



Modeling Risk of Soil Erosion in High and Medium Rainfall Zones of Pothwar Region, Pakistan

Arshad Ashraf^{1,*}, Muhammad Khubaib Abuzar², Bashir Ahmad,
Muhammad Munir Ahmad, and Qurban Hussain³

¹Climate Change, Alternate Energy and Water Resources Institute,
National Agricultural Research Centre, Park Road, Islamabad, Pakistan

²Bahria University, Islamabad, Pakistan

³Natural Resource Division,
Pakistan Agricultural Research Council, Islamabad, Pakistan

Abstract: Soil erosion is a major escalating problem effecting agriculture and water resource development in the Himalayan region. An integrated approach of using Revised Universal Soil Loss Equation (RUSLE) model and Geoinformatic techniques was adopted to assess risk of soil erosion in the Rawal and Ghabbir watersheds lying in the high and medium rainfall zones of Pothwar region, respectively. In Rawal watershed, high (soil erosion rate within 30-100 tons/ha/yr) and very high (>100 tons/ha/yr) risk zones of soil erosion were predicted over 3% and 2% areas, respectively. In Ghabbir watershed, high and very high risk zones were estimated over 29% and 14% areas, respectively. Soil erosion under various slope and land use classes was relatively higher in the Ghabbir than in the Rawal watershed, because of low and sparse vegetative grown under low rainfall condition in the former watershed. Rapid increase in urban development accompanied with loss of vegetation cover is critical in causing high risk of soil erosion in the Rawal watershed. The menace of soil erosion can be prevented through afforestation in various risk prone areas, together with, provision of adequate control over illegal wood cutting and overgrazing in the watersheds. In the gully and slopy areas, check dams and micro-catchments may be developed to control soil loss, which eventually provide suitable vegetative protection in the long run.

Keywords: Soil erosion, remote sensing, Pothwar, Himalayan region

1. INTRODUCTION

Soil erosion is becoming an extremely serious environmental problem [1] that has increased throughout the 20th century [2]. The soil erosion rates are the highest in Asia, Africa and South America averaging 30-40 t/ha annually [3], causing tremendous loss to the global productivity and economy. In locations where soil is shallow and land is sloping, like in the Ethiopian highlands [4], this can lead to an irreversible loss of soil and hence land degradation. Often, increases in water and wind erosion result from land use and climate changes that alter the land's vegetative cover, e.g., when forests are converted to agricultural land and land sliding owing to intense rainfall events. In Pakistan degradation of land and soil erosion

caused by water is a major environmental issue. About 16 million hectares (M.ha) of land (about 20 percent) in Pakistan is affected by soil erosion and out of this, 11.2 M.ha (70 percent) is affected by water erosion [5]. The factors that have great impact on the phenomenon of soil erosion are linked to topography, vegetation type, soil properties and landuse. Due to flash flooding and sheet erosion the nutrient rich surface soil is eroded away, that ultimately results in much reduced plant growth rate; furthermore, the more permeable subsoil layers trigger increased run off that results in low availability of water for plant growth. In addition to this, erosion also causes various off site effects, which include poor water quality due to eroded particles and sediment load.

Therefore, monitoring of soil erosion is important in order to assess and evaluate the magnitude of problem [6].

Soil erosion cannot be adequately assessed at watershed scale when performed through conventional methods. Existing methods for identifying the soil erosion areas are based on physical surveys that require extensive cost and efforts, usually not plausible to manage in small scale projects. The assessment of land degradation and soil erosion is a complex field of earth studies that needs long-term and multidisciplinary knowledge. A number of parametric models have been developed to assess the soil erosion from the drainage basins; however, "Universal Soil Loss Equation" [7] is the most widely used empirical equation to estimate yearly soil loss from agricultural basins [8-9], because of its convenience in application and compatibility with geographic information system (GIS) [10-12]. Digital elevation model (DEM) along with remote sensing (RS) data and Geographic Information Systems (GIS) can be successfully used to enable rapid as well as detailed assessment of erosion hazards [11-12]. While conventional practices to assess soil loss produce point-based information, RS makes it practical to measure hydrologic parameters on spatial scales. GIS integrates and combines the spatial analytical functionality for spatially distributed data.

The primary focus of this study is to predict risk of soil erosion in different rainfall zones of Pothwar region i.e. Rawal watershed in the high rainfall zone and Ghabbir watershed in the medium rainfall zone using Revised Universal Soil Loss Equation (RUSLE) and Geoinformatic techniques. The analytical functions of GIS were applied to derive different parameters of the RUSLE that were finally used to predict the intensity of soil erosion in the target watersheds.

