

Estimation of Soil Erosion by Using RUSLE and GIS for Small Mountainous Watersheds in Pakistan

Nasir A.¹, Uchida K.² and Ashraf M.³

ABSTRACT: Soil erosion has become a very serious problem in Pakistan. Deforestation, overgrazing and improper land use practices have reduced natural vegetation, leading to increased surface runoff causing soil erosion. About 65 percent of the Pothwar area has been severely eroded resulting in loss of fertile land and deposition in the downstream dams and reservoirs. A study was carried out to evaluate soil erosion by using Revised Universal Soil Loss Equation (RUSLE) with GIS at a sub-watershed of Lake Rawal (Satrameel) during 1989-96. Digital elevation data were used to develop contour and drainage maps of slope steepness and slope length based on digital elevation model (DEM). Moreover, rainfall erosivity factor was also determined by using erosivity models compared with rainfall. The monsoon rainfall was not uniformly distributed within and between seasons. Soil erosion risk was found to be the highest from July to September compared to other months. Annual runoff measured by a H-type flume, averaged 2.3 cm depth across the watershed. Over 203 runoff events were observed in which 131 runoff events had more than 25 mm rainfall. The predicted soil loss ranged from 0.1 to 28 t/ha/yr averaging 19.13 t/ha/yr. Combining the RUSLE with GIS tools was found useful for estimating soil loss on small size watershed for soil conservation and land use planning.

KEYWORDS: Soil erosion, Rainfall, Runoff, Erosion index, Erosivity factor, Pothwar, Pakistan.

INTRODUCTION

Inadequate watershed management has also resulted in excessive soil erosion and increased the incident of flooding. Large 13 rivers in the world carry annual sediment loads of over 5.8 billion tons. Among these, the Indus River in Pakistan ranks third with an annual sediment load of 435 million tons and an average sediment concentration of 2.49 kg m^{-3} (Belaud *et al.*, 1998). This leads to an increase in suspended sediments in aquatic system and marine, lakes, coastal and deep waters.

Out of a total geographical area of 80 million hectare (Mha), the suitable area for agriculture in Pakistan is about 29.6 Mha and 50.4 Mha is uncultivated. Almost 15.9 Mha of land (20% of total) is affected by soil erosion. Out of this,

11.2 Mha hectares is affected by water erosion. The highest rate of erosion is recorded in the Indus watershed between the Tarbela Dam (the world largest earth fill dam) and 90 km upstream side, where soil loss is estimated to be 150-165 t/ha yr. According to an estimate, the Indus River is adding 5,00,000 tones of sediment to the Tarbela reservoir every day, due to which the dam has lost about 35% of its reservoir capacity within twenty four years. Similarly, Warsak and Khushdil Khan reservoirs have almost silted up (Ashraf *et al.*, 2000).

About 17% of the cultivated area is rainfed and depends on rainfall for crop production. Rainfed areas are concentrated in Pothwar Plateau, northern mountains and northeastern plains of the country forming the largest contiguous block of dry-land farming in Pakistan. The occurrence of rainfall in these areas is highly erratic both in space and time with most of the rainfall occurring during monsoon (July to September). The Pothwar spreads over 2.2 Mha and the total cultivated area of Pothwar Plateau is around 1.0

¹Department of Structures & Environmental Engineering, University of Agriculture, Faisalabad, Pakistan.

²Department of Agricultural & Environmental Engineering, Kobe University, Japan.

³Pakistan Council of Research in Water Resources, Khyaban-e-Johar, H-8/1, Islamabad, Pakistan.

Mha. Geographically, it is located on the watershed of Soan River, which is one of the main tributaries of the Indus River. About 4.2 billion cubic metre (BCM) of water is lost from this Plateau as surface runoff annually (Bhutta, 1999).

Soil erosion is taking place at an alarming rate and is mainly due to deforestation in the North. The watershed in the scrub forests of the Pothwar are degraded due to overgrazing and illegal cutting (Shafiq *et al.*, 1998). Soil erosion has a major consequence of the terrestrial environment, which affects both cultivable and forest lands. It increases as the percentage of soil surface cover (vegetative cover, mulches *etc.*) decreases. Soil erosion creates serious problems in agriculture and water resources management by the removal of fertile soil and its subsequent deposition in reservoirs and lakes. Sediment yields decreases the live storage capacity and thus reduces life of lakes. The most important side effect of soil erosion is the eutrophication of streams, lakes and coastal waters. The transfer of fertilizer (nitrogen, phosphorous *etc.*) into a water body

enrich it, which in the presence of sunlight stimulate the growth of algae and other aquatic plants. The beautiful lake of Kallar Kahar, district Chakwal has lost almost half of its capacity due to unwanted vegetation. Another example of this is the siltation of Shah Pur dam, Fateh Jang (Ashraf *et al.*, 2000). The objective of this study was to evaluate soil erosion at Rawal Lake sub-watershed (Satrameel) by using RUSLE with GIS.

