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Assessing the Susceptibility to Water-Induced Soil Erosion: A Test in Kaushalya Watershed of the Himalayan Foothill Ecosystem

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Abstract

Soil erosion hazard maps can be an essential tool in erosion prone areas as they explain and display the distribution of hazards and areas likely to be affected in different magnitudes. Therefore, the aim of the present study is to map and evaluate the water-induced soil erosion susceptible areas in Kaushalya watershed of the Himalayan foothill ecosystem. Based on field survey and information analysis, eleven pertinent bio-physical parameters such as rainfall, vegetation coverage, soil type, geomorphology, slope angle, stream power, topographical curvature, drainage density, topographical wetness, land use/land cover and slope aspect have been identified as both the soil forming processes that control soil erodibility and the erosive power of running waters. Remote sensing data and geographical information system (GIS) has been integrated with the weighted index overlay (WIO) method for the identification and delineation of soil erosion susceptibility areas in the watershed. The obtained results reveal that 12.92 per cent, 27.11 per cent, 22.43 per cent, 28.02 per cent and 9.52 per cent areas of the watershed are under very low, low, moderate, high, and very high erosion susceptibility, respectively. The high soil erosion susceptible areas have been observed in areas with high terrain alteration, high relief and slopes with the intensity and duration of heavy precipitation storms during the monsoons, whereas very high erosion susceptibility areas have been observed on convex slope positions. In order to test the reliability of the adopted model for the soil erosion susceptibility map, validation procedures have been also executed.

Keywords: *Soil Erosion, Susceptibility, Kaushalya Watershed, Shiwaliks, RS and GIS.*

Introduction

Soil is the precious gift of nature to the mankind but ironically, it is also the most neglected resource on the earth (Ismile and Ravichandran, 2008). The formation of soil is slow, averaging 100-400 years for a centimeter of topsoil to develop (Lal, 2004). On the contrary, permanent soil degradation due to erosion can occur in a very short span of time. Soil erosion on large tracts of cultivable land has made vast areas economically unproductive which is seriously undermining millions of people's livelihoods (Prasannakumar *et al.,* 2012). It is second biggest problem, the world faces next to population growth (Pimentel, 2006). Soil erosion negatively impacts ecology and can lead to reduced crop productivity, food security, worsened water quality, lower effective reservoir water levels, flooding, habitat destruction and environmental safety (Dabral *et al.,* 2008; Park *et al.,* 2011; Pimentel and Burges, 2013).

Worldwide the loss from soil erosions is estimated to be about 400 billion dollar/year (Fletcher, 2006). About 30 per cent of the world's arable land has become unproductive as 60 percent of its soil has been washed away (Lohan and Gupta, 2003). Of this, two-thirds of degraded land is in Asia and Africa, where most of the world's poor live (Bahadur, 2009). The developing countries like India are more prone to this problem because of the inability of their farming populations to replace lost soils and nutrients (Shankar, 1999). About 53 per cent of total land in India is under soil erosion (Bagdi *et al.,* 2013). The problem is more serious in Himalayan foothill ecosystem of north India called Shiwalik is considered as one of the most degraded and fragile ecosystems of the country, where about 280 million tones of soil is lost annually due to steep terrain, poor vegetal cover, unstable geology and immature soil conditions (Jain *et al.,* 2001; Kumar *et al.,* 2012). An area of about 1.92 lakh ha in the Shiwalik foothills spread over the state of Haryana has been identified as one of India's eight most degraded rainfed agro-ecosystems (Grewal *et al.,* 2003).

By virtue of its geographic location spreading over Shiwalik of Haryana, Kaushalya watershed is equally environmentally sensitive area. The area of the watershed provide a spectacular picture of accelerated erosion due to high rainfall and high levels of runoff leading to severe water, food and fodder shortages (Arora *et al.,* 2006). The combined impact of these factors leads to continuous depletion in the fertility of soil as well as deterioration in the water quality (Lal, 2004). Considering the gravity, rate and amount of soil loss, several watershed development programmes are being implemented by State and Central Governments to conserve soil against erosion and to improve the soil fertility for sustainable development of the watershed (Kumar and Kushwaha, 2013). For this purpose, several treatment measures in the form of agronomic practices and engineering structure have been proposed. But construction of engineering structure requires lots of money. Thus, identification of most vulnerable areas to apply suitable procedure as per the site conditions and their application in correct way is the most important to achieve the desired results (Panhalkar, 2011). Therefore, the information on the spatial extent of erosion risk area and its severity are pre-requisites for soil conservation planning and implementation of effective soil and water conservation measures in any watershed.

