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Soil Erosion Susceptibility Assessment of the Lower Himachal Himalayan Watershed

Omvir Singh* and Jagdeep Singh

Department of Geography, Kurukshetra University, Kurukshetra – 136 119, India
***E-mail:** *ovshome@yahoo.com; ovshome@gmail.com*

ABSTRACT

Assessment of erosion status of a watershed is an essential prerequisite for integrated watershed management. It not only assists in chalking out suitable soil and water conservation measures to arrest erosion and conserve water but also helps in devising best management practices to enhance biomass production in watersheds. Keeping this in view, the present study has been undertaken by involving geospatial-statistical techniques to determine the critical and priority areas for soil and water conservation in Suketi watershed of the lower Himachal Himalayan region. A novel weighted sum analysis technique was used for ranking each of hydrological unit by obtaining the weightages from various morphometric parameters. This technique offers dynamic, effective and sustainable approach over traditional prioritization methods in which significance of each parameter were considered equally. Considering this approach, sub-watersheds were delineated into low, medium and high priority zones. The results illustrate that about 52 % of sub-watersheds of Suketi watershed are in moderate to high erosion and runoff susceptible zones. Therefore, these potential areas can be considered for preferential soil and water conservation planning. The results obtained from the study will be useful for various stakeholders such as agriculturists, water resource managers, conservation measures planners and decision policy makers for better management practices and decision making. The geospatial-statistical technique can be used for effective estimation of erosion status of watersheds leading to watershed prioritization for taking up soil and water conservation measures in watershed systems. Finally, this technique can be very useful in remote, rugged and inaccessible watersheds with absence of soil erosion and runoff monitoring.

INTRODUCTION

Soil erosion is a major environmental and agricultural problem worldwide and has far reaching economic, political and social implications (Thampapillai and Anderson, 1994; Grepperud, 1995). It has long-term impacts as it causes loss of fertile top soil and reduces the productive capacity of the land and thereby creates risk to global food security (Mosbahi et al., 2013). Globally, each year about 75 billion tons of soil is removed due to erosion, with most coming from agricultural land and as a result, around 20 Mha of land is lost. Of this, 1,903 Mha are subject to soil erosion by water and 548.3 Mha by wind erosion. In addition, soil erosion rates are very high in Asia averaging 13,800 t km^{-2} yr^{-1} (Oldeman, 1994; Pimentel et al., 1995). Furthermore, about 175 Mha of land in India, constituting about 53% of the total geographical area, suffers from effects of soil erosion and other forms of land degradation. Active erosion caused by water and wind alone accounts for 150 Mha of land and remaining 25 Mha land have been degraded due to ravines, gullies, shifting cultivation, salinity, alkalinity, and water logging. It has been estimated that in India about 5334 Mt (16.4 t ha^{-1}) of soil is detached annually, about 29% is carried away by the rivers into the sea and 10% is deposited in reservoirs resulting in the loss of the storage capacity (Narayan and Babu, 1983; Mandal and Sharda, 2011). Estimates also indicate that the loss of nutrients due to soil erosion ranges from 5.37 to 8.4 million tons thus involving a production loss of 30-40 million tons of food grain per year (Das, 2014). This problem is serious enough because India supports about 16% of world population on 2% of the global land area (Sebestian, 1995).

Currently, studies on soil erosion in India mainly focus on the Western Ghats (Rekha et al., 2011; Vandana, 2013; Sujatha et al., 2014), Vindhyachal and Satpura ranges (Javed et al. 2009; Aher et al., 2014; Chandniha and Kansal, 2014; Gajbhiye et al., 2014; Patil et al., 2015), arid region (Thakkar and Dhiman, 2007; Javed et al., 2011), Chhota Nagpur plateau (Biswas et al., 1999; Das, 2014) and north-eastern region (Suresh et al., 2004; Sarma and Saikia, 2012). Himalayan region, most parts of which are composed of weak and unstable formations such as sandstone, grits, shale and conglomerates. These formations are highly prone to soil erosion; therefore, more attention is needed. This area is also characterized by young mountain ranges with steep slopes, high seismicity, depleted forest cover, large-scale road construction, mining, cultivation on steep slopes, erratic monsoon pattern of rainfall, low water retention and high soil loss associated with runoff (Rawat and Rawat, 1994; Jain et al., 2000; Jain et al., 2003).

Assessment of erosion prone areas in the Himalayan region can be helpful for land evaluation where soil erosion is the main threat for the sustained agricultural production. Soil erosion assessment and mapping of erosion prone area serve the knowledge for soil conservation and land management (Sharma et al., 2012). Formulation of proper land management programs for sustainable agricultural development requires information on soil erosion (Bagherzadeh, 2014). Therefore, erosion assessment can be of great importance for any decision making and supportive in policy formulation for sustaining the environment as a whole coupled with the land productivity. Hence, it is essential to assess soil erosion risk.

