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GIS based risk modeling of soil erosion under different scenarios of land use change in Simly watershed of Pakistan

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Abstract

Soil erosion is a major environmental problem threating to agriculture and water resource development both developed and developing countries. Like other countries in the world, Pakistan is also dominated by mountain regions, barani lands and desert and facing with soil erosion problems. In this study, Revised Universal Soil Loss Equation (RUSLE), GIS and Remote Sensing technique was used to map the spatial distribution of the soil erosion risk in the Simly watershed, Islamabad, Pakistan. In Simly watershed, about 14 tons/ha/yr average soil erosion has been resulted. Area covered under very low risk zone of soil erosion (0 - 1 tons/ha/yr) was calculated as 41% and area covered under very high risk zone (> 100 tons/ha/yr) was calculated as 1.2%. The soil erosion in the agricultural and range land corresponds to 20.2 tons/ha/yr and 27.5 tons/ha/yr respectively. The soil erosion was found maximum under steep slopes (>30 deg) followed by gentle slopes (5-15 deg). In scenario l, all the scrub forest is assumed to be converted into range land, in which case the soil erosion increases to about 68.7% from the base land use of year 2013. In scenario 2, all the range land is assumed to be converted into agriculture land which increased to about 13% under this scenario. In scenario 3, all the range land of base land use of the year 2013 is assumed to be converted into scrub forest and a decrease of about 16.4% from that of the base land use in this scenario. There is a need to develop different strategies to control soil erosion, methodologies must be characterized for alternate soil loss risk zone corresponding to the risk levels.

Keywords: Soil erosion, land degradation, RUSLE, GIS and Remote Sensing.

1. Introduction

Soil erosion is becoming serious ecological issue (Stanley et al., 2000) throughout the 20th century (Angima et al., 2003) and is turning into a great degree of genuine natural issue, if not an emergency (Fu et al., 2005). The erosion of soil (30-40 tons/ha/yr) related problems has been highly noted in Africa, Asia and South American regions (Ananda and Herath, 2003), causing tremendous loss to the global productivity and economy. In shallow soil and sloping locations e.g., Ethiopian highlands (Tamene and Vlek, 2007), this could be a prime point to an irreversible soil loss and hence land deprivation. Land deprivation and erosion of soil created by rainwater is a key ecological topic in Pakistan. Out of Pakistan, almost 15.9 million hectares (Mha) area of aggregate land (20% of aggregate territory) is influenced by erosion of soil and 11.2 Mha (70%) out of this is influenced with rainwater disintegration (Nasir et al., 2006a).

To date, most investigations of soil erosion (Alam and Jamil, 2009; Bai et al., 2008; Gitas et al., 2009; IAEA, 2004) at the huge scale have emulated two general methodologies: (l) Assessment by the regional soil loss variables or accessible models (Bashir et al., 2013) and (2) Estimating soil loss inferring from graph and micro catchment gauges to catchments, watersheds and provincial gauges (Zhang et al., 2009; Braimoh and Vlek, 2008; Farhan et al., 2013). Both the methodologies have the generous impediment of spatial heterogeneity at the expansive scale, and more techniques need to be exercised for distinctive ranges.

The most generally utilized model for evaluating erosion is the Universal Soil Loss Equation (RUSLE) developed by Wischmeier and Smith (1978) which is focused around the parameters like R, K, LS and P elements. This equation is produced for the estimation of erosion from crop land and ordinary slanting regions however not from gully and stream channels. After a few upgrades the Revised Soil Loss Equation was determined same as USLE, which is relevant during distinctive circumstances. It assesses the power of erosion and its numerical qualities for the acceptance for wanting to control erosion (Renard et al., 1997).

Soil erosion was assessed by Nasir et al. (2006a) by utilizing RUSLE and GIS at Satrameel location in Islamabad during 1989-96. They evaluated soil loss running average 19.13 t/ha/yr in the area. The soil loss was the most astounding (28 tons/ha/yr) over the slopes with steep angle, while it ranges from 0.1 to 8 tons/ha/yr for horizontal soils. They decided that, topography and precipitation acts as the most imperative factors influencing erosion of soil in the sub-watershed area. Nabi et al. (2008) has utilized Morgan methodology to incorporate Remote Sensing and GIS for the assessment of soil erosion of Soan river basin in Potwar area. The soil loss evaluated for eleven separate types of land use extended from 1.93 to 6.34tons/ha/yr. The infertile area included soil loss of around 6.34 tons/ha/yr, which is the most astounding quality among other land use types. As indicated by Bashir et al. (2013) soil erosion because of water is turning into a genuine issue in downpour encouraged zones of Potwar area. Rawal Lake, a real source of water supply for Rawalpindi-Islamabad has diminished in its volume limit over the recent years. The information about temperature and precipitation of eighteen years (1988-2005) is utilized to figure Bagnouls-Gaussen aridity Index (BGI) and Modified Fournier Index (MFI) that is overlaid to produce erosivity map. Soil loss figured for both prospective (28 tons/ha/yr) and genuine risk loss (24 tons/ha/yr) by CORINE model incorporated with GIS and Remote Sensing systems demonstrated proficient and cheap approach to create soil risk erosion map.