Identify the soil erosion hazard risk is too complex and conventional method of mapping these lands based on field survey does not provide spatially explicit information (Kumar and Kushwaha, 2013). Hence, in order to quantify the volumes and identify soil erosion areas and to permit suitable risk evaluations by technology, various approaches and methodologies (ranging from rule-based physical- to empirical- to process-based models) have been developed and tested during the last 30 years in several areas throughout the world, at different spatial scale (Romkens *et al.,* 2001; Bahadur, 2009; Rahman *et al.,* 2009; Park *et al.,* 2011; Prasannakumar *et al.,* 2012). The most empirical and process based models are based on a huge body of experimental and monitored data and are powerful tools for predicting soil erosion rates by combining a prefixed set of physical parameters, based on certain standardized coefficients and procedures, which have been optimized from empirical observations in sample areas (Conoscenti *et al.,* 2008; Rahman *et al.,* 2009; Magliulo, 2012). But these methods have been suffered from a number of drawbacks concerning extrapolation and spatial scale effects. Moreover, land managers are more interested in the spatial distribution of soil erosion risk than in absolute values of soil erosion loss (Zhu, 2012). However, the rule-based physical erosion risk methods represent erosional processes in watershed more realistically than empirical methods because they consider the growing physical laws between various hydrological processes and erosion (Rahman *et al.,* 2009). These methods can easily be exported to different environments and require extremely detailed set of parameters and thoughtfully computation steps. Generally, the methods do not provide volumes of soil loss due to water erosion, but allow for the production of susceptibility maps at various scales by defining geo-statistical relationships between a set of physical attributes and the spatial distribution of the landforms related to water erosion processes. Hence, rule-based physical erosion risk models are paramount predictive tools for evaluating soil erosion susceptible areas and conservation planning which help in the implementation of erosion control strategy (Romkens *et al.,* 2001).

Keeping in view the importance of studying one of the major environmental threats, soil erosion in Kaushalya watershed of Shiwalik Himalayas, the best performing rule-based physical multi variables susceptibility model, has been applied to evaluate water erosion susceptibility by following a statistical approach aimed at defining spatial relationships between soil erosion and variability of eleven physical attributes. The main goal of the present study is to draw up a soil erosion susceptibility map able to well reproduce the distribution of ephemeral and permanent eroded areas and to indicate those portions of the watershed, at present not hosting erosion landforms, where new susceptible areas are more likely to occur in the future. Furthermore, a validation procedure based on a spatial random partition strategy has been applied to test the effectiveness of the predictive model.

Geo-Environmental Setting of the Study Area

The present study has been undertaken in Kaushalya watershed. Kaushalya is a main tributary of Ghaggar river. It is located on an off shoot and lies between 30° 44′ to 30° 55′ North latitudes and 76° 52′ to 77° 6′ East longitudes (Fig. 1 See page 48). It covers an area of about 138.19 km^2. The general slope of the Watershed is north-east to south-west and varies between 0^o to 62^o. The elevation varies between 387 to 2115 m above mean sea level and presents a panoramic view. Geologically the study area is of recent origin and composed of sand stone, mud stone and conglomerates hence, highly susceptible to fluvial erosion. Being located at the boundary of Himalayan fault zone, the watershed is prone to earthquakes. The watershed areas are characterized by sub-tropical, hot and sub-humid climate. It has three distinct seasons, namely dry summer season from March to June, hot and humid rainy season from July to September and winter season from October to February.

The study area has received bimodal rainfall pattern that enables two cropping seasons per annum i.e. *rabi* and *kharif*. The average annual rainfall of the watershed is more than 1100 mm. Approximately 80 per cent of the annual rainfall is received from June to September, whereas October, November and sometimes December are the driest months. The watershed also receives winter rains from the western disturbances originating in the Mediterranean region. The soils of the watershed are shallow, light in texture (loamy sand to light sandy loam), neutral to alkaline in reaction and deficient in nitrogen and phosphorus and responsive to zinc and potassium. The area is vulnerable to soil erosion, fertility and micro nutrients. The main erosive processes that affect the landscape are related to runoff waters and mass movements that cause a rapid evolution of slopes. The seriousness of the problems can be imagined from the fact that about 3-7 cm top soil layer often disappears during a single monsoon season. Overland flow processes (sheet, rill and gully erosion) particularly act in areas without vegetation cover, in cultivated fields and pasture lands. Besides, the poor soil health has resulted in stagnation of crop productivity.

Objective of the Study

- The main objective of the present study is to generate a composite map of assessing susceptible area for water-induced soil erosion in Kaushalya watershed by employing effective soil erosion determining factors.