For assessing soil erosion and subsequent prioritization for the watersheds, several methods have been designed in the past ranging from simple empirical models to process oriented physical based models (Jain et al., 2000; Baba and Yusof, 2001; Khan et al., 2001; Sharma et al., 2001; Chowdary et al., 2004; Ratnam et al., 2005; Pandey et al., 2007; Dabral et al., 2008; Javed et al., 2009; Pandey et al., 2009; Javed et al., 2011; Chen et al., 2011; Mosbahi et al., 2013; Jang et al., 2013; Patil et al., 2015). These empirical and process oriented models are cumbersome, data hungry and complex for watershed prioritization, which can be reinstated with less data requirement and effective techniques by using morphometric variables of watersheds (Aher et al., 2014).

Morphometry has been found to be efficient tools for identification and prioritization of erosion prone areas in watersheds. Physical characteristics of the watershed (shape, length of streams, drainage

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density and relief) are used as a tool in hydrological investigations and in resource management and conservation studies (Youssef et al., 2011). Comprehensive morphometric analyses provide an insight on basin evolution and its role in development of drainage morphometry (Esper Angillieri, 2008). Morphometric analysis is a significant tool for prioritization of micro-watersheds even without considering the soil type, rainfall and vegetation characteristics of the watersheds (Biswas et al., 1999; Jain and Goel, 2002; Das, 2014). Therefore, morphometric analysis has been extensively used to study the problems related to watershed management, resource conservation and sustainable development (Shrimali et al., 2001; Srinivasa et al., 2004; Vittala et al., 2004; Chopra et al., 2005; Vijith and Satheesh, 2006; Thakkar and Dhiman, 2007; Kar et al., 2009; Sreedevi et al., 2009; Javed et al., 2011; Magesh et al., 2011; Thomas et al., 2011; Magesh et al., 2012; Jasmin and Mallikarjuna, 2013; Magesh et al., 2013; Chandniha and Kansal, 2014; Kumar et al., 2015). These studies have shown that the shape parameters show a negative relation with runoff as well as soil erosion, while the other parameters (bifurcation, circulatory, form factor, texture, compactness and elongation ratios; drainage density; stream frequency) shows positive relation with soil erosion. Similar approaches were also followed by Hlaing et al. (2008) and Patel et al. (2012).

To sum up, morphometry is an important morphological indicator to assess the soil erosion susceptibility of watersheds and need to be estimated for the watersheds of fragile Himalayan ecosystem. It is observed that there is a lack of morphometric based studies to assess the soil erosion susceptibility in this region. Therefore, to fill the research gap, morphometric analysis has been undertaken for Suketi watershed, falling in Beas basin of Mandi district in the NW Himalayan region of Himachal Pradesh, India. In this study, Weighted Sum Analysis approach (Geospatial Statistical Technique) has been used for the assessment of critical erosion prone areas, which need to be provided with adequate soil and water conservation measures. Prioritizing erosion prone area in the watershed is essential where financial resources for executing a conservation plan are limited. This study will prove to be beneficial for remotely placed watersheds like Suketi and for those where direct observational setup is not available. The findings from this study could provide a scientific basis for future soil and water conservation planning and management in Suketi watershed.

STUDY AREA

Suketi is a seventh order watershed which falls under the left bank of the river Beas. It has a peculiar physiographic character because it encompasses a central inter-montane valley and surrounding mountainous terrain in the Lower Himachal Himalaya in Mandi district of Himachal Pradesh, India (Das and Haake, 2003; Das and Kaur, 2007; Bhargava et al., 2011). This watershed is socio-economically very important in Himachal Pradesh because it is well-known for grain production. The area of the watershed is about 422 km^2 and extends between latitudes 31º27'08" and 31º45'00" N and longitudes 76º48' 20" and 77º03'09" E (Fig. 1). The major tributaries are Chail khad, Kansa khad, Gangli khad, Dadour khad, and Ratti khad (Pirta, 2006) with dendritic to sub-dendritic drainage pattern (Pophare and Balpande, 2014). The watershed reflects late mature to monadnock stage of development of the fluvial geomorphic cycle. It has a perennial flow due to rainfall, snowfall and groundwater. It originates from an altitude of 2890 m amsl in the south-eastern part of the basin and confluences with the Beas at 760 m amsl in its northern most part. Huge sediment accumulation in the watershed indicates towards drainage reversal as a result of palaeo-tectonic activities (Bhargava et al., 2011). The major rock types in eastern sector of the watershed is composed of granite, gneisses, quartzites and phyllites, whereas the western part is occupied by sandstone, phyllite, schists, dolomites, limestones, quartzites, etc. The surface soil texture of the area is mainly of loamy type with light grey to brown colour.

The climate of the studied watershed is sub-tropical highland type in the scheme of Koppen's classification. The mean monthly temperature ranges from a minimum of 10.5ºC during January to the maximum of 21.5ºC during June. The weather in the area remains pleasant from April to October. The watershed receives precipitation both in the form of rain and snow. The average annual rainfall is about 1100 mm with average rainy days of 55-75 (CGWB, 2001, 2006, 2007). The area receives highest rainfall in the month of July and lowest in the month of November and December. Average seasonal percentage of annual rainfall for January to February is 7.2%, March to May is 6.3%, June to September is 81% and October to December is 5.4%. The mountain peaks of the study area experience snowfall during winter, which often comes down to 1300 m for a short period (Pirta, 2006). The predominant land use in the watershed is rocky outcrops (38%) followed by agricultural land (26%) and forest land (22%). Major anthropogenic activities are concentrated in the central part of the watershed.