Nasir et al. (2006b) integrated RUSLE with GIS tools and found effective in evaluating soil loss at watershed scale. The importance of main factors of RUSLE varies with geographic location and physical characteristics of the area. The study was adopted to assess risk of soil erosion in the Rawal and Ghabbir watersheds lying in the high and medium rainfall zones of Potwar region, respectively. An average rate of soil erosion predicted in the Rawal watershed was about 10.3 tons/ha/yr while in the Ghabbir watershed; it was about 22 tons/ha/yr. In Ghabbir watershed, high and very high-risk zones were estimated over 29% and 14% areas, respectively.

The present study has been fundamentally focused on examining the issue of soil erosion in Simly watershed with a specific end goal to moderate risk of soil loss and improve watershed wellbeing and life of the Simly dam. The particular objectives of the present study are 1) to assess the impact of various land use on soil erosion, 2) to analyze the spatial distribution of soil erosion in Simly dam on annual basis and 3) to propose measures for the reduction of soil erosion under different scenarios for watershed management. Revised Universal Soil Loss Equation (RUSLE), GIS, and Remote Sensing techniques were utilized to calculate the soil erosion. The analytical function raster calculator in GIS and supervised classification in remote sensing were applied to derive different parameters of the RUSLE that were finally used to predict the intensity of soil erosion in the target watersheds.

2. Materials and methods

2.1. Study area

Simly watershed is located between longitudes 72° to 74°E and latitude 32° 30' to 34.0° N over an area of about 162 km2 in north-eastern Potwar region of Pakistan (Figure 1). The study range lies predominantly in the mountainous tract of the Sub-Himalayan range. Its height ranges from 518 to 2,200 meters with a mean rise of 1,500 meters and an enduring ascent from south to north. The catchment is rhomboidal fit as a fiddle, 23 km long, around 7 km wide and is flanked on both sides by mountains extending from 648 m to 2,253 m. The Simly dam is situated 35 km northeast of Islamabad (Figure 1). The dam was built in 1982 on the Soan River to cater the water supply needs of the capital city Islamabad. The Simly supply has a stockpiling limit of 23,000 sections of land feet, which has been expanded to 33,000 sections of land feet by mid of 2005 (WAPDA, 2010). The day by day water supply to Islamabad capital domain is around 139.5 million liters (WAPDA, 2010). The topography of this research area is characterized by mountainous region with some steep slopes driving rainwater to structure various streams running at high speeds.

2.2. Data

In this study, Landsat 8 ETM+ (Enhanced Thematic Mapper) plus satellite image (path 150, Row 037) of November, 2013 was used as primary data. The Geotiff satellite image - Level 1 was obtained through online USGS source. The Google Earth images were used to supplement the image analysis for the verification of the land use classes. The secondary data included topographic map (published by Survey of Pakistan), soil map, land use map and geography from Soil Survey of Pakistan (SSP) was used. For topographic analysis the digital elevation model (DEM) of ASTER 30 m was acquired from online source. These datasets were easily available and cost effective.

For the assessment of soil loss in the watershed region, the recorded precipitation data of 2 meteorological stations of Islamabad and Murree for the year 2001-2013 was acquired from Pakistan Meteorological Department (PMD). This data was used to delineate rainfall zones and calculate erosivity (is a measure of the potential ability of soil, regolith, or other weathered material to be eroded by rain, wind, or surface runoff) R-factor. Based on this data, the rainfall recorded in the study area was from 990 mm to 1280 mm.

2.3. Data processing

The boundary of the watershed region was portrayed by utilizing DEM of ASTER 30 m of the territory in AVSWAT expansion in ArcGIS 10.2 software. The water channel of Simly watershed was considered as an exit location for the depiction of the watershed. Elevation map was created by DEM data which varies from 648m - 2253m above mean sea level (msl) (Figure 1). Using DEM data, map of slope was generated considering four classes of 1) flat to gentle (<5 degree); 2) medium (6-15 degree); 3) steep (16-30 degree) and 4) very steep (>30 degree). Analysis of the spatial variability of the land use classes were performed through both visual (ideal technique land use and land cover interpretation in medium and low resolution satellite images, its application being limited o high spatial resolution imagery because of the increase of details to recognize) and digital interpretation (widely accepted among the scientific community because of its statistical validation and automatic processing) (Puig et al., 2002). For qualitative study, visual interpretation technique was opted while for quantitative, digital interpretation. In visual interpretation, the area under different land uses was easily identifiable because of difference in tones, patterns, shape, size, color, texture and association of different features. Supervised classification was also performed using maximum likelihood method using ERDAS imagine 9.2 software, which is normally used to acquire reliable estimates of different land use in the study area for low resolution satellite images (Puig et al., 2002). Five land use classes were identified i.e., conifer forest, scrub forest, agriculture land, grassland and water bodies. To perform the process of supervised classification following steps were performed: 1) Feature Space Image 2) Defining Training Sites 3) Classification Process. Supervised classification technique was petitioned outlining land use classes by selecting training samples for every individual class focused on former information and knowledge of the field and training sites were defined in the feature space image of the study area Ground truthing was additionally completed using source information/data of Google earth image to verify the classification results. For defining and refining the signatures of different classes, two types of signatures non-parametric signatures and parametric signatures have been used. Supervised classification was adopted because it only considers the spectral value or one aspect for boundary class which make this classification easier and fast especially if the area of interest is large (Aryaguna and Danoedoro, 2016).

