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Prioritization of Soil Erosion Vulnerable Areas of Upper Patiala-Ki-Rao Catchment Located on Shivalik Hills

Sushma Walia[1*], Sarbjit Singh[1], Richa Babbar[1], Dikesh Chandra Loshali[2]
[1]Department of Civil Engineering, Thapar University, Patiala – 147 004, India
[2]Forestry and Land Use Division, Punjab Remote Sensing Centre, Punjab Agriculture University, Ludhiana - 141 001, India
E-mail: *sushmawalia@yahoo.com*; sarbjit@thapar.edu; richababbar@thapar.edu; dc_loshali@rediffmail.com*

ABSTRACT

In this research paper, morphometric analysis and prioritization were carried out for upper Patiala-Ki-Rao catchment lying on Shivalik hills of SAS Nagar district of Punjab and Panchkula district of Haryana state, India. Morphometric parameters were classified into three categories such as linear, areal and relief aspects. Remote sensing and geographic information system (GIS) was used to quantify these morphometric parameters along with hypsometric and erosion integrals to understand watershed characteristics. Soil, slope, and land use thematic layers were prepared and with the help of GIS overlay technique, erosion vulnerable areas were identified based on priority by using analytical hierarchical process (AHP) proposed by Saaty (1980). These thematic layers were assigned weightage and ranks were assigned to the categories within it on the basis of relative susceptibility to soil erosion. Based on the present study, the selected watershed was finally classified into high, medium and low priority areas susceptible to erosion. The results of the present study are useful to decision-maker for planning relevant soil conservation techniques according to the severity of erosion.

INTRODUCTION

Runoff induced soil erosion is a serious and continuous worldwide environmental problem affecting the quality of soil, land, and water resources (Rawat and Singh 2017; Rawat and Singh 2018; Pradhan et al. 2018; Edon and Singh 2019). In this process, the particles of the surface soil entrained with the impact of rainfall and runoff (Rawat and Singh 2017; Rawat and Singh 2018). The runoff is the excess rainwater retained on the surface after interception, infiltration, evaporation and detention storage (Patle et al. 2018). Water in flowing state as well as in detention storage protects the soil from the impact of falling rain and the rain-splash distribution, which decreases with increasing depth of overland flow as rain continues (Rawat and Singh 2017; Rawat and Singh 2018). However, if rainfall continues the overland flow eventually overtop these topographic depressions and flow downslope more quickly resulting in more soil loss. Storm water while flowing downslope entrain soil particles and essential nutrients from the topsoil layer, thereby degrading the quality of soil, clogs streams, decreases the capacity of reservoirs and increases the cost for maintaining water conveyance and storage structures. Slope, land use and soil type influence soil erosion and among these three, the slope has the greatest impact on erosion (Kumar et al., 2018a; Kumar et al., 2018b; Yadav et al., 2014; Yadav et al., 2016). As slope increases, velocity and volume of runoff increases which increases transport of surface soil and decreases infiltration. Whereas, ground vegetation shields the soil against the impact of rain and decreases the over-land flow velocity.

Many researchers have studied morphometric parameters and prioritize watersheds using remote sensing and GIS for decision making and adopting conservation techniques (Yadav et al. 2014; Yadav et al. 2016; Choudhari et al. 2018). Thakkar and Dhiman (2007) prioritized eight small watersheds by assigning ranks on the basis of morphology. Javed et al. (2009) investigated morphological and land use parameters to prioritize sub-basins of Kanera basin of Guna district of Madhya Pradesh by assigning ranks using GIS techniques. Uniyal and Gupta, (2013) prioritized Bhilangana watershed into high, medium and low categories by determining various morphometric parameters for each micro-watershed using spatial technology for decision making and conserving natural resources. Patil et al. (2013) characterize and prioritize Tulasi sub-watershed located on small tributary at Kolhapur district of Maharashtra by evaluating morphology for land rejuvenation and suggested that higher priority was given to the area where the erosion is higher. Ranjan et al. (2013), Pande et al. (2019) and Murmu et al. (2019) adopted the analytical hierarchical process developed by Saaty's to prioritize watersheds by assigning weightage to parameters and categorized them to different classes. Eshghizade et al., (2015) used the analytic hierarchy process to prioritize 18 experimental erosion fields of area 40 m^2 of Kakhk catchment located at Gonabad, Iran. They predicted that runoff depth plays an important role to increase soil loss, and vegetative cover plays a controlling role in soil erosion. Yadav et al. (2016) prioritized the upper Tons river basin of north India based on morphometric parameters using groundwater derived from topographic sheets and CARTOSAT data. Pradhan et al. (2018) quantified hydraulic parameters of soil with the ROSETTA model and then using the analytical hierarchy process generates the watershed prioritization map for soil and water conservation. Singh and Singh (2018) estimated the hypsometric curve and integral using micro-wave satellite data in the geographical information system environ-ment for Naina–Gorma river basin and its sub-basins. Farhan et al., (2018) prioritize seventy-six sub-basins of W. Mujib-Wala watershed of southern Jordan by studying ten linear aspects and shape parameters by designating ranks as per erosion level. Choudhari et al. (2018) calculated morphometric parameters of a watershed of Mula river basin, Pune district of Maharashtra, India to prioritize five sub-basins.