MATERIALS AND METHODS

Data used

In the present study, different datasets have been used which includes (1) Advanced space borne thermal emission and reflection radiometer (ASTER) data, with 30 m spatial resolution (2) Survey of India (SOI) topographical sheets nos. 53A/14, 53A/15, 53E/2 and 53E/3 (3) High resolution digital globe image data from Google Earth through the software Map Graber 1.0.7 in 7 m resolution. Additional information of the watershed was collected through primary and secondary sources.

Generation of Digital Input Maps

In the present study, Arc GIS (9.3) was used in geo-registration and vectorization of topological information at 1:50000 scale for the Suketi watershed. Digital elevation model (DEM) representing the watershed terrain was derived by vectorizing the contours of Survey of India (SOI) topographic maps and ASTER 30 m resolution data with spatial analysis tools (Fig. 1). Spatial analysis tools use logical, efficient and consistent algorithm compared to the manual approach of drainage extraction. A detailed procedure for extracting drainage network using the above mentioned tool has been discussed by Sarangi et al. (2004) and Youssef et al. (2011). Drainage lines on the topographic maps were vectorized and updated using the high resolution digital globe image data (derived from Map Graber 1.0.7 version software on a resolution of 7.0 m) from Google Earth for DEM manipulation. DEM manipulations (aspect, contour, slope, flow direction and accumulation, drainage network etc.) were done with ArcMap spatial analyst tool (Band, 1986; Tarboton et al., 1991; Ghoneim and El-Baz, 2007; Ozdemir and Bird, 2009). The manipulated DEM is then used to generate the drainage network using the concept of channel initiation threshold. The drainage and DEM generated in this manner were further used to delineate the boundaries of Suketi watershed and its seven sub-watersheds (designated as sub-watershed 1 to 7) (Fig. 1).

Computation of Morphometric Parameters

Number of streams and other measured parameters were created into attribute tables. The morphological characterization of the watersheds was carried out with the help of drainage patterns and others measured parameters using spatial analysis tools. The computed parameters include the linear, areal, shape and relief aspects of the watersheds. The basic morphometric parameters such as geometric (area, perimeter, basin length, length of the main channel) and stream