2.4. Measurement of soil erosion

The watersheds amount of erosion is interfaced to a difficult collaboration among the territory, geography, vegetation, soil, climate and land use. The RUSLE is the strategy generally received on the earth to anticipate amounts of rill erosion and gully from the land that is liable to diverse management procedures. The RUSLE is meant by the equation 1 (Wischmeier and Smith, 1978).

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

Where, A = Soil loss per unit area (tons/ha/yr); R = Rainfall-runoff erosivity factor (index); (MJ/hectare mm/yr); K = Soil erodibility factor (tons/ha/yr); LS = Slope factor (unit less); C = unit less management factor of cover; and P = unit less practice conservation factor. The values are input to create a map of original soil risk loss (Figure 2).

2.4.1 RUSLE factors Generation

In this study, maps of all RUSLE factors (R, S, K, LS, C and P) were calculated using equations 2-4 and all the results calculated through these factors were computed in GIS to get the final soil erosion map.

2.4.2.R- Factor (Erosivity)

Erosivity was calculated using below equation 2 (Arnoldus, 1980) which gives answer for inaccessibility of precipitation attributes data.

$$\text{Log } R = 1.93 \log \sum pi2/P2 - 1.52 \quad (2)$$

Where pi is the monthly and P is the annual precipitation.

2.4.3.K – Factor (Erodibility)

Erodibility is defined material with a greater or lesser degree of coherence is defined by its resistance to two energy sources: the impact of raindrops on the soil surface, and the shearing action of runoff between clods in grooves or rills. Erodibility was calculated using equation 3 (Lal and Elliot, 1994).

$$k = 2.8 \times 10 - 7 \times M1.14\,(1.2 - a) + 4.3 \times 10 - 3\,(b - 2) + 3.3 \times (c - 3) \quad (3)$$

Where M is the extent of soil particles (% residue + % fine sand)x(100 - % dirt), a is the percent of organic matter , b is the code number characterizing the soil structure (fine granular = l, fine granular = 2, coarse granular = 3, cross section or gigantic = 4), and c is the soil seepage class (quick = 1, quick to reasonably quick = 2, moderately fast= 3, moderately fast to slow = 4, slow = 5, very slow= 6) (Soil Survey Report, 1967).

2.4.5.LS Factor (length slope)

The map of length slope factor was figured using the DEM through "Spatial Analyst Extension" expansion of "ArcGIS" that was produced by Schmidt et al. (2003) using comparisons from Moore et al., (1993) for estimation of the steepness and length in slope as follows:

LS = Pow ([flowacc] * resolution / 22.1, 0.6) * Pow(Sin([slope] *0.01745) / 0.09, 1.3)) (4)

where, Flowacc = flow accumulation; Resolution = pixel size of the image used, and Slope = Slope.