From the literature review, it has been observed that various studies have been conducted to prioritize watersheds by using different parameters to access erosion vulnerable areas. The present study was conducted by investigating morphological parameters and hypsometry to understand watershed characteristics and further land-use, soil and topographic features were used to prioritize and identify erosion susceptible areas within the watershed to apply appropriate conservation practices.

STUDY AREA

The study area taken is upper Patiala-Ki-Rao catchments lying on Shivalik hills of Panchkula district of Haryana and SAS Nagar district of Punjab state, India as shown in Fig.1, located between North

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Fig.1. Location map of study area

30°.79' and East 76°.81' at the bottom left and North 30°.84' and East 76°.87' at the top right. The study area is situated at an elevation of 477 m above the sea level. Two tributaries originate from the steep hills of Shivalik at Panchkula and passing through the undulated forests and join together at Karoran villages of district SAS Nagar. The water flows in these tributaries from July to September during the monsoon. The main source of water in the area is rainfall and the average rainfall in the study area varies from 850 to 1250 mm during the rainy season, whereas some light intensity rain occur during winter from December to March. Most of the runoff producing rain erodes soil from the contributing basin. The maximum temperature recorded is (41-44ºC), whereas the minimum temperature recorded is (5-6ºC). As the aquifer is very deep approximately 250 mbgl, the villagers depend on rain water for agriculture. Maize and fodder are the main cultivating crops of the area. The main occupation of local residents is farming, cattle grazing and animals for transportation and carrying goods. The area was semi-arid, ecologically fragile, and highly prone to erosion. Growing population and land prices, proximity to Chandigarh and other developed areas has led to haphazard development and deforestation that affect the fragile ecosystem of the area.

The area comprises the Shivalik deposits which are alluvial detritus derived from the sub-aerial wastes of the mountains, and swept down by the seasonal ephemeral streams and rivers (Wadia, 1976). These are composed of grey and hard sandstones, siltstones and red and purple shales along with pseudo conglomerates from middle Miocene to Helvetian age. The exact information about the age of these deposits is not available. Geologists argue that these were deposited during the Pleistocene and the recent periods (Wadia, 1976).

MATERIALS AND METHODS

Morphology and Hypsometry

In this study, the spatial analyst hydrology tool of ArcGIS 10.3 was used to quantify morphometric parameters and hypsometric integral to understand the hydrological behaviour of watershed. ASTER DEM of 30 m resolution has been used for watershed delineation, flow accumulation and flow direction raster's to evaluate linear, areal and relief aspects of morphology directly or indirectly. These morphometric parameters characterize the watershed and help to understand the hydrological behaviour of watersheds. The methodology to quantify these morphometric parameters is given in Table 1.

Linear Aspect

In this analysis, Horton-Strahler classification has been used to study the linear aspect of the watershed. The watershed was classified as a seventh-order watershed. Bifurcation ratio is considered as a relief index and dissection, which is an important parameter for drainage basin analysis. The higher bifurcation ratio value indicates distortion in the area. The stream number and bifurcation ratio increases with decreases of stream order except stream order 5 where it decreases as compared to stream order 6 as shown in Table 2, indicating that the area was tectonically active. Overland flow length is the length of water that flows on the surface before entering in certain stream channels. The length of the overland flow was 0.0125 km. The smaller value of overland flow indicates that the runoff quickly enters the stream even if the rainfall is less.