Materials and Methods

i. Data Sources

The adaptation of appropriate tools and techniques in any scientific investigation is necessary for proper interpretation because they act as foundation stones of the study. Different sources and types of data have been used in this study. The present study has utilized remote sensing data and employs geo-spatial technology to assess the susceptible areas to water induced soil erosion in the study watershed. The remote sensing data (LISS-IV MX) of high resolution satellite images of 5 m cell-size from National Remote Sensing Centre (NRSC) website acquired on October 25, 2015 for NDVI and land use/ cover map derivation. Ancillary data like Survey of India (SOI) topographic map of 1:50,000 scale has been procured from SOI regional office, Chandigarh to prepare the base map and drainage layers of the study area. Moreover, about 100 high resolution Digital Globe Image tiles for the study area from Google Earth have also been downloaded using the Map Grabber 3.2 software. For slope and topographical analysis (slope angle, stream power index, topographical curvature, topographical wetness index, and aspect of slope) Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM) with 30 m spatial resolution from Global Land Cover Facility (GLCF) website acquired on October 25, 2015 has been used. Information regarding soil and geomorphological types have been generated from the District Resource Atlas maps of Panchkula district prepared by Haryana Space Application Centre (HARSAC), Hisar. The data related to annual rainfall of the study watershed have been procured from Deputy Director General Office, India Meteorological Department, Northern Region, Chandigarh. Based on the above-mentioned data, several thematic maps have been produced. The methodologies adopted for calculating the water-induced soil erosion susceptibility hazard index (WiSESHI) within the study area has been summarized in the methodological flow-chart (Fig. 2 See page 49).

ii. Selection of the Determining Factors

The selection of the soil erosion determining factors is a key starting-point in any statistics-based susceptibility assessment procedure. The soil erosion is influenced by a wide range of factors. As highlighted by Ayalew *et al.,* (2005), there are no universal guidelines for selecting the parameters that influence soil erosion in susceptibility mapping. Therefore, to assess the water-induced soil erosion susceptibility of an area, a range of evaluation criteria, objectives and pertinent attributes should be identified according to the current knowledge with respect to the problem situation (Rahman and Saha, 2008). The existing literature about soil erosion by water point out that the rates of soil erosion are mostly determined by the interrelationships between intensity of hydraulic forces and erodibility of soil (Bryan, 2000). Hence, the determining factors in water-induced soil erosion susceptibility assessments should be selected among those controlling both the parameters mentioned above. Therefore, based on field survey, information analyses and suggested by several authors, eleven soil erosion determining factors (rainfall, vegetation cover, soil texture, geomorphology, slope angle, stream power, topographic curvature, drainage density, topographical wetness, land use/ cover and aspect of slope) were selected.

iii. Development of Water-induced Soil Erosion Susceptibility Hazard Index (WiSESHI)

The prime goal of the present study is to prepare a map and evaluate the water induced soil erosion susceptible areas in Kaushalya watershed. For this, all selected soil erosion determining factors have been quantified and rasterized to specific pixel size. Furthermore, each sub-class of the selected soil erosion stimulating factor has been ranked ranged from 1 to 5. The value '5' is assigned to the highest soil erosion triggering sub-class, whereas value '1' is assigned to the lowest sub-class pertaining to the specific soil erosion determining factor. For example, the lesser the vegetation cover in an area, the greater will be the amount of soil loss. Therefore, in this study, rank '5' has been assigned to very low, whereas rank '1' has been assigned to very high vegetation cover category. A similar scheme of rankings has been followed for other factors depending on their relative importance (Table 1). Moreover, the weightages of individual soil erosion determining factor have been calculated by considering its role in the soil erosion based on rank sum method (Table 2). The values thus obtained have been applied to assign the weightage to a selected soil erosion determining factor (Table 1 and 2). The maximum weightage has been given to the factor which has the highest susceptibility to soil erosion (rainfall) and the minimum being to the lowest susceptible factor (aspect of slope).