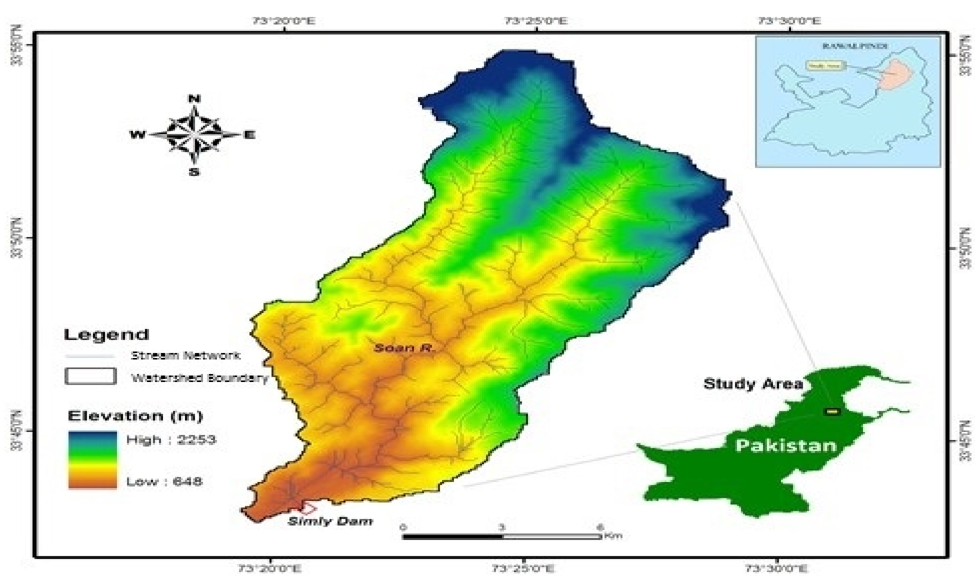

Fig. 1. An overview of Simly Watershed Boundary. Elevation declines towards South-West in the study area.

2.4.6.C Factor (cover management)

The cover Management factor rest upon vegetation type, phase of development and percentile estimation of cover. International Center for Agricultural Research in the Dry Areas (ICARDA) calculated diverse vegetative cover types from the defensive impact of vegetation and additionally the cultivating practices impact that incorporate the turn and types of crops (Oweis and Ashraf, 2012). On the premise of these values, C values were doled out to Simly watershed.

2.4.7.P Factor (conservative practice)

The support practice factor P represents the impacts of those practices that help in keeping soil from erosion by decreasing the rate of water spillover. It was watched that there was no such practice in the region of Simly watershed. Consequently, estimation of 1 was relegated for estimation of potential soil loss in the watershed region.

The response of various parameters of soil risk assessment was calculated considering future watershed changes in land use. The conversion of various land covers within 2001-2013 periods made the basis for emergence of these scenarios. Different scenarios are reported like all forest planting, 50% forest and 50% grass, 95% forest and 5% crop where the land area with slope 5% was used for crop production (Wang et al., 2006). The scenarios 1 and 2 are identified with diverse instances of deforestation while situation 3 relates to an afforestation case. These scenarios are focused around our field encounter that extensive urbanization is happening on the cost of wood cutting and continuous conversion of rangeland and scrub forest into agriculture land/built up land. Also, wood cutting is bringing about degradation of the scrub forest into shrubs and bushes.

3. Results and discussion

The interpolated (Inverse distance weighted (IDW) strategy was adopted for addition upheld within the Spatial Analyst Extension). Annual average rainfall values ranged between 1200 and 1600, higher in the eastern part of the watershed. 12 years rainfall data was collected from Pakistan Meteorological Department (PMD) from 2001-2013 on daily bases. The minimum monthly rainfall of 19.57 mm was measured in the month of November and maximum 289 mm in July. The minimum and maximum annual rainfall was measured as 1224 mm and 1560 mm respectively (Figure 3a). The precipitation dissemination was mapped using addition capacity of GIS to calculate the R factor. The values calculated for R factor ranging from 986 mm and 1280 mm expand s from north to south in the Simly watershed area (Figure 3b).

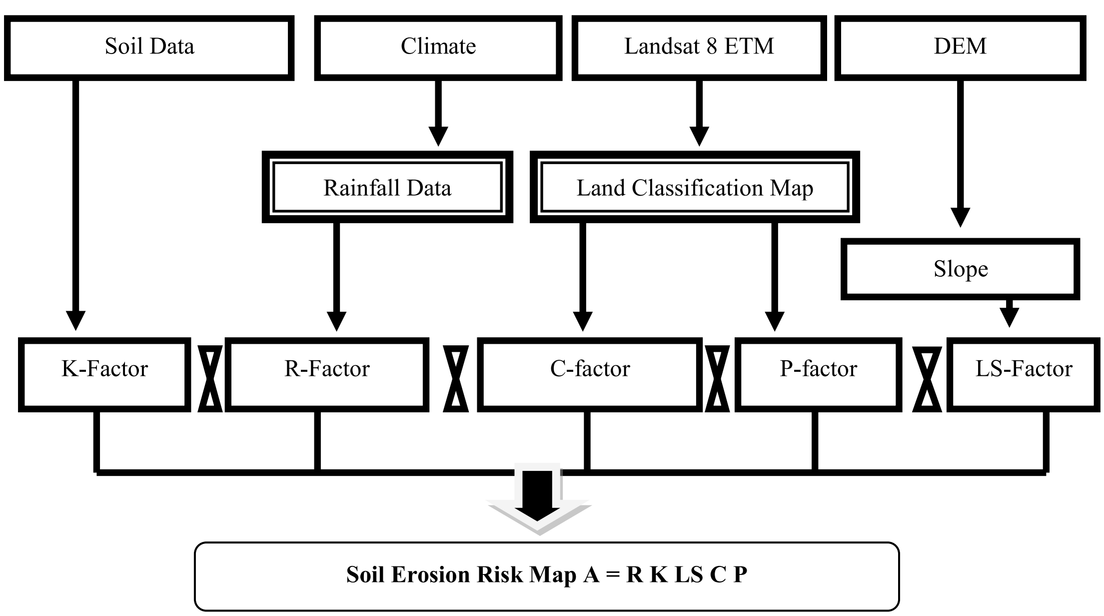

Fig. 2. Conceptual diagram of methodology.