1.1 Geographic Setup of the Study Area

The study watersheds lie within high and medium rainfall zones of Pothwar plateau comprising western Himalayas in Pakistan (Fig. 1). Rawal watershed lying in high rainfall zone within longitudes $73^{\circ} 03' - 73^{\circ} 24' E$ and latitudes $33^{\circ} 41' - 33^{\circ} 54' N$ covers an area of about 272 km^2 in the

vicinity of capital territory of Islamabad. The main river flowing here is Korang which was dammed near the city supplying water on an average rate of 22 million gallons per day (MGD) for households and irrigation purpose in Rawalpindi and Islamabad area. The elevation in the watershed ranges within 523-2145 meters above mean sea level (masl) with mean of about 904 masl (Fig. 2). The climate is sub-humid to humid sub-tropical where rainfall is highly erratic both in space and time. The mean annual rainfall is about 1275 mm. There are two types of natural forests found in the mountains i.e. scrub forests (xerophytic forests of thorny and small-leaved evergreen species) up to 1000 to 1200 m elevation and coniferous forests, pure and mixed with hardwood species, from 1200 m elevation to the tree limit [13]. Topography of the watershed consists mainly of small stumpy hills in the southern parts to steep mountainous sides which trigger the water runoff on the slopes at high velocities eroding the good land in the downstream. Crops and water supplies are suffering highly from soil loss due to water erosion comprising of sheet, rill and gully erosion during rainfall season.

Ghabbir watershed lies within longitudes $72^{\circ} 0' - 72^{\circ} 2' E$ and latitudes $32^{\circ} 45' - 32^{\circ} 46' N$ in the southwestern part of Pothwar plateau (Fig.1). The watershed stretches over an area of about 417 km^2 , out of which 85% consists of hills/gullies and nullahs while the rest is flat/terraced land [14]. About 78% of the watershed area comprises of flat to gentle slope. The elevation ranges from 355 to about 938 masl towards southeast (Fig. 2). About 55% area falls within 500-700 masl and 19% above 700 masl elevation. Mean annual rainfall is about 529 mm. Ghabbir is the main tributary of Soan River flowing in this watershed. Mean annual flow of the stream works out to be 47.4 million cubic meters (MCM), about 71% of which comes in July up to September. Mean annual runoff is about 21% of the catchment annual rainfall [15]. Two main landforms in this watershed are: river terrace and redeposited loess plain. River terrace is considerably higher than the present day hill torrent beds and their active and sub-recent plains. The Soan River near the dam site forms a narrow valley with high steep slopes

