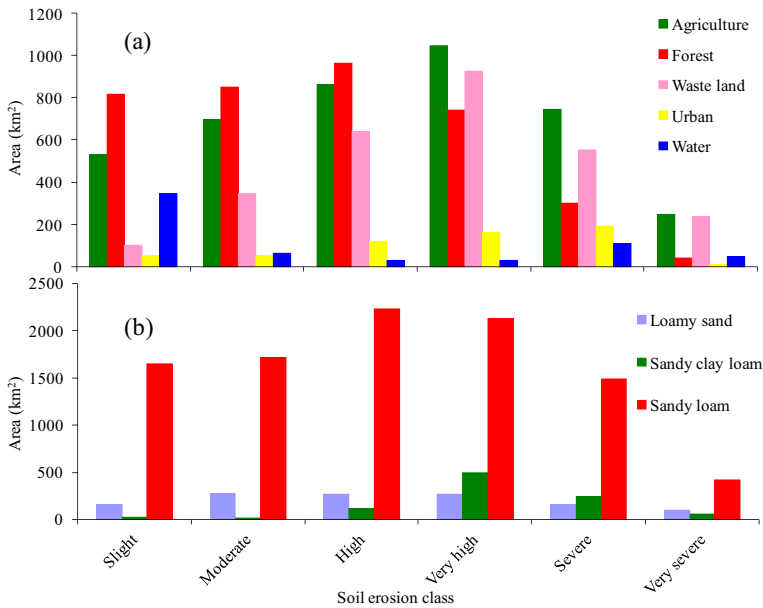


Fig. 5 The area of different soil erosion class with respect to land use (a) and soil (b) in Damodar catchment

catchment. Figure 6 also reveals the erosion area under three major land uses in the catchment, and indicates that the major erosion area falls under the agriculture land and waste land which is 34.78 and 23.63 %, respectively. From the analysis it has been found that the catchment is under high threat of soil erosion due to its soil properties and land uses and might create problems of water quality, soil degradation and reduction of water storage capacity of the reservoirs which have been constructed for water storage and supply for different needs in the catchment.

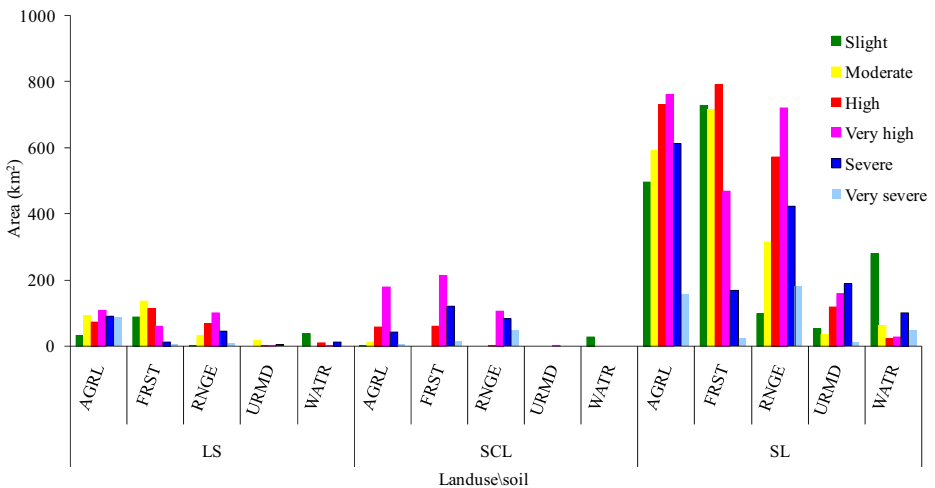


Fig. 6 Distribution of area of soil erosion classes under combination of soil types and land use classes (AGRL, Agriculture; FRST, Forest; RNGE, Waste land; URMD, Urban; WATR, Water; LS, Loamy sand; SCL, Sandy clay loam; SL, Sandy loam)

4 Conclusions

Sediment yield is one of the major factors deciding the soil erosion susceptible areas in the watershed/catchment. In this study, SWAT model has been successfully calibrated and validated for simulating runoff and sediment yield at the watershed level in the Damodar catchment and applied to the whole catchment for identification and prioritization of critical erosion prone regions at watersheds and HRUs levels. The study revealed that there is difference in actual area under a particular soil erosion class when compared between watersheds and HRUs levels prioritization approach. By using watershed approach, the effect of specific areas within watershed contributing high or low sediment yield is normalized and shows respectively lower or high sediment yield from the whole watershed. Also the watershed based approach does not give an idea about these specific area locations within the watershed to start with an appropriate and cost effective sediment control measure. To contrast this, HRUs based approach may provide an idea about the specific areas within watershed contributing high and above sediment and thus more appropriate management strategy can be adopted. HRUs based analysis specifically identifies the areas within the watersheds, based on landuse and soil type combination, having similar hydrological response properties in the catchment at different watersheds. In this study, the HRUs based analysis has showed that about 67.52 % area of Damodar catchment is under critical erosion zone because of a combined effect of sandy loam soil, and wasteland and agriculture as land use condition. Finally the study concludes that identification and prioritization of critical areas should be carried out at smaller units like HRUs to get clear idea of problematic portions within the watersheds while taking into account factors such as landuse and soil type which are most responsible for soil erosion in the watershed/catchment due to their properties. The suggested HRUs based approach will be more helpful to the resources managers to identify the specific critical erosion areas which deserve priority attention within watershed/catchment for soil and water conservation to improve the soil fertility and water availability in the reservoirs under high sedimentation rate.

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