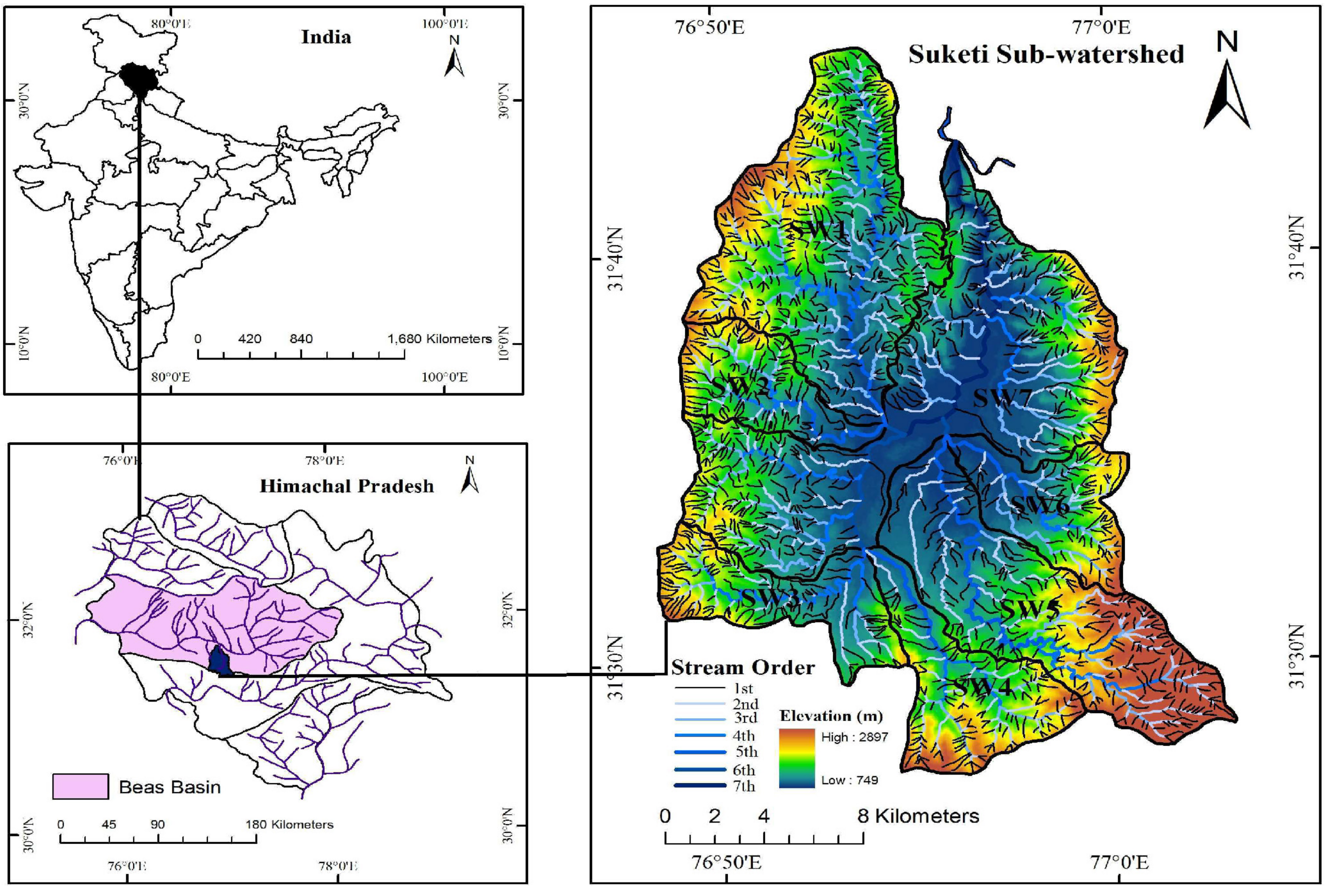

Fig.1. Location of Suketi watershed in Himachal Pradesh along with ASTER Digital Elevation Model (DEM) and drainage network.

(number and length of streams) parameters were obtained from the natural drainage system layer. The length of the watersheds was calculated by summing the length of the main stream channel and the distance from the top of the main channel to the watershed boundary (Altaf et al., 2013). The stream network ordering was designated by using nomenclature system of Strahler (1964).

Morphometric Parameters for Prioritization

Different parameters of the watershed geometry have been considered as erosion risk assessment factors in the natural drainage systems (Aher et al., 2014). However, in this research, stream frequency, drainage density, drainage texture (areal parameters), circulatory ratio, form factor, elongation ratio, compactness coefficient and basin shape (shape parameters) have been used for prioritization of sub-watersheds for preferential treatments.

Ranking Based Morphometric Parameters

Generally, stream frequency, drainage density and drainage texture ratio show a positive correlation with land and water degradation factors (Aher et al., 2014). Therefore, ranking was done by assigning highest priority, i.e., 1 for the sub-watershed having maximum value of the parameter, and least priority ranking is given to the sub-watershed having minimum value of the parameter. However, the remaining shape parameters (circulatory ratio, form factor, elongation ratio, compactness coefficient and basin shape) generally show a negative relationship with the land and water degradation factors. Consequently, ranking was done by assigning highest priority, i.e., 1 for sub-watershed having minimum value for the parameter and similar procedure was followed until the last priority number.

Weighted Sum Analysis (WSA) and Final Ranking

After the ranking of each selected erosion assessment parameters, the correlation matrix was designed and correlation coefficients calculated. Subsequently, the grand total was obtained from sum of the correlation coefficients. The final weightages were computed for each parameter by dividing the sum of correlation coefficient of each parameter by grand total of correlations. By giving these weightages to selected parameters, following model is formulated to assess the final priority of a particular watershed. The formulated model is as follows:

$$\text{Prioritization} = (0.250.F_s) + (0.403.D_d) + (0.218.T) - (0.032.R_c) - (0.073.F_f) - (0.073.R_e) + (0.226.C_c) + (0.081.B_s) \quad (1)$$

where, F_s is the stream frequency; D_d the drainage density; T the drainage texture; R_c the circularity ratio; F_f the form factor; R_e the elongation ratio; C_c the compactness coefficient and B_s is the basin shape. Finally the compound parameters values of all the seven sub-watersheds were estimated on the basis of weightages of each selected erosion assessment parameters. Based on the compound parameter value the sub-watershed having the least value is assigned the highest priority denoted by 1, the sub-watershed with next least compound parameter value is assigned a priority denoted by 2, and so on. The sub-watershed that got the highest value of compound parameters was assigned the last priority. The same procedure was adopted by others for prioritization of sub-watershed within a catchment (Jain and Goel, 2002; Pandey et al., 2007; Aher et al., 2014).

The approaches of watershed prioritization (Patel et al., 2012; Das, 2014; Gajbhiye et al., 2014), rating was done by compound parameter value, in which equal importance was given to all the morphometric variables. For identification of potential areas for erosion risk assessment and management, equal importance to these variables is unfair as each watershed system has its own characteristics. Likewise, fewer studies were undertaken in Himalayan region to quantify,

Table 1 Methodology adopted for computations of morphometric parameters for Suketi and its sub-watersheds