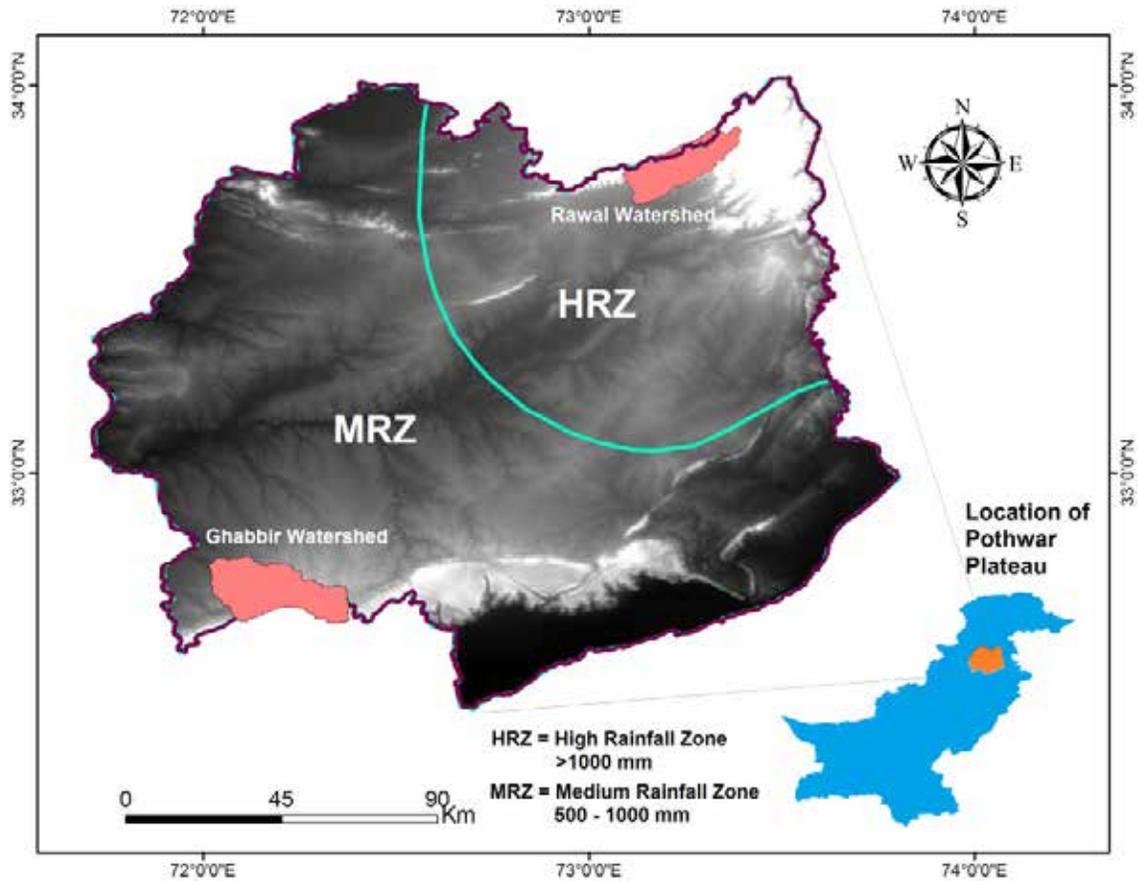


Fig. 1. Location of two watersheds in high rainfall zone (HRZ) and medium rainfall zone (MRZ) of Pothwar plateau in Pakistan.

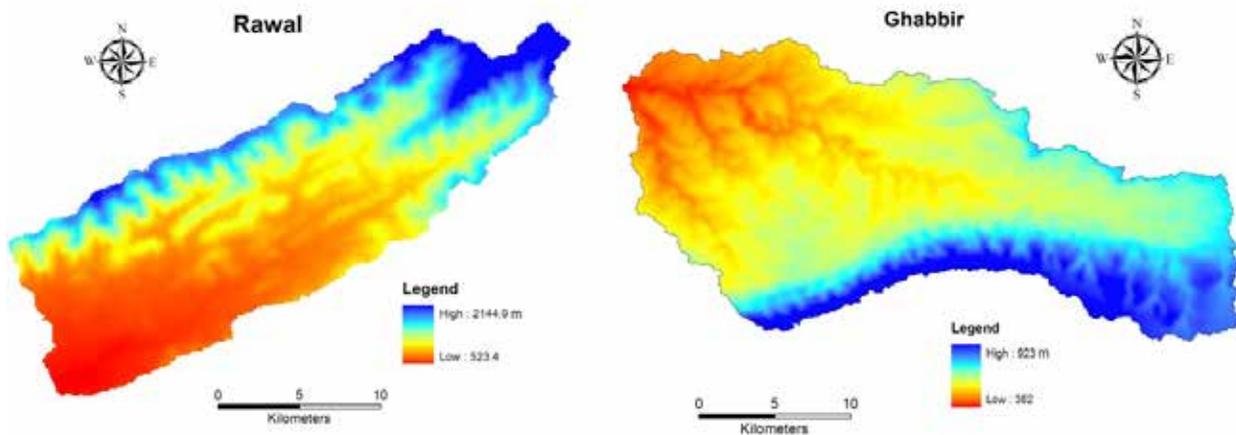


Fig. 2. Elevation increases toward northeast in Rawal watershed and toward southeast in Ghabbir watershed.

on both sides. The main crops grown are wheat, groundnut, millet and mustard.

Extensive deforestation has left the land surfacely bare that leading to a problem associated with rill and gully erosion in Pothwar region (Fig. 3). It not only erodes the soil but also causes the sedimentation of water courses [16]. Rapid urban development and deforestation especially in the low lying areas, illegal cutting due to high market value of forest wood and intensive use of forest wood for household needs, ineffective forest management and forest diseases are accelerating deforestation rate in the watershed area [17].

2. MATERIALS AND METHODS

In the present study, Landsat ETM plus image data of 2010 and 2009 (Path 150, Row 037) were used as primary data to study landuse/landcover of Rawal and Ghabbir watersheds. The images were downloaded from <http://www.landsat.org>. The images contain 7 plus bands with mainly spatial resolution of 30m. The secondary data included rainfall data (1985-2010) from Pakistan meteorological department; topographic map of 1:50,000 scale published by Survey of Pakistan; soil, landuse and geology from Soil Survey of Pakistan. For topographical analysis, digital elevation model (DEM) of ASTER 30 m downloaded from <http://www.gdem.aster.ersdac.or.jp/> and SRTM-Shuttle Radar Topography Mission 90 m from the USGS ftp server at <ftp://e0srp01u.ecs.nasa.gov/srtm/> were used. Global Positioning System (GPS) surveys were conducted to acquire ground control points (GCPs), soil samples and socio-economic data from the target areas.

Time-series rainfall data of Mianwali, Islamabad, Jhelum, Murree, Satrameel and others meteorological stations, covering mostly 1985-2010 period, was acquired from Pakistan Meteorological Department (PMD) and National Agricultural Research Center (NARC). The rainfall data was used to delineate different rainfall zones and estimate erosivity R-factor for this study. Medium rainfall zone (500-1000mm) and high rainfall zone (>1000mm) were delineated

using interpolation technique in GIS, which exhibited 73% and 27% coverage respectively, in the Pothwar region (Fig. 1).