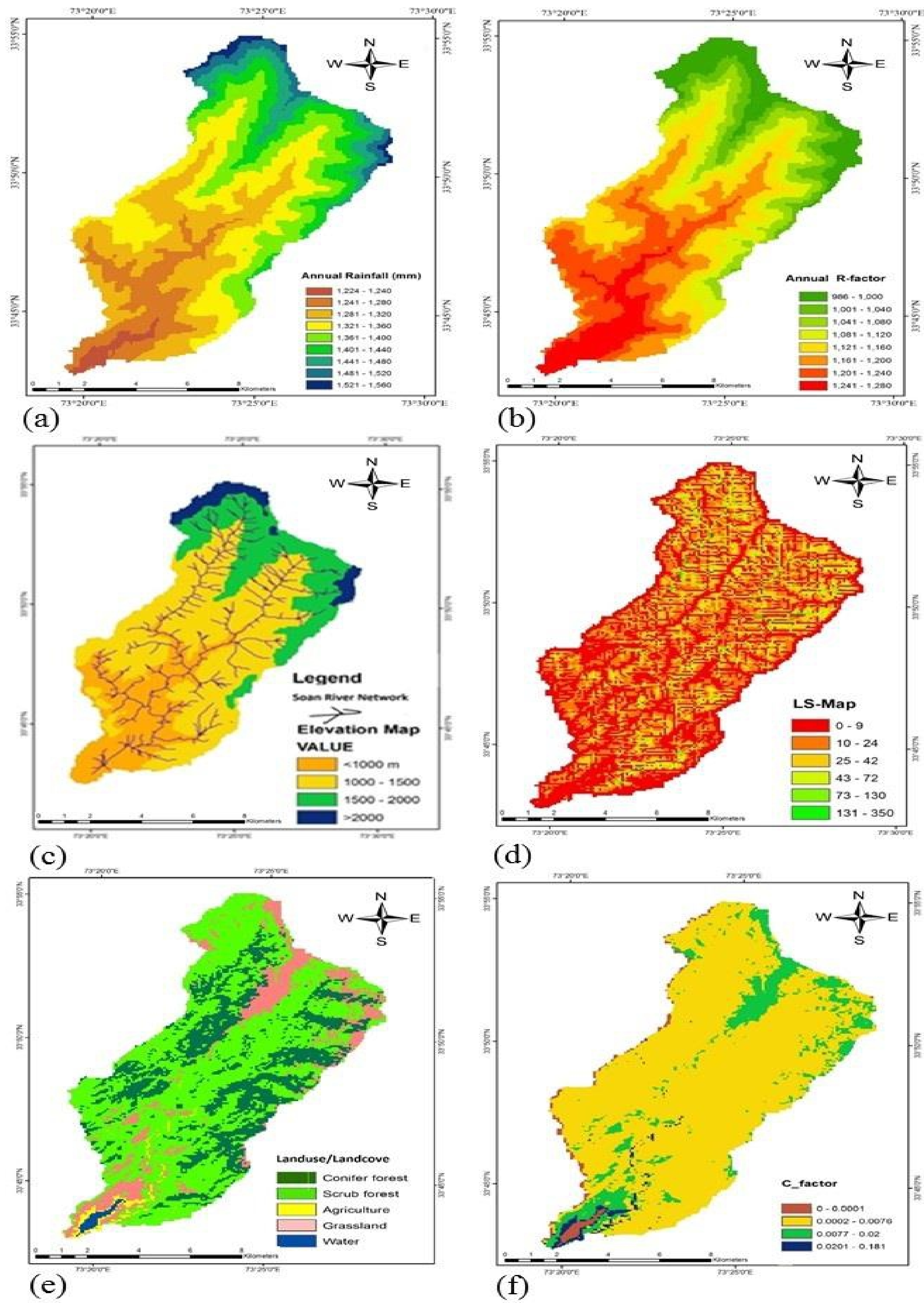

Fig. 3. (a) Spatial distribution of annual rainfall in the study area, (b) spatial distribution of annual R- factor in the study area, (c) slope map, (d) slope steepness factor (LS), (e) extent of various types of land use/land cover, (f) C-factor Map.

K factor value 0.07 to 0.2 was used in soil loss equation to find the erosion rate in the study area (Ashraf et al., 2017) because the soil in the Simly watershed is fine to medium sandy clay loam texture. The soil has high potential of detachment which results in high runoff.