Table 1: Soil erosion susceptibility parameters used in weighted index overlay

Sr. No	Map Unit/Class	Area (km^2)	Area (%)	Rank	Influence (Per cent)
1	**Rainfall**				**16.67**
	<1000	24.22	17.52	1	
	1001-1050	30.14	21.81	2	
	1051-1100	33.33	24.12	3	
	>1150	50.49	36.54	4	
2	**Vegetation Cover**				**15.15**
	Very High	58.11	42.05	1	
	High	43.38	31.39	2	
	Moderate	23.93	17.32	3	
	Low	10.63	7.70	4	
	Very Low	2.13	1.54	5	
3	**Soil Texture**				**13.64**
	Coarse Loamy	0.58	0.42	5	
	Loamy	0.51	0.37	4	
	Loamy-Fine Loamy	31.31	22.66	4	
	Silty Loamy-Saline	1.95	1.41	2	
	Clayey-Loamy	2.50	1.81	3	
	Fine Loamy	1.01	0.73	2	
	Loamy- Coarse Loamy Skeletal	18.07	13.07	4	
	Loamy -Fine loamy Skeletal	12.27	8.88	3	
	Loamy-Loamy Skeletal	22.08	15.98	2	
	Loamy Skeletal	26.01	18.82	2	
	Fine Loamy- Sodic Skeletal	5.96	4.31	2	
	Water body Mask	6.30	4.56	1	
	Habitation Mask	9.63	6.97	1	
4	**Geomorphology**				**12.12**
	Shallow Valley Fill (<10m)	8.57	6.20	1	
	Sand Bars	0.88	0.64	2	
	Piedmont Alluvium-Shallow (<10m)	11.02	7.97	4	
	Piedmont Alluvium-Moderate (10-20m)	28.25	20.44	3	
	Structural Hill-Less Dissected	16.41	11.87	4	
	Structural Hill-Moderately Dissected	53.71	38.86	4	
	Structural Hill-Highly Dissected	19.36	14.01	5	

5	**Slope**				**10.61**
	Nearly Level (<3.0°)	18.51	13.39	1	
	Gentle (3.0°-6.0°)	17.04	12.33	2	
	Moderate (6.0°-15.0°)	29.66	21.46	3	
	Steep (15.0°-30.0°)	52.15	37.74	4	
	Very Steep (>30.0°)	20.83	15.07	5	
6	**Stream Power**				**9.09**
	Very High (>5.0)	11.80	8.54	5	
	High (4.0-5.0)	40.83	29.55	4	
	Moderate (3.0-4.0)	60.35	43.67	3	
	Low (2.0-3.0)	14.96	10.83	2	
	Very Low (<2.0)	10.25	7.42	1	
7	**Topographical Curvature**				**7.58**
	Convex (>0.1)	36.52	26.43	2	
	Liner (-0.1- 0.1)	61.43	44.45	1	
	Concave (<-0.1)	40.24	29.12	3	
8	**Drainage Density**				**6.06**
	Very High (>5.0)	18.35	13.28	5	
	High (4.0-5.0)	34.71	25.12	4	
	Moderate (3.0-4.0)	37.73	27.30	3	
	Low (2.0-3.0)	27.83	20.14	2	
	Very Low (<2.0)	19.57	14.16	1	
9	**Topographical Wetness**				**4.55**
	Very High (>5.0)	27.62	19.99	5	
	High (4.0-5.0)	27.13	19.63	4	
	Moderate (3.0-4.0)	21.17	15.32	3	
	Low (2.0-3.0)	34.71	25.12	2	
	Very Low (<2.0)	27.56	19.94	1	

10	**Land use/ Land Cover**				**3.03**
	Built-up Land	9.63	6.97	1	
	Water bodies	6.30	4.56	2	
	Orchards/Plantation	2.25	1.63	4	
	Cultivated Land	23.14	16.75	5	
	Dense Forest	23.85	17.26	3	
	Open Forest	30.73	22.23	4	
	Dense Scrubs	25.81	18.68	3	
	Open Scrubs	9.76	7.06	4	
	Open Land	6.71	4.86	5	
11	**Aspect of Slope**				**1.52**
	West Direction	38.45	27.82	5	
	East Direction	30.62	22.16	4	
	Flat	1.28	0.93	3	
	South Direction	42.88	31.03	2	
	North Direction	24.96	18.06	1	
12	**Total**	**138.19**	**100**		**100**

Table 2: Calculation of normalized weight for each soil erosion susceptibility parameters for weighted index overlay

Sr. No.	Parameters of Criteria	Straight Rank (rj)	Weight (*n-rj+1*)	Normalized Weight (*wj*)	Criteria Weight (*Per cent*)
1	Rainfall Map	1	11	0.17	16.67
2	Vegetation Map	2	10	0.15	15.15
3	Soil Texture Map	3	9	0.14	13.64
4	Geomorphology Map	4	8	0.12	12.12
5	Slope Map	5	7	0.11	10.61
6	Stream Power Index Map	6	6	0.09	9.09
7	Topographical Curvature Map	7	5	0.08	7.58
8	Drainage Density Map	8	4	0.06	6.06
9	Topographical Wetness Index Map	9	3	0.05	4.55
10	Land use/ Land Cover Map	10	2	0.03	3.03
11	Aspect of Slope Map	11	1	0.02	1.52
N=11	**Sum**		**66**	**1**	**100**