MATERIAL AND METHODS

Location of Study Area

The mountain watershed locally called Satrameel is situated in the watershed of Rawal Lake near Islamabad in the southern part of Margala hills, between latitude 33° 30' to 33° 45' and longitude 72° 30' to 72° 45'. The drainage area of the Satrameel watershed is 12.74 ha. The area falls in one of the hilly area identified as having deforestation problems of natural vegetation, over grazing and cutting of trees. The degraded scrub forest of Satrameel watershed, which drains into Rawal Lake is shown in Figure 1. The surface

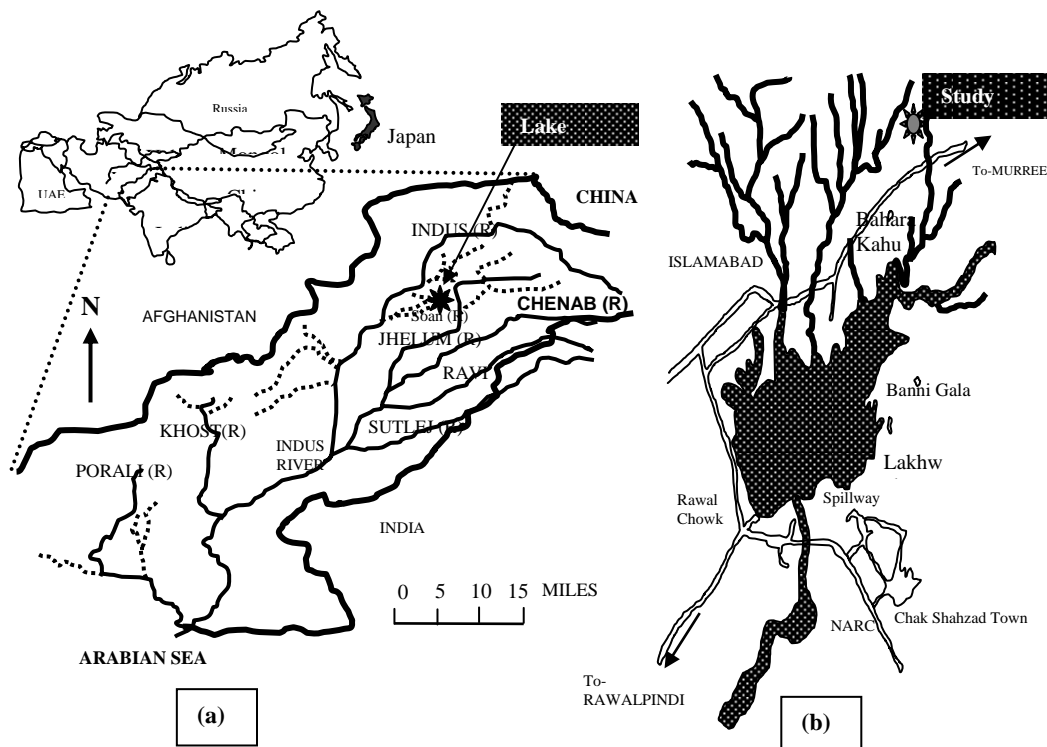


Figure 1: (a) General View of River Network in Pakistan and (b) Drainage Inlet of Rawal Lake

runoff was measured with 'H' type flume and F-type water level recorder (Figure 2). The rainfall was measured with a standard rainfall gauge installed at the observatory of the watershed.



Figure 2: Flume and Water Level Recorder to Measure Surface Runoff in the Satrameel Watershed

RUSLE Factors Generation

The Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.*, 1997) has been widely used for both agricultural and forest watersheds to predict the average annual soil loss. This equation is a function of six input factors: rainfall erosivity; soil erodibility; slope length; slope steepness; cover management; and support practice. These factors vary over space and time and they depend on other input variables. The product of slope length (L) and slope steepness (S), called the combined topographical factor (LS), indicates the effect of topography on soil erosion. According to Biesemans *et al.* (2000), out of all input factors for RUSLE, soil loss is the most sensitive to the LS factor.