The watershed boundaries were marked from DEM data using AVSWAT model. The dam sites of Rawal and Ghabbir watersheds were taken as outlet points for delineation of the boundaries. Topography, infrastructure, drainage network were delineated for base map preparation. Image classification was performed using maximum likelihood algorithm usually applied to acquire reliable estimates of landcover. Signatures were evaluated through contingency matrix achieving accuracy of over 90% during pre-classification phase. Slope map was generated from DEM, which consists of four classes i.e. flat to gentle (<5 deg), medium (5-10 deg), steep (15-30 deg) and very steep (>30 deg). These classes were used to evaluate risk of erosion over different slopes in the target areas.

RUSLE model was selected based on its relatively low input data requirements; the optimum accommodation of RS data available and their adaptability to GIS based processes. The model is mainly adopted widely to predict rates of gully and rill erosion from the field that is subject to different management techniques. RUSLE is a straightforward and empirically based model that has the ability to predict long term average annual rate of soil erosion on slopes using data on rainfall pattern, soil type, topography, crop system and management practices [18]. In RUSLE, five major factors are frequently being used to measure soil loss of an area under observation. Each factor numerically calculates the specific conditions that affect the rate of soil erosion at a specific location. The RUSLE is represented by the following equation:

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

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 = Cover management factor (unit less)

P = Conservation practice factor (unit less)

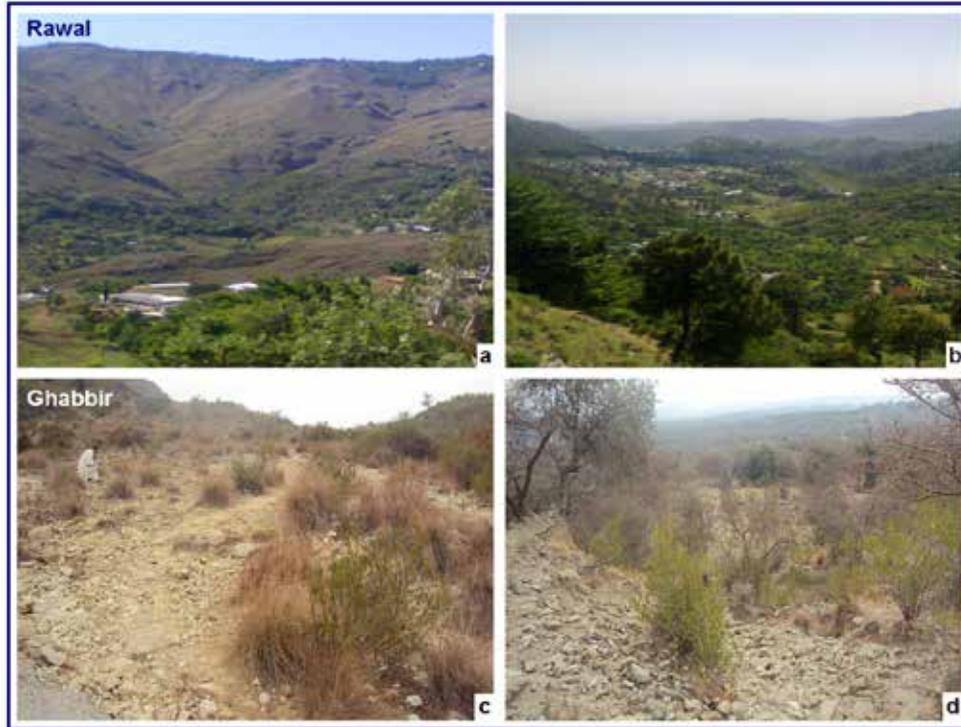


Fig. 3. In Rawal watershed, deforestation due to wood cutting and rapid urbanization (a&b) is critical in exaggerating the risk of land degradation (Photo courtesy: M. Amir Saeed). In Ghabbir watershed, factors like sparse vegetation and improper land management are contributing to the soil erosion risk (c & d).