After assigning the rankings to each sub-class, selected soil erosion determining factor maps have been reclassified using spatial analyst tools in ArcGIS 9.3 platform. Depending on their corresponding relative importance, weights have been assigned and subsequently, the development of WiSESHI has been processed. For better confidence level and accuracy, the weighted linear combination (WLC) has been adopted to derive the overall WiSESHI. The WLC technique is a decision rule for deriving composite maps and most often used in decision models using GIS (Malczewski *et al.,* 2003). In WLC, the values of all factors have been overlaid and multiplied with corresponding weight value in each grid and the integrated value is used to determine the soil erosion susceptibility hazard condition. The integrated assessment value of each grid is the sum of the corresponding weight values of all the factors have been expressed in the following equation.

$$WiSESHIi = \sum_{j=1}^{n} Fij \times Wj$$

where, *WiSESHIi* is the soil erosion susceptibility hazard index value of grid *i*, F*ij* is the *rank* value of grid *i* of factor *j*, *Wj* is the weight of factor *j* and *n* is the total number of factors. Thereafter, using the ranking and weightage of each soil erosion stimulating factor from Table 1 the final model for WiSESHI has been stated as:

$$WiSESHI = \sum (Fj_1 \times Wj_1 + Fj_2 \times Wj_2 \ldots\ldots\ldots Fj_n \times Wj_n)$$

Finally, to demarcate the soil erosion susceptible areas in Kaushalya watershed, all the soil erosion stimulating factor maps have been added in raster calculator tool in GIS environment. In the computed index, high WiSESHI values represent a high soil erosion hazard and vice-versa. The result computed from WiSESHI is a continuous value and, therefore, according to the equality distribution function, the results of the developed index have been graded in five levels of hazard (very high, high, moderate, low and very low) using the equal distance cluster principle. Each level presents the spatial distribution and regional difference of soil erosion hazard for the area.

iv. Procedure for Validation of WiSESHI

When natural resources, environmental and ecological systems are modelled and mapped with the aid of GIS and remotely sensed data, there is a need for validation for the developed model to ascertain whether its predictions match the expected results or not. However, in the present study, the predictive power of the WiSESHI has been tested. The prediction rate and success rate curves suggested by Magliulo *et al.,* 2009 have been obtained by intersecting the final soil erosion susceptible output map (prediction image) with the test and training subset of actual soil eroded area respectively (Fig. 4). The comparison of the predicted soil erosion susceptible areas and actual eroded areas for the Kaushalya watershed has been shown in Fig. 5. Finally, in order to validate the predicted results, field surveys are also conducted. During field visit, with the help of WiSESHI map, susceptible soil erosion sites have been cross-checked by selected samples from each erosion category. The photographs so taken during the field survey has been shown in Plates A and B (See page 50).

Results and Discussions

i. Rainfall

Rainfall is a major factor which affects soil erosion throughout the world (Ziadat and Taimeh, 2013). The impact of raindrops on the soil surface can break down soil aggregates and disperse the aggregate material. Soil movement by rainfall (raindrop splash) is usually the greatest and the most noticeable during short duration and high-intensity rainstorms. Therefore, distribution map of annual rainfall has been prepared using the capabilities of Ordinary Kriging estimator of Spatial Analyst Tool in GIS environment. In this study, amount of rainfall has been divided into four classes (Fig. 2 and Table 1). Average annual rainfall in the study area varies between 952 to 1177 mm and moves from north-western to north-eastern part of the watershed. Annually, more than 80 percent of the area in Kaushalya watershed receives rainfall above 1000 mm.

ii. Vegetation Cover

Vegetation cover is one of the most sensitive indicators to soil loss (Thakur, 2012). The existence of vegetation cover has decreasing effects on soil erosion susceptibility because it protects the soil from raindrop impact and splash, reduces the erosive action of surface runoff, and allows excess surface water to infiltrate (Conforti *et al.,* 2014). In this study, vegetation cover map has been derived from LISS-IV MX satellite images using Normalized Difference Vegetation Index (NDVI). The NDVI is the most common form of vegetation index, which is mathematically represented as:

$$NDVI = (NIR - R) / (NIR + R)$$

where, NIR and R stand for the near-infrared and red bands of LISS-IV MX image respectively. The derived vegetation cover map has been classified into very high, high, moderate, low and very low categories, while more than half of the area in Kaushalya watershed has been represented by a good cover of vegetation (Fig. 2 and Table 1).