Aspect	Morphometric parameters	Definition/formula	References
Linear aspect	Stream order (N_u)	Hierarchical rank	Strahler (1964)
	Bifurcation ratio (R_b)	$R_b = N_u/N_u+1$ Where, R_b = Bifurcation ratio N_u =Total no. of stream segments of order 'u' N_u+1=Number of segments of the next higher order	Schumm (1956)
	Mean bifurcation ratio (R_{bm})	R_{bm} = Average of bifurcation ratios of all orders	Strahler (1957)
	Length of main channel (Lm)	Length along longest water course from the outflow point of the upper limit of catchment boundary	
	Length of the stream of order u (Lu)	Length of the stream	Horton (1945)
	Mean stream length (L_{sm})	$L_{sm} = L_u/N_u$ Where, L_{sm} = Mean stream length L_u =Total stream length of order 'u' N_u=Total number of stream segment of order 'u'	Strahler (1964)
	Stream length ratio (R_L)	$R_L = L_u/N_u-1$ Where, R_L = Stream length ratio L_u =Total stream length of order 'u' N_u-1=The total stream length of its next lower order	Horton (1945)
	Length of overland flow (L_o)	$L_o = 1/D_d*2$ Where, L_o = Length of overland flow D_d = Drainage density	Horton (1945)
	Basin length (Lb)	Distance between outlet and farthest point on the basin boundary	Ratnam et al. (2005)
	Basin perimeter (P)	Length of watershed divide which surrounds the basin	
Areal aspect	Basin area	Area enclosed within the boundary of watershed divide	
	Drainage density (D_d)	$D_d = L_u/A$ Horton (1932) Where, D_d = Drainage density L_u =Total stream length of all orders A=Area of the watershed (km^2)	
	Stream Frequency (F_s)	$F_S = \Sigma N_u /A$ Where, F_s = Stream frequency ΣN_u =Total no. of stream of all orders A=Area of the watershed (km^2)	Horton (1932)
	Drainage texture (D_t)	$D_t = D_d*F_s$ Where, D_t = Drainage texture D_d = Drainage density F_s = Stream frequency	Smith (1950)
Shape aspect	Basin shape (Bs)	Bs= Lb^2/A Where, Lb = Basin length A = Area of the watershed	Gregory and Walling (1973)
	Circulatory ratio (R_c)	$Rc= 4*\pi*A/P^2$ Where, Rc = Circulatory ratio π=Pi value i.e. 3.14 A=Area of the watershed (km^2) P^2 =Square of the perimeter (km)	Miller (1953)
	Elongation ratio (R_e)	$R_e = 2/L_b*(A/\pi)^{0.5}$ Where, R_e = Elongation ratio L_b = Watershed length A=Area of the watershed (km^2) π=Pi value i.e. 3.14	Schumm (1956)
	Form factor (F_r)	$F_r = A/L_b^2$ Horton (1932) Where, F_r = Form factor A=Area of the watershed (km^2) L_b^2 =Square of watershed length	
	Compactness constant (C_c)	$Cc=0.2821P/A^{0.5}$	Horton (1945)
Relief aspect	Watershed relief (R_h)	R_h=H-h Where, R_h = Relative relief of the watershed H = Maximum elevation of the watershed H = Minimum elevation of the watershed	Schumm (1956)
	Relief ratio (R_r)	$R_r=R_h/L_b$ Where, R_r = Relief ratio R_h = Relative relief of the watershed L_b = Watershed length	Schumm (1956)
	Ruggedness number (R_n)	$R_n=R_h*D_d/1000$ Where, R_n = Ruggedness index R_h = Relative relief of the watershed D_d = Drainage density	Schumm (1956)

correlate and analyze several morphometric parameters for watershed prioritization where demarcation can be done by weightages of the individual morphometric variable. To overcome these drawbacks, WSA approach was used in this study because it utilizes ranking as well as statistical correlation analysis to attain better accuracy in prioritizing smaller hydrological units than that achieved in previous methods.

RESULTS AND DISCUSSION

Morphometric Analysis

Morphometric analysis of the Suketi watershed and its sub-watersheds has been performed through the measurement of linear (perimeter, basin length, length of main channel, stream length, stream order and number, stream length ratio, bifurcation ratio and length of overland flow), areal (area, stream frequency, drainage density any and texture), shape (form factor, elongation ratio, circulatory ratio, compactness constant and basin shape) and relief (watershed relief, relief ratio, ruggedness number) parameters. The standard computational procedures for calculating these parameters and obtained results of the delineated watersheds are given in Table 1 to 6.

Ranking of Sub-watersheds Based on Morphometric Parameters

Morphometric characterization of Suketi and its sub-watersheds performed through the analysis of linear, areal, shape and relief parameters reveal that different hydrologic systems behave differently as a result of their inherent individual characteristics. It was also revealed that no single parameter can explain the erosion susceptibility of a watershed for concerted planning and management. In the present study, the areal parameters such as stream frequency, drainage density, drainage texture and shape parameters like circulatory ratio, form factor, elongation ratio, compactness constant and watershed shape were used for the prioritization of sub-watersheds. Shape parameters show negative correlation with runoff and soil erosion, while areal parameters show positive correlation with soil erodibility (Thakkar and Dhiman, 2007; Aher et al., 2014). Based on the direct relationships for the areal parameters, the highest value of parameters was given rank 1; the immediate higher value was ranked 2 and so on, whereas for the shape parameters, the lowest value of a parameters was given rank 1; the lower value than this was ranked 2 and so on. The ranking of sub-watershed concerning areal and shape parameters is presented in Table 7. Relief parameters consider some of the linear, areal and shape parameters of the watershed which have already been considered for prioritizing the sub-watersheds. Therefore, to avoid repetition, relief parameters have been ignored.