Areal Aspect

The areal aspect represents two-dimensional watershed properties. The area drained by the entire range of streams that originated in that area and discharged to a single point is termed as a drainage area. The drainage area of the basin was computed from the topological polygon delineated from the DEM by using the Geometry function in an attribute table. Drainage density is the ratio of the sum of all stream length of different order to the area of the basin. Geology and land use of the basin influence the drainage density. High drainage density and low channel maintenance constant values of studied watershed points to a highly dissected surface that affects the rainfall-runoff and infiltration response time in the basin. It clearly shows that the area is impermeable with erodible lithology. Drainage texture is an important parameter in geomorphology and depends on the terrain's lithology, infiltration capacity and relief aspect (Horton, 1945). More drainage texture for study area indicates dissected basin which points towards more erosion. Drainage density and drainage frequency product is referred to as infiltration number; higher infiltration number for the study area predicts impermeable lithology, lower infiltration, and higher is the runoff. Basin shape is helpful to understand the basin hydrology, which is predicted by elongation ratio, shape factor, and circulatory ratio. In this study, the order of elongation ratio, circularity ratio and form factor

Table 1. Morphometric parameters with formula and reference

S. No.	Morphometric Parameters	Formula/Method	Reference
1	Stream Order (u)	Hierarchical Rank	Strahler (1964)
2	Stream Number (Nu)	Total no. of stream segments of order 'u'	Horton (1945)
3	Sum total stream length (Lu)	Total stream length of all orders (km) GIS software analysis	Strahler (1964)
4	Basin perimeter(Pb)	Perimeter of the Basin (km) GIS software analysis	
5	Basin length (Lb)	Longest dimension of the basin parallel to the principal drainage line (km) GIS software	Schumm(1956)
6	Bifurcation Ratio	Rb= Nu/Nu+1 Where, Rb = Bifurcation RatioNu = Total no. of stream segments of order 'u'Nu+l= Number of segments of the next higher order	Schumm (1956)
7	Mean Bifurcation Ratio	Average bifurcation ration of all orders	Schumm (1956)
8	Length of overland flow	Lg =A/2Lu where, Lu = Total stream length of all orders (km), A = Area of the watershed (km^2)	Horton (1945)
9	Basin Area(A)	Area of the Basin (km2) GIS software analysis	Schumm (1956)
10	Drainage Density(Dd)	Dd = Lu/A Where, Lu=Total stream length of all orders, A= Area of the Basin (km^2)	Horton (1932)
11	Drainage Intensity(Di)	Di = Fs/Dd Where, Fs=Stream frequency, Dd=Drainage Density	Finiran (1968)
12	Constant of Channel Maintenance (C)	C = 1/Dd Where, Dd=Drainage Density	Schumm (1956)
13	Stream Frequency(Fs)	Fs = Nu/A Where, Nu=Total no. of streams of all orders and A= Area of the Basin (km^2)	Horton (1932)
14	Circulatory Ratio (Rc)	Rc= 4×ð×A/P² Where, A=Area of the Basin (km^2), P = Perimeter (km)	Miller (1953)
15	Elogation Ratio(Re)	Re =1. 128 A Lb , where,A = Area of the basin (km^2), Lb = basin length (km)	Schumm (1956)
16	Form Factor(Rf)	Rf = A/Lb^2, where A = Area of the basin (km^2), Lb = basin length (km)	Horton (1932)
17	Compactness Constant(Cf)	Cf =Pb/2√πA where Pb =Perimeter of basin (km), A = Area of the basin (km^2)	Gravelius (1914)
18	Infiltration Number (If)	If= Fs* Dd Where, Fs=Stream frequency, Dd=Drainage Density	Faniran (1968)
19	Drainage Texture(Rt)	Total no. of stream segments of all orders per perimeter of Basin	Horton (1945)
20	Total Relief(H)	H = h – h1 where, h = Maximum height (m)h1 = Minimum height (m) GIS software analysis using DEM	Hadleyand Schumm (1961)
21	Relief Ratio(Rhl)	Rhl = H/Lb, where, H = Total relief, Lb = basin length	Schumm (1963)
22	Relative Relief(Rr)	Rr = H/Pb where, H = Total relief, Pb =perimeter of basin (m)	Melton(1957)
23	Ruggedness Number(Rn)	Rn = Dd*H/1000	Strahler (1968)

decrease respectively in their values as shown in Table 3. The smaller value of form factor predicts it as an elongated basin.