iii. Soil Texture

The role of the soil texture is of utmost importance in determining soil erodibility because water infiltration primarily depends upon it. Fine-textured materials (clay) are generally characterized by a low infiltration favouring runoff and erosional processes (Anbazhagan *et al.,* 2005). The soil map of the watershed shows that soils range from highly mature to poorly developed soils which frequently appear strongly degraded on the surface by water erosion (Fig. 2 and Table 1). Major soil texture in the study watershed consists of loamy skeletal, loamy to loamy skeletal (34.8 per cent), loamy to fine loamy (22.7 per cent) and loamy to coarse loamy skeletal (13.1 per cent).

iv. Geomorphology

Geomorphology is considered as a critical factor for soil erosion susceptibility studies (Conforti *et al.,* 2014). Various geomorphic units are subject to different susceptibilities under the impact of active hydrological processes. The study area exhibits diverse geomorphological conditions due to its location, topography and geology (Table 1). Structural hills (64.7 per cent) and piedmont alluvium (28.4 per cent) are the most widespread geomorphological units. Structural hills are characterized by terrace surfaces, profiles and valleys, whereas piedmont alluvium is characterized by poorly embedded sand stone, conglomerates, sand rocks, clay and sand.

v. Slope Angle

The steepness of the slopes plays a crucial role in the preparation of the erosive process susceptibility maps in a given territory. Slope angle controls the surface run-off infiltration and the velocity of water flow. In the steep slope area, the run-off is high allowing less time for it to infiltrate and results into more erosion (Adiat *et al.,* 2012). In this study, the slope angle map has been produced automatically in ArcGIS 9.3 software using the ASTER DEM and has been divided into five categories (Fig. 2 and Table 1). Majority of the study area (about 53 percent) displays slope angle values ranging from steep to very steep slope subordinately, from 15^o to $>30^o$.

vi. Stream Power Index

Stream power index (SPI) is one of the main factors controlling slope erosion processes (Nefeslioglu *et al.,* 2008). Moreover, the areas with high stream power indices have a great potential for erosion (Kakembo *et al.,* 2009). Further, it is a measure of the erosive power of water flow and mathematically represented as:

$$SPI= \ln (As \times tan\beta)$$

where, As is the local upslope contributing area derived from flow accumulation raster and β is slope raster. The values of SPI factor have been categorised into five classes and the maximum area (62 per cent) falls under moderate to high SPI (Fig. 2 and Table 1).

vii. Topographical Curvature

Topographical curvature is described as the curvature of a contour line formed by intersecting a horizontal plane with the surface. The useful geomorphological information pertaining to erosion mapping can be extracted through its analysis (Davoodi *et al.,* 2015). The topographical curvature map of the watershed was produced in ArcGIS 9.3 software using ASTER DEM. In the case of topographical curvature, negative curvature exhibits concave, zero curvature represents flat, and positive curvature depicts convex. The values of topographical curvature indicate that maximum surface area of the watershed (55.6 percent) is convex and concave slope (Fig. 2 and Table 1).

viii. Drainage Density

Drainage density is a parameter sensitive to the erosional development. It shows the landscape dissection, runoff potential, infiltration capacity of the land, climatic conditions, and vegetation cover of the area (Avinash *et al.,* 2011). It is defined as the ratio of sum of the drainage lengths of the area. Drainage lines have been extracted from toposheets, whereas density map has been determined by using the line density algorithm in Spatial Analyst tool of ArcGIS 9.3 software. Drainage density map has been categorised into five classes using natural breaks classification scheme (Fig. 2 and Table 1). In the watershed, drainage density ranges from 1.12 to 6.53 km/km^2, with an average of 3.23 km/km^2, while 38.4 percent of the area exhibits very high to high values of drainage density.

ix. Topographical Wetness Index

Topographical wetness index (TWI) is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction and correlated with soil erosion process. It presents the spatial distribution of wetness conditions, which is defined according to the following equation (Conforti *et al.,* 2011).

$$TWI = \ln (As/\tan\beta)$$

where, *As* is the local upslope contributing area derived from flow accumulation raster and β is slope raster. Using raster calculation tool in ArcGIS 9.3, the TWI map has been prepared and divided into five classes using density slicing method (Fig. 2 and Table 1). The highest values of TWI in watershed have mostly been found in valley bottoms, terrace surfaces and gentle slopes.