Final Ranking of Sub-watersheds Based on Weighted Sum Analysis

After assigning ranks to above mentioned erosion assessment parameters, a correlation matrix was designed. Statistical correlation matrix showed that circularity ratio, form factor and elongation ratio have a negative correlation with most of the parameters (except few, e.g. elongation ratio shows positive with circularity ratio). Correlation analysis also showed that stream frequency bears highest correlation coefficients with drainage texture (0.857) followed by drainage density (0.821) and then compactness constant 0.714. Circularity ratio showed strongly negative correlation with stream frequency (-0.714) (Table 8). Similarly, the results for the correlation between stream frequency, form factor, drainage density, circularity ratio, drainage texture ratio, elongation ratio, compactness constant and basin shape are also computed and depicted (Table 8). The grand total obtained from sum of correlation is 8.857. The final weightages are calculated for each parameter by dividing the sum of correlation coefficient of each parameter by grand total of correlations. Finally,

Table 2. Drainage parameters of Suketi and its sub-watersheds

Sub-watershed code	Area (km^2)	Perimeter (km)	Basin length (km)	Length of main channel (km)
Sub-watershed 1	95.98	50.57	16.86	18.04
Sub-watershed 2	25.87	25.46	9.62	11.09
Sub-watershed 3	32.43	33.65	9.70	11.45
Sub-watershed 4	37.17	32.92	11.91	12.95
Sub-watershed 5	74.77	45.97	19.85	23.09
Sub-watershed 6	29.20	28.11	10.07	09.92
Sub-watershed 7	126.64	74.14	24.00	29.04
Suketi	422.02	113.30	31.20	44.91

Table 3. Stream order and lengths of Suketi and its sub-watersheds

Sub-watershed code	Stream numbers in different orders						Order wise total stream lengths (km)					
	1	2	3	4	5	Total	1	2	3	4	5	Total
Sub-watershed 1	397	84	20	4	1	506	199.6	56.67	38.01	18	13.58	325.90
Sub-watershed 2	103	27	4	2	1	137	60.09	13.69	6.17	4.24	6.87	91.06
Sub-watershed 3	102	21	5	2	1	131	68.25	18.29	6.13	13.3	0.61	106.60
Sub-watershed 4	133	27	6	2	1	169	61.95	23.25	9.05	5.82	6.61	106.70
Sub-watershed 5	216	44	10	2	1	273	115.6	51.99	14.54	12.4	17.06	211.60
Sub-watershed 6	89	23	6	2	1	121	47.78	14.34	13.75	3.71	6.08	85.66
Sub-watershed 7	369	83	18	4	0	474	210.00	69.032	42.44	18.80	0.00	340.20
Suketi	1409	309	69	18	6	1811	763.23	47.26	130.09	76.32	50.18	1267.71

Table 4. Linear aspects of Suketi and its the sub-watersheds

Sub-watershed code	Bifurcation ratio					Stream length ratio				
	I/II	II/III	III/IV	IV/V	Mean bifurcation ratio	II/I	III/II	IV/III	V/IV	Length of overland flow
Sub-watershed 1	4.73	4.20	5.00	4.00	4.48	0.28	0.67	0.47	0.75	0.15
Sub-watershed 2	3.81	6.75	2.00	2.00	3.64	0.23	0.45	0.69	1.62	0.14
Sub-watershed 3	4.86	4.20	2.50	2.00	3.39	0.27	0.34	2.17	0.05	0.15
Sub-watershed 4	4.93	4.50	3.00	2.00	3.61	0.38	0.39	0.64	1.14	0.17
Sub-watershed 5	4.91	4.40	5.00	2.00	4.08	0.45	0.28	0.85	1.37	0.18
Sub-watershed 6	3.87	3.83	3.00	2.00	3.18	0.30	0.96	0.27	1.64	0.17
Sub-watershed 7	4.45	4.61	4.50		4.52	0.33	0.61	0.44	0.00	0.19
Suketi	4.56	4.48	3.83	3.00	3.97	0.32	0.53	0.59	0.69	0.17

Table 5. Areal aspects of Suketi and its sub-watersheds

Sub-watershed Code	Drainage frequency	Form factor	Elongation ratio	Circularity ratio	Drainage density	Drainage texture	Compactness constant	Watershed shape
Sub-watershed 1	5.27	0.34	0.66	0.24	3.40	17.90	1.46	3.39
Sub-watershed 2	5.30	0.28	0.60	0.25	3.52	18.64	1.41	4.75
Sub-watershed 3	4.04	0.34	0.66	0.18	3.29	13.27	1.67	4.04
Sub-watershed 4	4.55	0.26	0.58	0.22	2.87	13.05	1.52	4.51
Sub-watershed 5	3.65	0.19	0.49	0.22	2.83	10.33	1.50	7.13
Sub-watershed 6	4.14	0.29	0.61	0.23	2.93	12.16	1.47	3.37
Sub-watershed 7	3.74	0.22	0.53	0.14	2.69	10.06	1.86	6.66
Suketi	4.29	0.43	0.74	0.21	3.00	12.89	1.55	4.78

Table 6. Relief aspects of Suketi and its sub-watersheds

Sub-watershed code	Watershed relief (m)	Relief ratio	Ruggedness number
Sub-watershed 1	1260	74.73	4278.20
Sub-watershed 2	1120	116.42	3942.30
Sub-watershed 3	1060	109.28	3483.00
Sub-watershed 4	1320	110.83	3788.47
Sub-watershed 5	2040	102.77	5773.77
Sub-watershed 6	1300	129.10	3813.63
Sub-watershed 7	780	32.50	2096.27
Suketi	2060	66.00	6188.05

the compound parameter values of all the seven sub-watersheds were estimated on the basis of weightages of each morphometric component (Table 9).