Relief Aspect

The difference between the watershed peak and lowermost elevation is total relief. In the present study, the peak and the lowest elevation point is at 603 and 390 respectively. The ratio of total relief to the distance adjacent to the length of the watersheds horizontally along the main drain is the relief ratio. Higher relief ratio indicates higher soil loss, whereas higher ruggedness number of the study area as shown in Table 4 predicts topography of badlands and highly vulnerable to soil erosion.

Table 2. Linear aspect parameters

Stream Order, u	Stream Number, Nu	Sum total stream length, Lu (km)	Bifurcation Ratio	Length of overland flow (km)	Basin perimeter, P (km)	Basin length, L (km)
1	5982	410.0		0.012	16.86	5.908
2	2518	114.0	2.375			
3	957	38.66	2.631			
4	519	20.40	1.843			
5	158	6.474	3.284			
6	198	7.911	0.797			
7	61	2.772	3.245			

Table 3. Areal aspect parameters

Basin Area, Au (km^2)	14.96
Drainage Density, Dd (km^{-1})	40.14
Drainage Intensity, Di (km^{-1})	17.31
Constant of Channel Maintenance, C (km^{-2})	0.025
Stream Frequency, Fs (km^{-2})	694.94
Circulatory Ratio, Rc	0.6605
Elongation Ratio, Re	0.739
Form Factor, Fr	0.428
Compactness Constant, Cf	1.23
Infiltration Number, If	27894.4
Drainage Texture, Rt (km^{-1})	616.28
Minimum Eroded Volume (km^3)	0.708

Table 4. Relief aspect parameters

Total Relief (m)	213
Relief Ratio, Rh	0.036
Relative Relief, Rr	0.0126
Ruggedness Number, Rn	8.549

Hypsometry

The percent hypsometric technique was utilized to get hypsometric curves for the study watershed. The hypsometric curve was generated by taking relative area (a/A) on the x-axis and relative height (h/H) on the y-axis as shown in Fig.2. In which 'a' is the area bounded by a pair of contours, and 'A' is the total area of the basin. Whereas 'h' is the higher elevation of the selected pair of contours above the base, and 'H' is the total height of the basin. Hypsometric integrals below 0.30 are generally considered as denuded or old basin, and hypsometric integrals greater than 0.60 were considered unstable or young basins. In between 0.30 to 0.60 watersheds were considered as a stable or mature stage (Singh and Singh 2018). The percentage of hypsometric and erosion integrals were computed using the following equation:

$$H_i = \frac{Elev_{mean} - Elev_{min}}{Elev_{max} - Elev_{min}}$$

Where Hi is the percentage of the existing volume compared to the basin's original volume. $Elev_{mean}$ is the mean elevation estimated

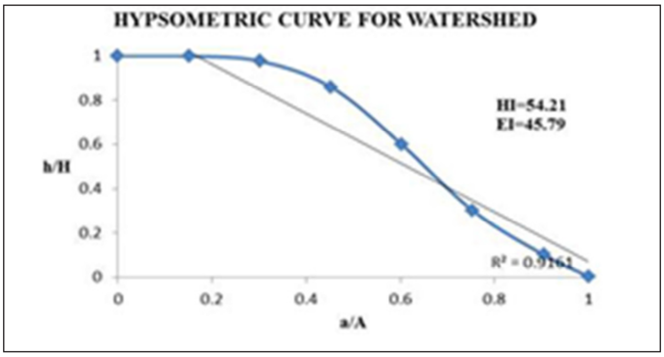

Fig.2. Hypsometric curve for study watershed

from the perceptible contours of the watershed; $Elev_{min}$ and $Elev_{max}$ are the lowest and extreme elevations of the watershed. The hypsometric curve obtained for study watershed is of S-shape with concave upward for higher elevation and convex downward for lower elevation. In the present study, the computed value of hypsometric integrals is 54.2, which indicates mature stage.