x. Land Use/ Land Cover

Land use/ land cover types play a significant role in infiltration, evapo-transpiration, run-off, sediment generation, and stability of slopes. Barren and sparsely vegetated areas are affected by faster erosion, whereas existence of dense vegetation cover has decreasing effects on soil erosion susceptibility (Dai *et al.,* 2001). The land use/ land cover map of the watershed has been prepared by using hybrid classification method on LISS-IV MX satellite image. Land use types thus obtained have been grouped into nine classes (Fig. 2 and Table 1). The most common land use types within the study area are forest (39.5 per cent), scrubs (25.7 per cent) and agriculture land (16.8 per cent).

xi. Aspect of Slope

The aspect of slope affects duration of sun-light exposition, precipitation intensity, moisture retention, vegetation cover which subsequently stimulate the erosion process. Also, it can play a prominent role in rock weathering process and the formation of pedo-regoliths cover especially in drier environments (Sidle and Ochiai, 2006). The slope aspect map has also been produced from the ASTER DEM and has been grouped into five classes (Fig. 2 and Table 1). Slopes facing south and west directions dominate the watershed areas. East and north facing slopes in the study area are somehow less frequent.

xii. Results of Water-induced Soil Erosion Susceptibility Hazard Index (WiSESHI)

A water-induce soil erosion susceptibility assessment has been attained for the Kaushalya watershed by means of a geo-statistical multivariate approach. The spatial distribution of the susceptibility classes and their corresponding statistics has been reported in Fig. 3 (see page 49) and Table 3. The results presented in Table 3 show that about 13 per cent of the study area has been classified as very low soil erosion risk, about total 50 per cent of the watershed has been under low (27.1 per cent) to moderate (22.4 per cent) in WiSESHI. Total about 38 per cent of the land area characterized by high and very high susceptibility level indicates a great danger of erosion risk on the larger part of the land in the studied watershed. It reveals that the study area is in moderate to high erosion risk level on the whole. This result is a good agreement with the earlier studies in the similar conditions based on such quick monitoring methods (Jain *et al.,* 2001; Kumar *et al.,* 2012; Thakur, 2012; Sharma and Thakur, 2016). The areas with moderate to high erosion risk have been continuously distributed in the north-eastern part of the study area and sporadically distributed in the central parts where the soil and water conservation practices should be focused. Shallow soil depth and steep terrain in these areas contribute much to the high soil erosion susceptibility risk. The surfaces displaying the low to moderate susceptibility, almost exclusively occurred along the south and south-western parts of the watershed. These areas are mainly distributed in low to moderate altitudes and gentle to low slope gradient belt near the areas where the vegetation cover is good. The greatest erosion susceptibility arises from cultivation and spoiled vegetation.

A comparison between the susceptibility map and the land use/ land cover map highlight the fact that the areas mostly susceptible to soil erosion occur on both the cultivated and uncultivated areas (Fig. 2 and 3 see page 48). On the contrary, good relationships have emerged between the spatial distribution of the susceptibility classes and the geo-morphological/ lithological complexes, slope angle classes, upslope contributing area with high slope length, and stream power index values with a clearly concave topographic transverse profiles. The rainfall erodibility factor has been shown as an expected response, and has effect on the distribution of erosivity. Further, the results indicate that soils with medium to fine texture have low infiltration rates and, therefore, higher overland flow are subject to high rates of water runoff with the eroded soil being carried away in the water flow. In this analysis, the important role played by the parameters such as slope gradient, curvature, stream power, vegetation cover, and soil texture. Therefore, preservation of natural vegetation, proper land-use planning and appropriate conservation processes should be the top priority when formulating policy for the management of soil erosion.

xiii. Validation Results of the Developed WiSESHI

The critical strategy in prediction models is the task of validating the predicted results that can provide meaningful interpretation of the results. Fig. 4 is showing a high gradient in the first part which smoothly decrease monotonically. The prediction curve shows that 55 per cent of the total eroded area of the validation sets falls within 10 percent of the very high susceptible category. It

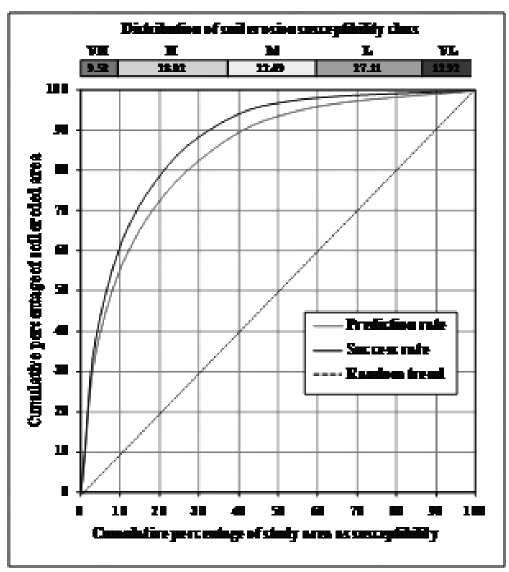

Fig. 4 Prediction and success rate curves showing the accuracy of the used susceptibility model