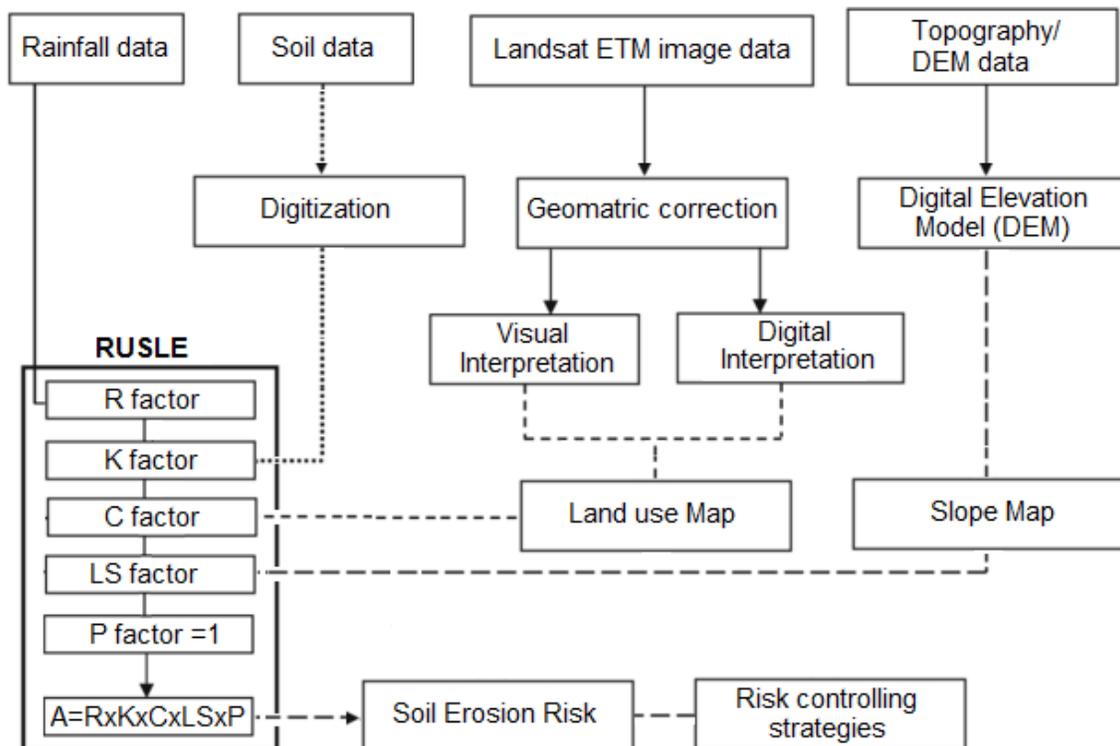


Fig. 4. Flowchart of steps followed to assess soil erosion risk in the present study.

Arnoldous [19] established a relationship between the R factor and Fournier index which is based on monthly rainfall data. R factor of RUSLE was derived from equation 2.

$$\log R = 1.93 \log p_j^2 / P^2 - 1.52 \quad (2)$$

Where, ' p_j ' represents the monthly and ' P ' the annual rainfall.

Topography effects soil erosion in the area that is calculated by LS factor in USLE that defines the effects of slope length factor L and slope steepness factor S . It indicates the degree of erosion risk according to the cumulative slope length derived from DEM. Generally if length of slope (L) increases then total erosion of soil increases and also soil erosion area increases because of progressive amassing of runoff in the down slope track. The LS-factor was calculated from the DEM using equation 3 in spatial analyst extension of ArcGIS [20].

$$\text{Pow}([\text{flowacc}] * \text{resolution} / 22.1, 0.4) * \text{Pow}(\text{Sin}([\text{slope}] * 0.01745) / 0.09, 1.4) * 1.4 \quad (3)$$

Where,

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

The factor maps of R , K , LS , C and P were prepared in GIS and integrated to compute RUSLE in the form of a composite map of soil erosion. L and S factors affect slope length and steepness, and C and P give the impact of cropping and management and to control erosion by using different practices. Latter, influential factors leading to higher erosion rates and risk reduction options to be adopted in the target watersheds were studied. Methodology used for predicting soil erosion in the present study is shown in Fig. 4.

3. RESULTS AND DISCUSSION

3.1 Assessment of RUSLE Factors

The estimation of different factors of RUSLE model were performed through processing thematic and image data in GIS and finally analysis of soil erosion risk was carried out and risk zone map was developed. In Rawal

watershed, annual R values ranged between 230 and 713 which tend to increase towards north and northeast in the watershed. In Ghabbir watershed, the interpolated R values ranged between 169 and 292 that indicated an increase in the eastern part following the rainfall trend in the watershed.

K value in Rawal watershed varied from 0.07 to 0.2. Overall fine to medium sandy clay loam texture dominates the study area. The soil in upper reaches is generally shallow/moderately deep, calc and medium textured. Minor part in the valley plains generally comprises of sandy loam soils. The watershed's soil has high detachment potential due to which it lost its top skin easily and generates high runoff rates and amounts.

LS values in Rawal watershed ranged between 0-384, the higher values of which were concentrated mainly in the northern and northeastern parts, whereas the lower ones occurred in the valleys along the main streams possibly because of the existence of low slopes (Fig. 5). Higher values of LS mean the more risk of soil erosion in the area. In Ghabbir watershed, the LS values ranged within 0-98.4, the higher ones concentrated mainly in the southeastern dissected hills and in the northwestern gully area.