The quantitative analyses of all the three morphometric aspects and the hypsometric analysis predicts that the selected watershed is highly susceptible to soil erosion, which is also validated by field observations on Patiala-Ki-Rao. The field survey clearly revealed the eroded bare hills and the deposition of eroded sand on the stream bed after the rainy season as shown in Fig.3. Taking into account the high susceptibility of soil erosion, the prioritization of watershed it is necessary to identify erosion vulnerable areas for the planning and construction of the necessary soil and water conservation structures to control erosion. Watershed slope, soil types and land-cover are the primary causes responsible for soil erosion, therefore soil, slope and land-cover maps are prepared. Analytical hierarchical process (AHP) has been used to generate the final raster with the help of overlaying technique, to identify the areas susceptible to erosion based on priority.

RESULT AND DISCUSSION

Land-use/Land-cover

The land use/land cover information is needed for understanding the crop management factor (Kumar et al. 2018b; Singh et al. 2010a; Singh et al. 2010b; Singh et al. 2018). High-resolution world view satellite data was digitized to prepare a land use/land cover map. Six land use classes identified in the watershed area namely: forest, scrub land, agriculture, settlements, roads and stream shown in Fig.4. The major land use category of the selected watershed was non-arable forest rangeland and the coverage by vegetation on an average is moderate with small woody bushes, grasses, and trees. The main tree classes found in the area are *Eucalyptus tereticornis*, *Dalbergia sissoo*, *Acacia nilotica* and *catechu*. The main bush classes are *Lantana indica, Karonda, Z. numularia, Mehnder*, *Adatoda* and *Murraya koengii* and indigenous grasses like *Kana, Eulaliopis binnata, Dholu, S. spontaneum, Bansa, Cynadon dactylon* and *Aristida* are common in this area. During monsoon season stream network hinder the connectivity to the upper areas at several places where the road along the stream merges into the stream. To overcome this problem construction of bridges and roads are in progress.

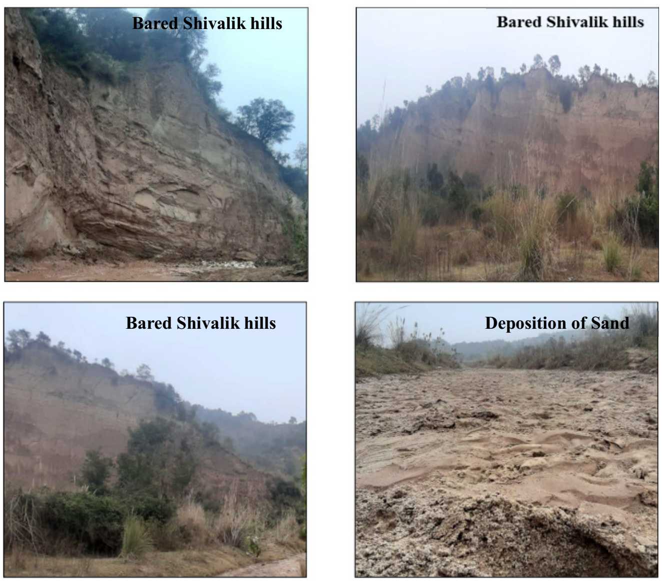

Fig. 3. Field photographs of study area showing bared Shivalik hills and deposition of sand on stream bed.

Soil

Soil map of the upper Patiala-Ki-Rao river basin was prepared by using NBSS and LUP soil map of Punjab and Haryana states. The map was geo-referenced to digitize different soil mapping units using ArcGIS 10.3. The selected area has been divided into three soil mapping units and the same has been taken in this study for assigning different soil parameters as shown in Fig.5 and Table 5. The texture of the soils varies from loam to loamy sand with low to medium moisture retention capacity. The percentage of organic matter in the surface soils ranges from 0.03 to 0.15. This may be due to the sweeping of surface soil with rains before proper decomposition. The soils were light textured and easily erodible with pH ranging from 8.0 to 8.2. Permeability of soil was very low even in the sandy phase. The stream bed surface covered with stones sand, silt, clay and conglomerates deposits.