Prioritization of Sub-watersheds for Soil Erosion Susceptibility

In prioritization rating, the sub-watershed with the smallest compound parameter value will receive the highest priority, the next compound parameter value will receive second rank and likewise the ranking of each sub-watershed will be ascertained. The sub-watershed 2 receives highest priority ranking with compound parameter value (0.694), followed by sub-watershed 1 with the compound parameter value of (1.290), and the least priority rating has been given to sub-watershed 7 with highest compound parameter value of 7.589. The prioritization ratings obtained from WSA technique showed that morphometric characterization tool represented the important factors for appraising vulnerability of soil and water resources and will be the efficient method over data hungry conventional soil and water risk assessment methods especially when there is limited or unavailability of data.

Final prioritization map of the Suketi watershed along with prioritization ranking of seven sub-watersheds has been given in Fig. 2. The highest value of priority ranking for sub-watershed 2 signifies the greater extent of erosion, and it becomes the potential area for urgent provision of soil and water conservation interventions. Furthermore, the sub-watersheds of Suketi watershed were delineated into three priorities from high to low priority levels with ranges allotted hierarchically from compound parameter values and given in Table 10. The evaluated results illustrate that in the study area, 52.28% of area (five sub-watersheds) are in moderate and high susceptible zones, which indicates prospective areas for better conservation works for the efficient watershed planning and management (Fig. 3). Low priority for soil erosion was obtained for sub-watershed 5 and sub-watershed 7 with an areal extent of 47.72%.

CONCLUSIONS

Suketi watershed has been facing anthropogenic pressure in the form of deforestation, silting of agricultural lands, intensification of improper agricultural practices, sand mining and reckless urbanization. These practices have, in turns resulted in degradation of land and

Table 7. Preliminary ranking of various morphometric parameters of Suketi at sub-watershed scale

Sub-watershed code	Drainage frequency	Drainage density	Drainage texture	Circularity ratio	Form factor	Elongation ratio	Compactness constant	Basin shape
Sub-watershed 1	2	2	2	6	6	6	2	2
Sub-watershed 2	1	1	1	7	4	4	1	5
Sub-watershed 3	5	3	3	2	7	7	6	3
Sub-watershed 4	3	5	4	3	3	3	5	4
Sub-watershed 5	7	6	6	4	1	1	4	7
Sub-watershed 6	4	4	5	5	5	5	3	1
Sub-watershed 7	6	7	7	1	2	2	7	6

Table 8. Correlation matrix of morphometric properties of Suketi for the sub-watersheds

	Stream frequency	Drainage density	Drainage texture	Circularity ratio	Form factor	Elongation ratio	Compactness constant	Basin Shape
Stream frequency	1.000	0.821	0.857	-0.714	-0.464	-0.464	0.714	0.464
Drainage density	0.821	1.000	0.964	0.964	-0.714	-0.714	0.750	0.500
Drainage texture	0.857	0.964	1.000	-0.679	-0.643	-0.643	0.679	0.393
Circulatory ratio	-0.714	0.964	-0.679	1.000	0.214	0.214	-1.000	-0.286
Form factor	-0.464	-0.714	-0.643	0.214	1.000	1.000	-0.214	-0.821
Elongation ratio	-0.464	-0.714	-0.643	0.214	1.000	1.000	-0.214	-0.821
Compactness constant	0.714	0.750	0.679	-1.000	-0.214	-0.214	1.000	0.286
Basin shape	0.464	0.500	0.393	-0.286	-0.821	-0.821	0.286	1.000
Sum of correlations	2.214	3.571	1.929	-0.286	-0.643	-0.643	2.000	0.714
Grand total	8.857	8.857	8.857	8.857	8.857	8.857	8.857	8.857

Table 9. Prioritization and final ranking for Suketi sub-watersheds for soil erosion susceptibility

Sub-watershed code	Compound parameter constant	Priority ranking
Sub-watershed 1	1.290	Second
Sub-watershed 2	0.694	First
Sub-watershed 3	3.629	Fourth
Sub-watershed 4	4.556	Fifth
Sub-watershed 5	6.669	Sixth
Sub-watershed 6	3.573	Third
Sub-watershed 7	7.589	Seventh

Table 10. Delineation of compound parameter values into different priority levels

Priority type	Priority level	Sub-watershed	Area (%)
High	< 2.99	Sub-watershed 1, Sub-watershed 2	28.87
Medium	2.99 to 5.29	Sub-watershed 3, Sub-watershed 4, Sub-watershed 6	23.41
Low	> 5.29	Sub-watershed 5, Sub-watershed 7	47.72

water resources in the watershed. In the light of these facts, the present study was aimed at prioritizing the Suketi watershed in the lower Himachal Himalayas on the basis of susceptibility to soil erosion. The identification of critical soil erosion prone areas is a pre-requisite for developing and implementing the best management practices of land and water conservation. Therefore, morphological characterization was carried out through the measurement of linear, areal, shape and relief aspects by employing a more logical WSA technique. This technique offers dynamic, effective and sustainable approach over traditional watershed prioritization methods in