The estimations of LS factor were determined utilizing ASTER DEM of 30 m resolution. LS values range from 0-350, 5% area has as low LS value while 95% region has high LS value (Figure 3d). There is more risk of soil erosion if the LS values (greater than 100) are higher in rugged relief (Yue-Qing et al., 2009; Kouli et al., 2009).

Different land use classes were identified after processing the image on ERDAS IMAGINE. Five classes were distinguished by utilizing the Landsat ETM + 30 m image data for the year 2013 (Figure 3e). 84.8% area is covered as forest (conifer and scrub), 13.1% area covered as grassland and 1.5% area is covered as agriculture land. The overall accuracy of the land use map was 86.81% with value 0.79 for Kappa coefficient.

International Center for Agricultural Research in the Dry Areas (ICARDA) has provided different vegetative cover types from the protective effect of vegetation as well as the farming practices effects that include the rotation and type of crops (Oweis and Ashraf, 2012). On the basis of these values C factor value for conifer and scrub forest was assigned 0.0076, for agriculture 0.181, grassland 0.02 (Figure 3e). No such practice was observed for Simly watershed area. For that purpose, P value of l was assigned for estimation of potential soil loss in the watershed area (Oweis and Ashraf, 2012).

The no-vegetation area related to watershed has been observed as insignificant practice of conservation (Oweis and Ashraf, 2012). Although in the study area, some agricultural land included such conservation practices in scattered form. To estimate the conservation soil loss, a least conservative practice has been assumed with high conservative factor (P) value of l (Oweis and Ashraf, 2012).

3.1. Assessment of soil erosion and risk mapping

Simly watershed (Figure 4) was classified into 5 risk classes i.e., 0-l, 1-10, 10-30, 30-100 and > 100 tons/ha/y and these classes lies under 5 zones i.e., very high, high, medium, low and very low based (Almeida-Guerra et al., 2012).

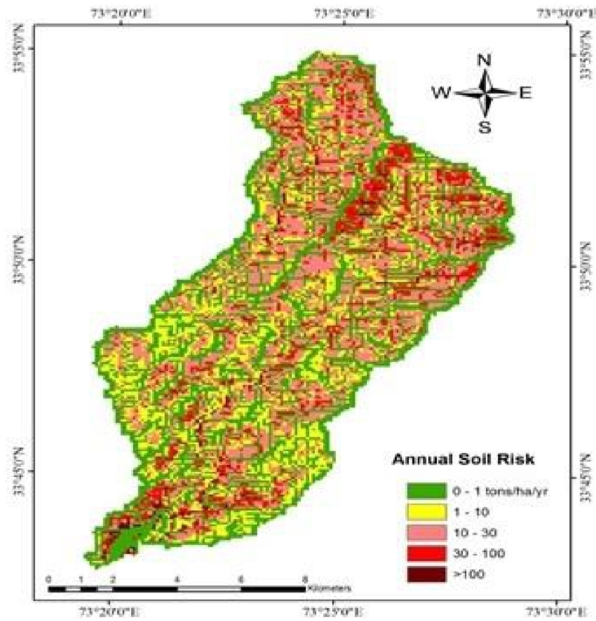

Fig. 4. Soil erosion risk map of Simly watershed area.

The results uncover a normal rate of around 14 tons/ha/yr soil erosion in the Simly watershed range and these calculations were done by zonal statistics in ArcGIS. Erosion rate was high in grassland area that is 27.51 tons/ha/yr and minimum in water area is 0.01 tons/ha/yr (Figure 5). Same study conducted in Rawat watershed area revealed that average soil erosion is 10.3 tons/ha/yr which also laid in the same Potwar region which is 18 km away from Simly watershed (Ashraf et al., 2017). The erosion rate was around 11 tons/ha/yr in forest cover area and 20.2 tons/ha/yr in agriculture land area.

Around 78% of the watershed range includes level to gentle slope. The soil erosion was discovered greatest under steep slopes more prominent than 15 deg i.e., around 34.87 tons/ha/yr at slope >30 deg than gentle slope (5-15 deg) that is 10.6 tons/ha/yr. On level to gentle (<5 deg), the rate of erosion was evaluated 4.83 tons/ha/yr (15 deg) (Figure 6).

The medium risk zone of erosion (intensity within l0-30 tons/ha/yr range) was estimated 30.4% of the watershed area. Very high risk of soil erosion> 100 tons/ha/yr was calculated 1.2 % of the watershed area. Maximum area was covered under very low erosion rate 0-1 tons/ha/yr that is 40.6 % (Figure 7).