The C -factor was determined from the landuse/landcover types in the watersheds. In Rawal watershed, five major landuse/landcover classes were identified i.e. conifer forest, scrub, rangeland, agriculture land, open soil/rocks, built-up land and water (Fig. 6). Over 7.4% area comprises of agriculture land while 38.8% is scrub forest (Table 1). The rangeland comprising shrubs and grasses are found over 36.8% area. The open soil lacking any vegetation cover stretches over 4.8% area in the watershed. In Ghabbir watershed, over 48% area comprises of agriculture land and 24% scrub forest. Rangeland (scattered shrubs and grasses) exists over 10% area, whereas open soil stretches over 17% area (Table 1). As landuse/landcover plays an important role in controlling soil erosion and at specific conditions, it provides protection to soil against its transportation. Higher C -factor demonstrates higher risk of erosion, e.g., C value for open soil/rocks was assigned 0.176 due to lack of

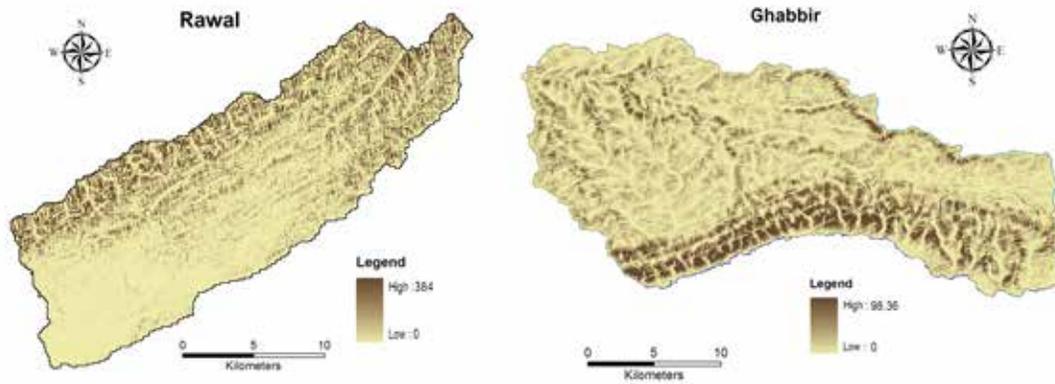


Fig. 5. LS factor maps indicating degree of soil erosion risk in the two watersheds.

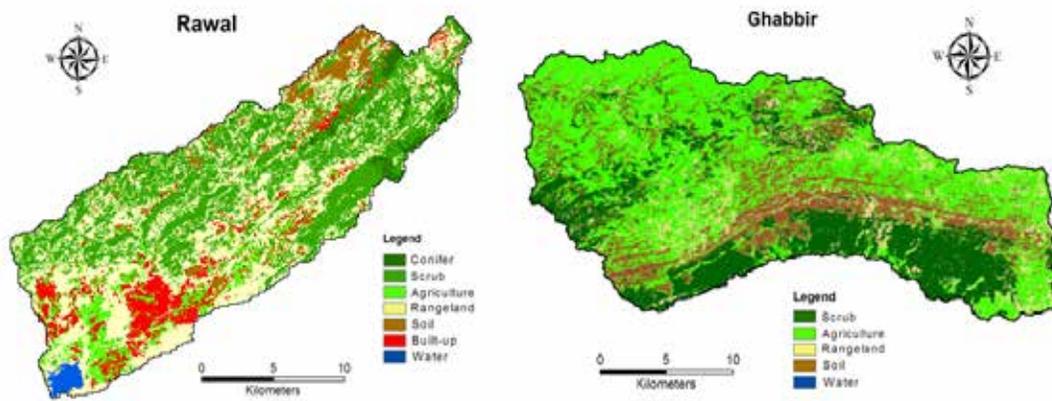


Fig. 6. Extent of various landuse/landcover types in the two watersheds.

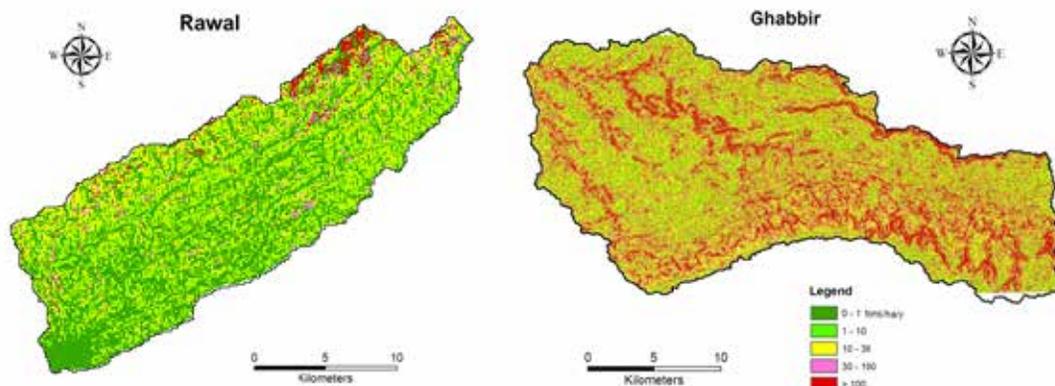


Fig. 7. Intensity of soil erosion risk in the target watersheds.

Table 1. Land use/land cover distribution in the two watersheds.