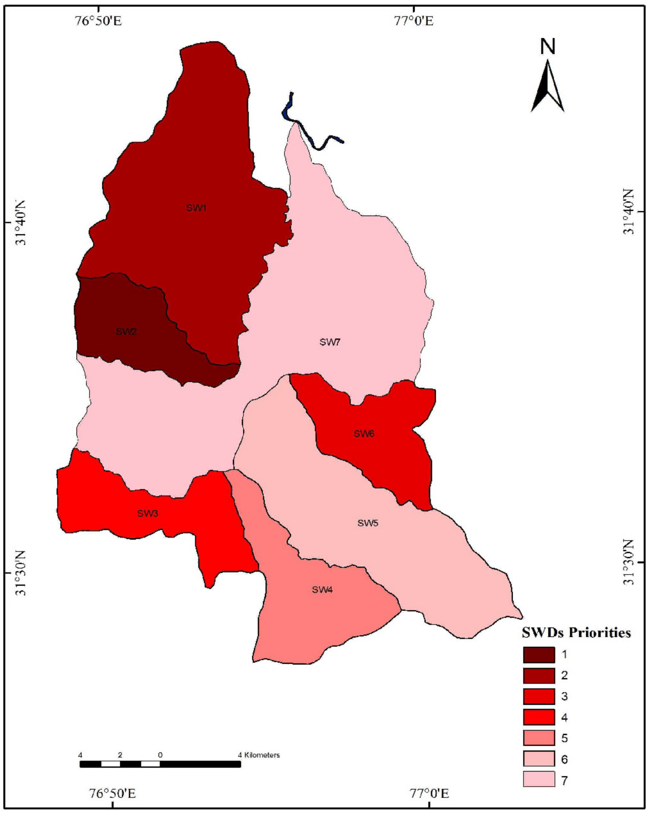

Fig.2. Sub-watersheds prioritization ranking map based on WSA values for the Suketi watershed.

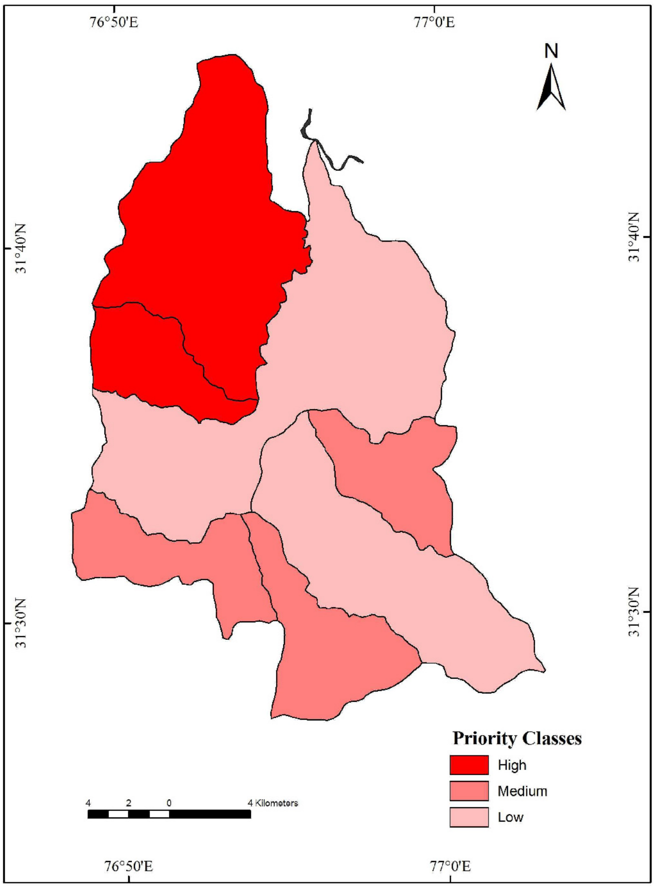

Fig.3. The priority wise classification of sub-watersheds at Suketi watershed.

which significance of several characterization parameters were considered equally. The results show that sub-watershed 2 obtained first ranking on the basis of integrated weightage analysis. Priority wise classification map will be useful in classification of conceivable zones for management over the prevailing hydro-geomorphologic conditions. Prioritized classification conferred that sub-watershed 1 and 2 falls in the highly susceptible zones, which indicates potential top priority areas for soil and water conservation works for the efficient watershed management planning. The land use pattern (waste land and scrub land about 70 per cent) can be held responsible for higher soil erosion in these sub-watersheds in comparison to other. Identification of prospective zones for planning and management of conservation measures at micro-level leads towards sustainable development and establishment of control measures over the entire watershed at similar instance. The conservation strategy recommended include building up of water harvesting structures, reduce the pressure on land, replacing the agricultural land with natural vegetation and restriction on infrastructural development such as brick kilns, reduction in density of residential buildings and running of forestry programmes under the Suketi sub-watersheds. Coupling of geospatial tools with statistical method resulted in demonstration of WSA as one of the viable and significant technique, particularly over the data hungry prioritization approaches. To conclude, this approach will be useful to different stakeholders such as agriculturists and natural resources managers for better decisions making.

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