Rainfall Erosivity Factor (R)

The rainfall factor is defined as the number of erosion index units in a normal year's rain. An index unit is a measure of the erosive force of a specific rainfall. To arrive at an R-value, each major rainfall event in a year having normal rainfall is identified. The events are all subdivided into per hour periods and the energy, E of each per hour is estimated based on the precipitation index, (I) during that period. The product of rainfall erosion index (EI_{30}) reflects how total energy and peak intensity (I_{30}) are combined in each particular rainstorm indicating the ability of the rainstorm to cause erosion. The total R-value for the year is obtained by adding all the EI_{30} values for the entire year (Wischmeier *et al.*, 1969).

$$R = \sum EI_{30} \quad \dots \quad (1)$$

$$E = 210.3 + 89 \log(I) \quad \dots \quad (2)$$

where:

R = rainfall factor (MJ.mm/ha/hr/yr);

E = rainfall energy (MJ/hr);

I_{30} = precipitation intensity during each storm (mm/hr); and

I = increment of rainfall storm (mm).

Soil Erodibility Factor (K)

The soil of the watershed has been developed on shale and sand stone. Owing to perpetual rejuvenation of land surface by active water erosion, the soil is not predominantly very old and deep. Soil developed on the sand stone are moderate to weak medium sub-angular blocky in structure and sandy loam to sandy clay loam in texture (Nasir *et al.*, 2002). Wischmeier and Smith (1978) have produced a nomograph, modified to SI units by Foster *et al.* (1981) from which the K factor was extracted by assigning values that correspond to the soil types contained within the Satrameel watershed.

Cover Management Factor (C)

The cover management factor reflects the effect of cropping and management practices on the soil erosion rate (Renard *et al.*, 1997). Shrub forest is the only significant vegetation in the Satrameel watershed so it can be assumed that no vegetation rotation occurred in this watershed. Shafiq *et al.* (1997) reported that the study area falls under scrub forest zone and supports mixture composed of *Olea ferrogenea* (Wild Olive), *Dodonea viscosa* (Sanatha) *Crissa spinarum* (Granda) and *Acacia modesta* (Phulai). The vegetation cover is different in different aspects, however on an average there were about 42 plants per 100 m² (Figure 3). The watershed is being extensively used for cattle grazing and cutting fuel wood by the community, due to which plants have been deformed to bushes. The C factor adopted from Wischmeier and Smith (1978) for scrub forest area is 0.014.

Support Practice Factor (P)

The effect of tillage practices on soil erosion is described by the support practice factor within the RUSLE model (Renard *et al.*, 1997). There are

presently no soil conservation support practices being utilized in the Satrameel watershed. Contemporary water harvesting techniques like eyebrow and check damming are used for the improvement of plants canopy (Figure 3.) Given this scenario, the RUSLE model was run with a P factor of 1.0 to predict soil erosion under current conditions of no soil conservation support practice.



Figure 3: Vegetation in the Study Area

Slope Length and Steepness Factor (LS)

Within RUSLE, slope length is considered by the L factor, a sub-component of LS. Slope length is defined as the horizontal distance from the origin of over flow to the point, where either the slope gradient decreases to a point where deposition begins, or runoff becomes focused into a defined channel (Wischmeier and Smith, 1978; Renard *et al.*, 1997). The digital elevation data set was laid over the existing contour map for watershed and missing data points were estimated by linear fits from adjacent data points. The program was designed to examine the elevation of 8 grid points at fixed distances away from the central grid point (1 grid point for each of the 8 cardinal compass direction). The distance to each data set from the central grid point was determined based on the DEM parameters. From this information, the maximum negative gradient and the slope length distance was found. The drainage shape was assigned to the central grid point based on 8 grid points that were either higher, lower, or at the same elevation, as the central point.

Due to the small size of watershed (12.74 ha) and relative steepness, the research area has dense drainage system. The main streams can be considered as a separate drainage network and drain to one point. For example, suppose a

square watershed or hydrological unit has a length and width of 80 m. In a 10 m resolution digital elevation data, this results in a grid with 8 rows and 8 columns. The grid data points on the perimeter of the watershed were treated as a special case and flow was made restricted to discharge into the watershed. The drainage direction is determined by the direction of the largest weighted elevation drop (E_d) (Jenson and Domingue, 1988) calculated by:

$$E_d = (H_c - H_n) \cdot p \quad (3)$$

where:

H_c and H_n are the elevation of the center grid and the neighbour grid, respectively; and p is the weight factor for the direction and equals: $1/dx$ in the x direction, $1/dy$ in the y direction and $1/\sqrt{dx^2 + dy^2}$ in the diagonal direction. If dx equals dy , and p equals to 1 for the cardinal directions then $1/\sqrt{2}$ is equivalent to 0.707 for the diagonal directions.