Slope

The slope is an important feature for understanding the nature of the terrain. A higher degree of slope leads to more runoff, less infiltration and more erosion. The raster layer of slope in degrees was derived from DEM in ArcGIS 10.3 software and divided into four categories as shown in Figure 6. The slope of the terrain in a watershed adversely affects both soil and water resources. As the slope gradient increases, the volume and speed of the surface runoff increases, making the downstream area of watershed susceptible to flooding with an increase in soil erosion. Slope map of study area indicates towards higher runoff and soil erosion potential, therefore, there is need to quantify runoff and soil loss for the conservation of precious natural resources.

Table 5. Soil Classifications

Soil Mapping Unit	Description	Soil Taxonomy
001	Loamy skeletal soil with loamy surface on very steep slopes, moderately shallow to moderately deep moderately eroded and moderately gravelly, excessively drained	Typic Ustorthents
003	Calcareous, loamy Skeletal soil with loamy soil surface on moderately steep slopes, moderately shallow with severe erosion and moderate stoniness	Typic Ustorthents
005	Coarse loamy skeletal soil with loamy surface on very steep to steep slopes with severe erosion, moderately shallow to Moderately deep, excessively drained, severely gravelly	Typic Ustorthents

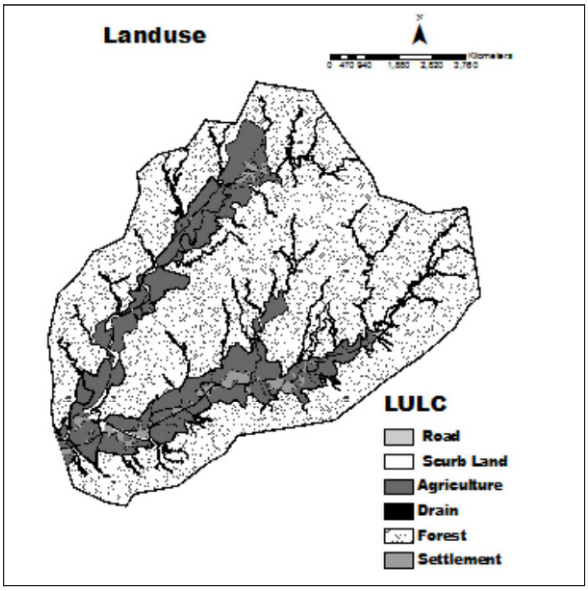

Fig.4. Landuse Map of Study Area

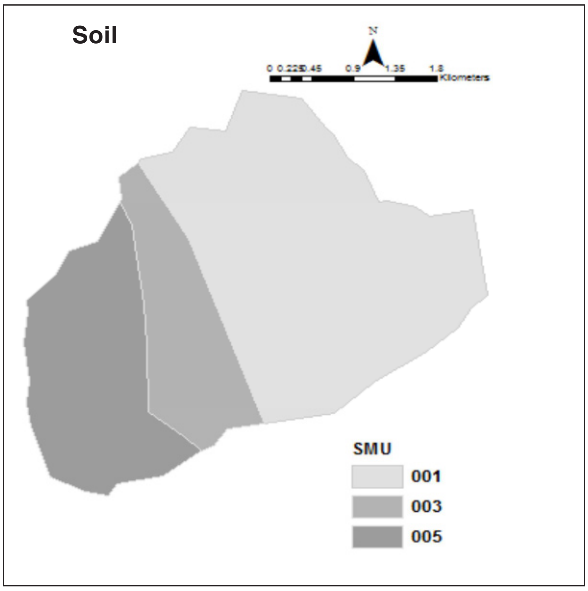

Fig.5. Soil Map of Study Area

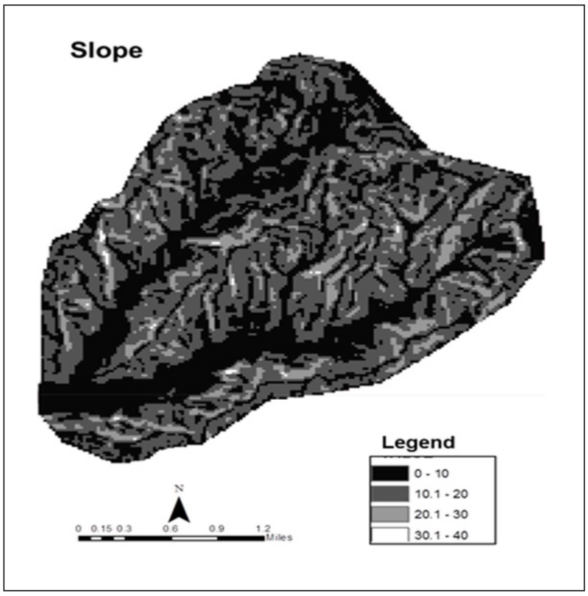

Fig.6. Slope Map of Study Area

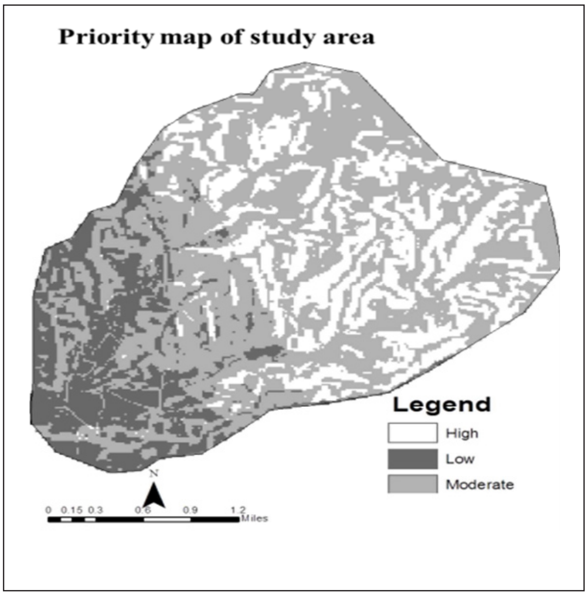

Fig.7. Priority Map of Study Area

Prioritization of Watershed

Various researchers dealing with the problem of determining areas vulnerable to erosion within a watershed, ranked the areas according to the priority. In the present study, RS and GIS have been used for the characterization and prioritization of watersheds for decision- making and planning conservation techniques to save precious natural resources with the help of the analytic hierarchy process (AHP) proposed by Saaty (1980). As shown in Fig.7, the study area was divided into high, medium and low priority classes, which is very useful for making decisions, planning and implementing conservation practices accordingly. In this method weightage was assigned to each layer and ranks were assigned to each category within the layer in terms of priority for soil erosion