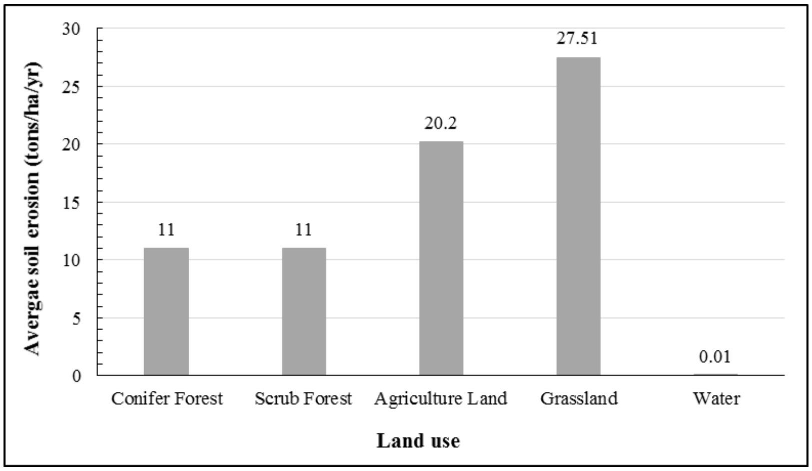

Fig. 5. Soil erosion under various land use/land cover classes.

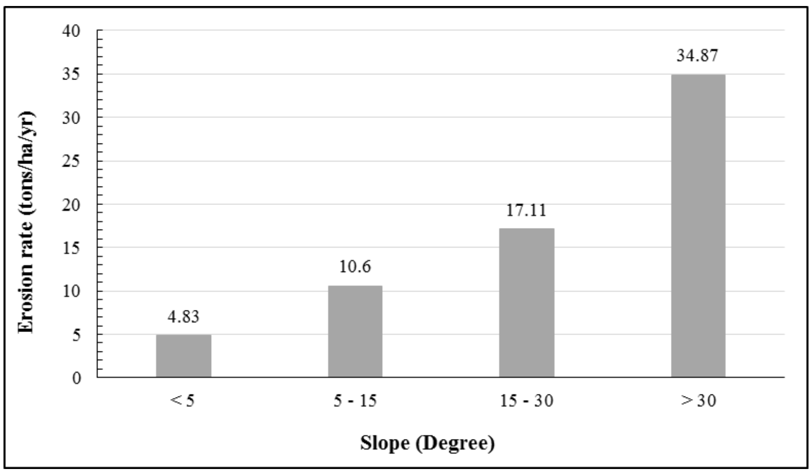

Fig. 6. Average erosion rates under different slopes.

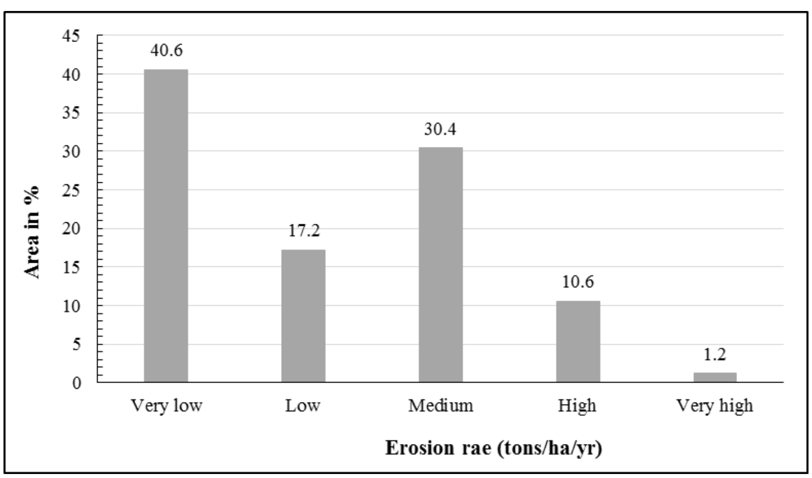

Fig. 7. Percentage coverage of five erosi on risk zones.

Table 1 shows the erosion intensity against the different land use under different erosion classes. It is observed that erosion was 33.6 tons/ha/yr under low class against scrub forest that is high among all five erosion classes. Lowest erosion was calculated under very high erosion class against water class that is 0.01 tons/ha/yr. Table 2 shows area coverage under erosion classes at different slope (degree).

3.2. Land use change scenarios

The scenarios l and 2 additionally portray plausible states of urbanization other than variable deforestation conditions in the watershed zone.

In scenario 1, all the scrub forest is assumed to be converted into rangeland (Rangeland increased~9%). The mean annual soil risk is estimated about 14 tons/ha/y under this scenario i.e. soil erosion increases to about 68.7% from the base land use of 2013. In scenario 2, all the rangeland is assumed to be converted into agriculture land (Agriculture land increased to~13%). The annual soil erosion was estimated over 42 tons/ha/y under this scenario.

In scenario 3, all the rangeland of base land use of 2013 is assumed to be converted into scrub forest (afforestation case). The scrub cover increases to about 71%. The soil risk indicated a decrease of ~16.4% from that of base land use in this scenario. The area coverage for different land use classes under all scenarios was calculated shown in Table 3 and the soil risk map under these scenarios is shown in Figure 8.