The output flow path information was then used to construct flow diagrams showing direction and gradient. It is obvious that this type of model can be used as a valuable tool in erosion analysis for such small size watersheds. These drainage directions are used to develop the flow path of watershed (Figure 4). The flow paths were then laid on contour maps for watershed. The 3-dimensional surfaces were constructed using the elevation data and enhanced by showing the flow paths superimposed on that. Since each discrete contains the information about the flow direction and maximum gradient within each element, the percentage of area for any given gradient within the watershed is easily found.

For each grid the length of horizontal slope (S) is:

$$S = 10.8 \sin \theta + 0.03 \quad (4)$$

where: (θ) is the slope angle.

when implementing on GIS:

$$L = (m + 1) \left(A / 22.1 \right)^m \quad (5)$$

where: m = slope length exponent, A = upslope contributing area (m^2), 22.1 = standard plot length in m.

$$m = \beta / (1 + \beta) \quad \dots \quad (6)$$

where: β is ratio of rill to inter-rill erosion.

$$\beta = 11.16 \sin \theta / 3.0 (\sin \theta)^{0.8} + 0.56 \quad (7)$$

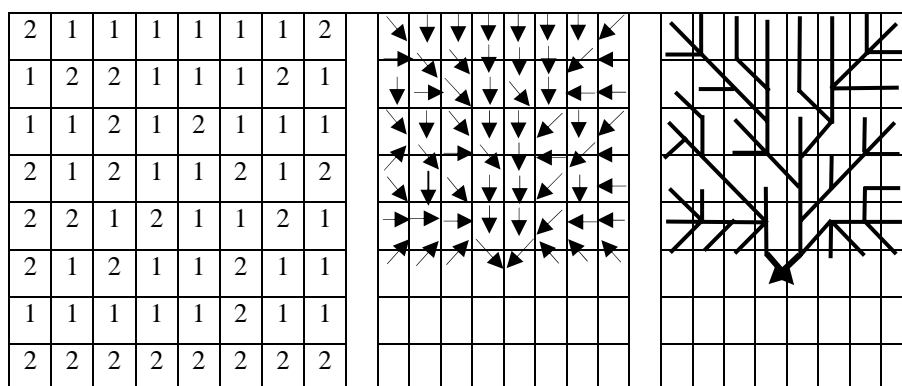


Figure 4: Flow Direction for each Elementary Grid of the Watershed

RESULTS AND DISCUSSIONS

Distribution and Rainfall Data Analysis

The total rainfall at Satrameel watershed ranged from 787 to 1668 mm/yr. The 1990 was the wettest year with 1668 mm/yr (about 30% greater than the average) and 1989 was driest with 787 mm/yr rainfall (about 40% lesser than the average). The average annual rainfall of 1378 mm was received from the watershed. There were great temporal variations in the rainfall.

The characteristic of rainfall was divided into two parts: monsoon and non-monsoon seasons. Table 1 shows that about 63 to 70% rainfall was received during monsoon (July to September) and the rest 26 to 37% in the other parts of the year (Figure 5). The maximum total rainfall per day varied from 76 to 347.5 mm during monsoon and 26 to 78 mm in non-monsoon seasons.

During the study period, it was observed that rainfall within the years and over the years was quite variable with a coefficient of variation (CV) 132% and 19%, respectively. The rainfall intensity (I_{30}) in about 83% of all rainfall events was less than 50 mm/hr, 12% were in the range of 50 to 75 mm/hr, and only 5% were greater than 75 mm/hr. During the monsoon and non-monsoon seasons, 92 and 38 rainfall events had more than 25 mm rainfall, respectively.

The seasonality index is the ratio of difference between the wettest and driest six months rainfall amounts over annual rainfall. The seasonality

index value in the Satrameel watershed is 0.39. This index value of more than 0.13 indicates the presence of a marked wet season in this area. The rainfall data collected for this watershed indicated that, the duration of the storms varied from 60 to 2200 minutes during the monsoon. The cumulative annual values of the erosion index (EI_{30}) for the study period ranged from 987.5 to 2150 MJ mm/ha hr. About 87% of erosion index was recorded during the monsoon. Figure 6 shows the relationship between rainfall and kinetic energy, whereas Figure 7 shows that one value of erosion index is extremely high as compared to other values. The reason is shown in Figure 6 which indicates that this rainfall storm have four increments of rainfall. When these increments are combined and multiplied with maximum rainfall intensity (I_{30}), it created high value of EI_{30} . This storm has the highest rainfall (347.5 mm) during the study period.