Landuse class	Rawal Watershed		Ghabbir Watershed	
	Area (km ²)	Area %	Area (km ²)	Area %
Conifer	6.3	2.3	-	-
Scrub	105.5	38.8	100.1	24
Agriculture	20.1	7.4	202.2	48.5
Rangeland	100.1	36.8	41.7	10
Soil	13.1	4.8	72.6	17.4
Built-up	24.2	8.9	0.0	0.0
Water	3.0	1.1	0.4	0.1
Total	272	100	417	100

vegetation cover while it was 0.0076 for forest cover. ICARDA calculated 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 [21]. For conservative soil loss estimation, high value of conservation practice factor, i.e., P=1 was used, assuming that there exist at least conservative practice in the target areas.

3.2 Prediction of Soil Erosion Risk

The two watersheds were classified into 5 risk zones of soil erosion, i.e., very high, high, medium, low and very low based on the criteria defined by Almeida-Guerra et al. [22]. An average rate of about 10.3 tons/ha/yr soil erosion was revealed in the Rawal watershed area. About 5.6% area collectively falls under high (30-100 tons/ha/yr) and very high (>100 tons/ha/yr) risk of soil erosion that concentrated mainly in the northern and northeastern parts of the watershed (Fig. 7). Low risk of soil erosion (<1 ton/ha/yr) extended over 37% area while medium risk (1-10 tons/ha/yr) prevailed over 11% area (Fig. 8). Maximum erosion was predicted from open soil/rocks class, i.e., at an average rate of about 81 tons/ha/yr (Fig. 9). Major area in the watershed falls under medium slope class (about 37%) followed by flat to gentle class (35%) while steep and very steep classes stretch over 27% and 1% areas, respectively. Maximum soil erosion was predicted over very steep slope (>30 deg), i.e., about 20.4 tons/ha/yr followed by steep slope (15-30 deg), i.e., 18.4 tons/ha/yr (Fig. 10). Removal of

a forest cover from steep slopes has led to accelerated surface erosion besides increase in the surface runoff. On flat to gentle slope (<5 deg) the rate of erosion was estimated over 3 tons/ha/yr while on gentle slope (5-15 deg) it was about 10 tons/ha/yr. These results compare well with other studies and local data [23-24]. According to Nasir et al. [23], 0.1 to 8 tons/ha/yr of soil loss was predicted for flat areas. Major soil losses appear to be associated with the areas where bulldozing and land leveling have been carried out for construction work. In order to control the risk of soil erosion, strategies should have to be defined separately for each soil erosion risk zone in accordance of the severity of the risk involved.

An average rate of about 22 tons/ha/yr soil erosion was predicted in the Ghabbir watershed. Approximately 25% of the watershed area comprising mostly of rainfed agriculture and open soil was under very low risk of soil erosion (<1 ton/ha/yr). Medium risk zone of soil erosion (10-30 tons/ha/yr) was estimated over 21% and high risk zone (30-100 tons/ha/yr) over 29% of the watershed area (Fig. 8). In southern Pothwar, geological erosion is active and the gullies are eroding the main terrace. Very high risk of erosion (>100 tons/ha/yr) entailing open soil/rocks with steep slopes was predicted over 15% area. The agricultural which is generally rainfed and crop cover exists only during specific period of a year, indicated erosion at an average rate of about 19 tons/ha/yr (Fig. 9). Maximum erosion appears to occur from open soil/rock class (i.e., about 36 tons/ha/yr lower than that of the Rawal watershed,

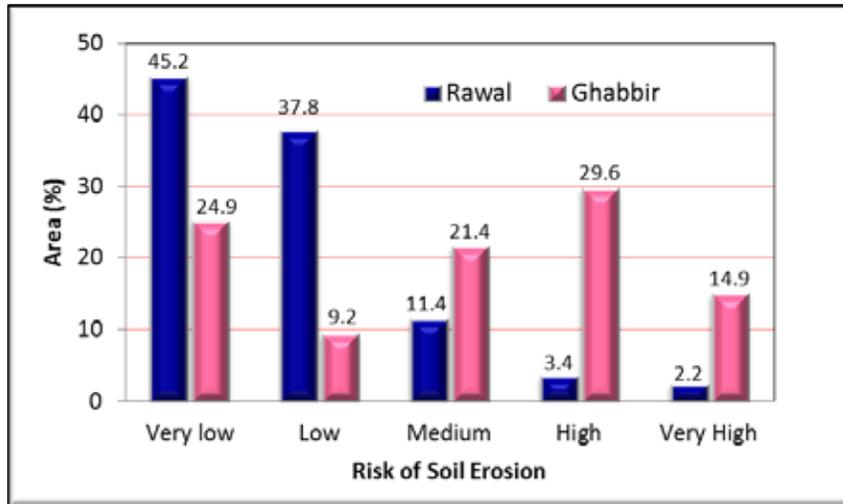


Fig. 8. Percentage coverage of soil erosion risk in the two watersheds.