Table 1. Area coverage under erosion classes at different land use (km^2).

Slope Class	***Conifer Forest***	***Scrub Forest***	***Agriculture***	***Grassland***	***Water***	***Total***
<1	15.8	33.6	0.82	8.4	1.05	**59.82**
1—10	6.9	21.1	0.17	0.8	0	**29.14**
10—30	13.9	32.8	0.15	4.2	0.001	**51.191**
30—100	2.7	6.9	0.36	7.1	0.03	**17.2**
>100	2.7	0.9	0.92	0.7	0.01	**38.041**
Total	**42**	**95.3**	**2.42**	**21.2**	**1.091**	**162**

Table 2. Area coverage under erosion classes at different slope (degree).

Slope Classes (tons/ha/yr)	**< 5 deg**	**5 - 15 deg**	**15 - 30 deg**	**> 30 deg**	**Total**
< 1	6.8	29.7	24.77	0.98	**62.25**
1 - 10	3.16	19.55	7.33	0	**30.04**
10 - 30	0.68	14.6	33.7	1.98	**50.96**
30 - 100	0.24	4.12	11.37	1.72	**17.45**
> 100	0.12	0.098	0.84	0.32	**1.378**
Total	**11**	**68**	**78**	**5**	**162**

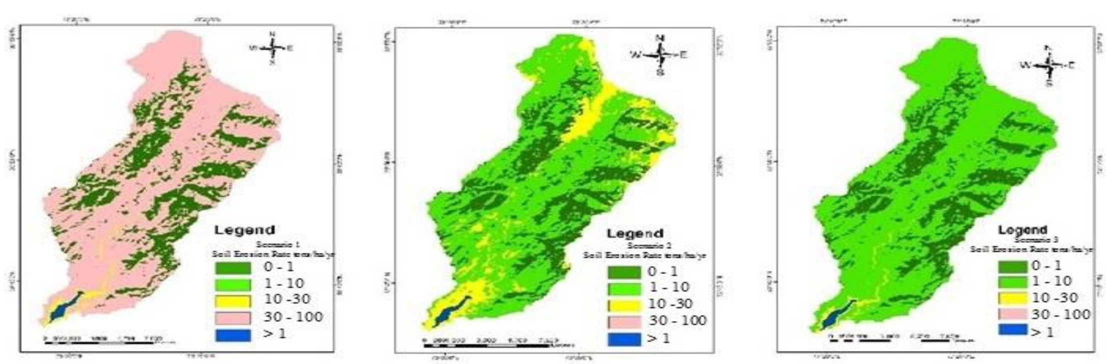

Fig. 8. Land use Distributions and their different scenarios.

Table 3. Coverage area for different land use classes under scenario (Area km2).

Land use	Area	Scenario 1 %	Scenario 2 %	Scenario 3 %
Conifer forest	42.14	26.01	26.01	26.01
Scrub forest	95.2	0	58.76	71.85
Agriculture	2.42	1.49	14.58	1.49
Grassland	21.2	71.85	0	0
Water	1.091	0.6734	0.6734	0.6734
Total	**162**	**100**	**100**	**100**

Conclusion

The results revealed that integration of RUSLE with GIS is found useful in estimating the soil erosion at watershed level. The focus of the study was not only limited to estimate the soil erosion but also to develop different scenarios to reduce risk of soil erosion in the Simly watershed. The results of the study reveal an average rate of about 14 tons/ha/yr soil erosion in the Simly watershed. The conversion of various land covers within 200l-2013 period formed the basis for developing the scenarios. Rainfall pattern shows increase events which also contributing towards more soil erosion in the target area. These different scenarios will be helpful for evaluating the risk of soil erosion. Scenario 1 in which all the scrub forest is assumed to be converted into range land so, in this case the soil erosion increases to about 68.7%. In scenario 2 the all the rangeland is assumed to be converted into agriculture land and the annual soil erosion was estimated over 42 tons/ha/yr and in Scenario 3 in which all the rangeland of base land use of2013 is assumed to be converted into scrub forest (afforestation case). The soil risk indicated a decrease of about 16.4% from that of base land use. It is observed that due to rapid urbanization in the Simly watershed area is critical in exaggerating the risk of soil erosion. Risk of soil erosion can be prevented through afforestation (Ashraf et al., 2017) in the different risk prone areas which studied in the 3 scenarios. Check dams should be developed not only to reduce soil erosion but also to provide suitable vegetation cover over a longer period. Proper agriculture practice can also reduce the risk of soil erosion. There should be a regular monitoring system in which field based approach and with the use of high resolution remote sensing data can be more effective for the better management of small watersheds.

Limitations and future directions

For large size watershed areas these results are significant for baseline data preparation but for accurate and comprehensive analysis, it is recommended to use high resolution satellite images and DEM. Sub basin study will also leads towards more appropriate results.

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