has been also observed that the prediction tends to overlap the success-rate curve and they are both far from the random trend. Furthermore, the validation procedure results show that the predictive power of the model is high-quality; therefore, about 87 per cent of the eroded area of the validation sets is correctly classified as falling in high and very high susceptibility classes (Fig. 5). Hardly about 2 per cent of the study area has been displaying low to very low susceptibility levels. It shows a clear association between the distribution of soil eroded area and the geographical variability of the susceptibility levels.

Table 3 Degree of susceptibility to water-induce soil erosion in Kaushalya watershed

Susceptibility class	Area (km^2)	Area (Per cent)
Very Low	17.85	12.92
Low	37.47	27.11
Moderate	30.99	22.43
High	38.72	28.02
Very High	13.16	9.52
Total	**138.19**	100.00

According to the method by Magliulo *et al.,* (2009), the susceptibility assessment procedure has been considered to be correct. Besides, ground verification of resulted sites (Plates A and B see page 50) also reveals that there are various visual indicators of erosional features *i.e.* severally eroded piedmonts, weak horizons, terraced cultivation, stream bank erosion, landslides, and degraded forest area also in association with the predicted results. Thus, the result of cross validation indicates the accurate choice of parameters and methodology for the present study.

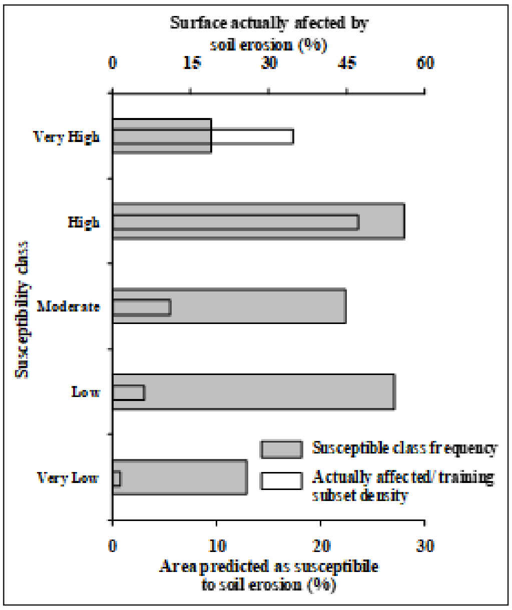

Fig. 5 Relative frequency distributions of the susceptible area and actually affected area

Conclusions

Assessment of soil erosion susceptible area is essential for the proper planning and management of natural resources and to mitigate the future soil erosion disasters. Therefore, the aim of the present study is to map and evaluate the water related soil erosion susceptible areas in Kaushalya watershed of the Himalayan foothill ecosystem.

In conclusion, the research points out that using the spatial distribution of soil erosion landforms and the geographical variability of erodibility parameters, a reliable susceptibility map of water erosion phenomena can be be produced. The study shows that the high soil erosion susceptibility has been observed in areas with high terrain alteration, high relief and slopes with the intensity and duration of heavy precipitation during the monsoons. The moderate soil erosion hazard areas can be considered as focal regions for protection and recovery. Hence, the first step should be taken to protect the area from further erosion, and then priority should be given to reduce the soil erosion and restoring destroyed vegetation. Moreover, the method used in this study has given results that have been in good accordance with the pre-existing literature and fully met the requirements of the statistical validation method. Therefore, the generated soil erosion susceptibility map can provide a basis for comprehensive and sustainable land management, and the methods used in this study are valid for generalized planning and assessment purposes to identify areas that are susceptible to soil loss. Such soil erodibility assessment method has been observed to be relatively easy to apply and this can allow frequent updating of the assessment procedure. Frequent updating is particularly important when the susceptibility to extremely dynamic processes, such as the water-induced ones, is assessed. Moreover, this is a site-specific model and applied at a local scale, but if the good accuracy data of determining factors are available at any scale, the proposed approach is easily exportable to other areas having the same geo-environmental conditions with regard to risk assessment on soil erosion by appropriate adjustment of some factors with local relevance.

Finally, the study illustrates that the ways of evaluating soil erosion susceptible zones presented in this study are practical and may prove to be useful for the decision makers and planning authorities, particularly for soil scientists and conservationists in other parts of the world with relatively low data and time requirements.

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