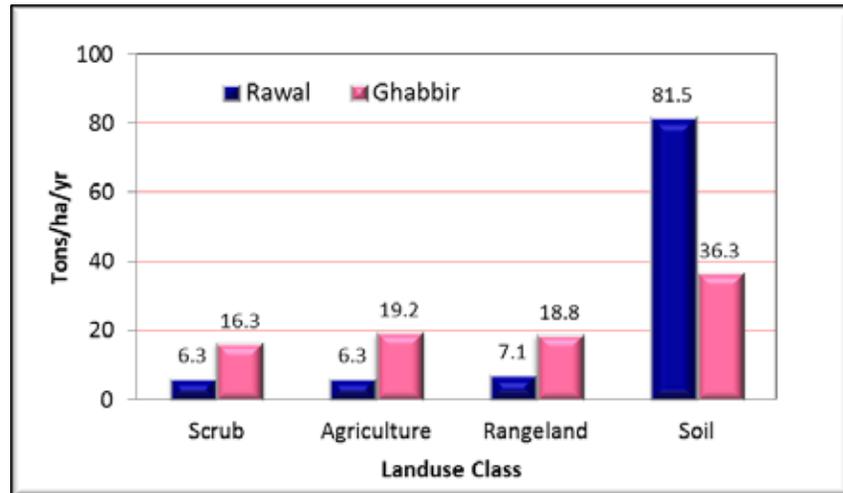


Fig. 9. Rate of soil erosion predicted under various landuse classes.

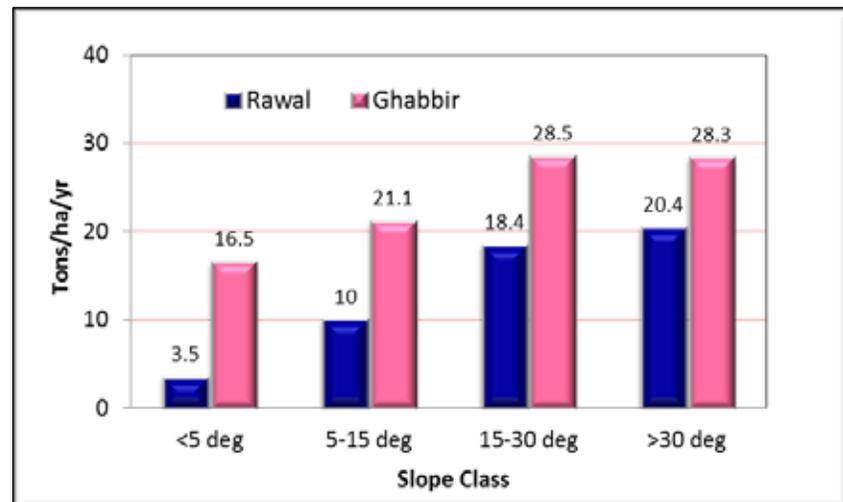


Fig. 10. Soil erosion predicted over various slope classes.

likely because of higher stoniness nature of the Ghabbir soils). In fact, soils in this watershed have been formed in alluvial material and in re-deposited Loess that are generally well-drained. Geological erosion is also active here and the gullies are eroding the main terraces. The rate of erosion was about 28 tons/ha/yr from the steep slopes (>15 deg) and 21 tons/ha/yr from the gentle slopes (5-15 deg), the areas concentrated mostly in the central valleys and southeastern hilly terrain of the watershed. Interventions that reduce runoff and conserve soil moisture may be adopted to reduce soil erosion risk in such gully/dissected and sloppy areas. Conservation structures would not only reduce the runoff but also trap sediments, conserve soil and moisture for future land rehabilitation of the area.

4. CONCLUSIONS

Integration of RUSLE with GIS tools was 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. 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. Soil erosion under various slope classes was relatively high in the Ghabbir likely due to presence of low and sparse vegetative cover in the watershed. Similarly, soil loss from the scrub forest, agriculture and rangeland was higher in the Ghabbir than in the Rawal watershed, because of scattered/sparse vegetation grown under low rainfall condition in the former watershed. In Rawal watershed, deforestation due to rapid urban development is critical in exaggerating the risk of land degradation. Also increase in intensity of rainfall events under changing climate, would exaggerate the risk of land sliding and eventually erosion and sedimentation. The menace of soil erosion can be prevented through afforestation in various risk prone areas, together with, adequate control over illegal wood cutting and overgrazing in the region. In gully and sloppy areas, check dams and micro-catchments should be developed that would not only reduce soil loss but also help

in providing suitable vegetative protection in the long run. Terrace farming would be helpful in reducing soil erosion, providing higher retention of moisture for crop use, removing surface runoff water at a non-erosive velocity and reforming land surface over sloppy lands. A regular monitoring of land degradation is necessary using high resolution satellite imageries integrated with in-situ information. Integrated modeling and field based approach can prove effective in deriving suitable land and water management strategies for sustainable development of the rainfed region.

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