susceptibility. ArcGIS overlaying technique was used to generate the final raster after assigning weightage and ranking to each layer according to the priority for soil erosion susceptibility. The values assigned to weightage and ranks based on available information and expert knowledge. As it is known that, the slope has the greatest impact on the erosion process as compared to land-use and soils, therefore more weightage has been assigned to the slope. The slope was again divided into four sub-categories in which a higher degree of the slope has been assigned higher rank as compared to a lower degree of slopes. Similarly, suitable weightage was assigned to each layer and ranks were assigned to each sub-category within the layer in terms of priority for soil erosion susceptibility. In the present study slope, land-use and soil thematic layers were prepared using the ArcGIS overlay technique, watershed areas susceptible to erosion were identified and prioritized into three different categories. The three different categories are low, medium and high priority based on soil erosion vulnerability, which was validated with field investigations.

CONCLUSION

Based on the present study the watershed is classified into three categories: high, medium and low priority susceptible to soil erosion. These categories provide guidelines to decision maker for adopting relevant soil conservation techniques and best-suited BMPs to control the adverse effects of soil erosion based on priority. Following protection measures are recommended to selected watershed areas according to the severity of soil erosion vulnerability.

- On the drainage line of the watershed check dams are recommended to reduce the channel gradient for area falling under high priority.

- Bunds have to be constructed at the area susceptible to high soil erosion. These structures are also useful for increasing groundwater and conserving soil and water resources.
- Gully plugs have to be constructed at the confluence to reduce the velocity of flow.
- For overall rejuvenation trees, plants and soil binding grasses have to be planted on degraded areas of the watershed
- Water harvesting structures were recommended to be built on lower-lying areas to conserve water for agricultural and recharging the groundwater table. These conservation structures also prevent lower-lying areas from flooding during heavy rains.
- Forests have to be protected from grazing and tree cutting.

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