Drainage Network

The Satrameel watershed consists of a very rugged mountainous terrain. However, in the soil erosion analysis, it is necessary to represent the terrain conditions in terms of some quantitative values to facilitate a meaningful interpretation. This watershed occupied 445-grid cell in the total drainage area of 12.74 ha and each grid had area 286.36 m². Figure 8 shows that the watershed has two main streams joined at the measurement station. The main stream has its own drainage network with different small streams.

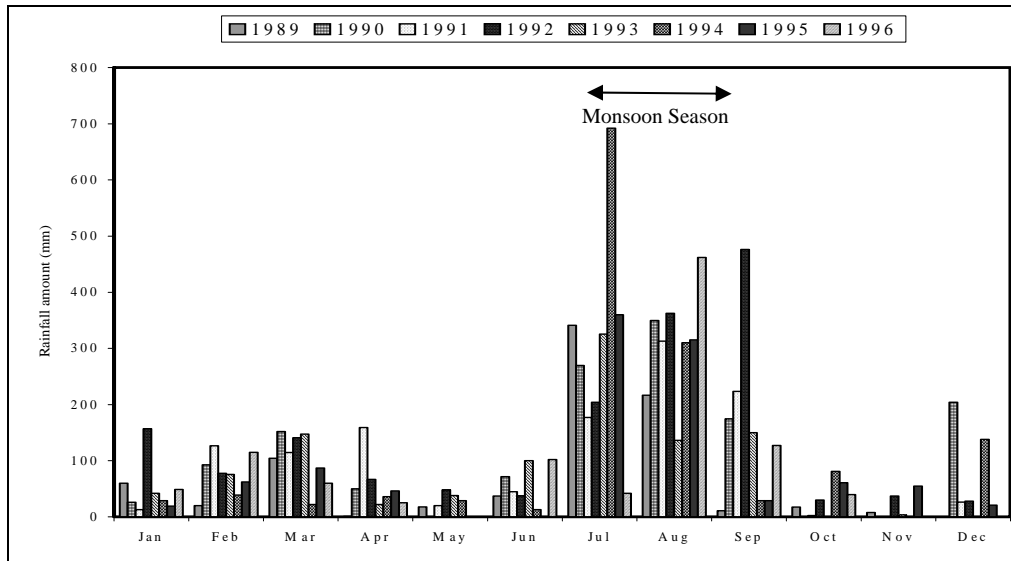


Figure 5: Monthly-accumulated Rainfalls in the Study Area

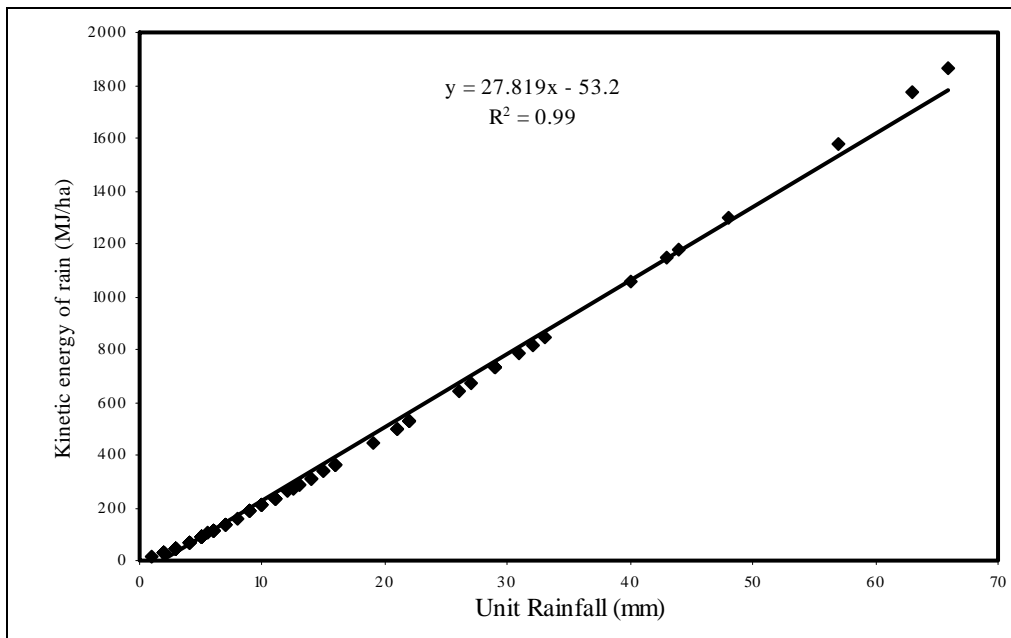


Figure 6: Relationship between Rainfall with Kinetic Energy (KE)

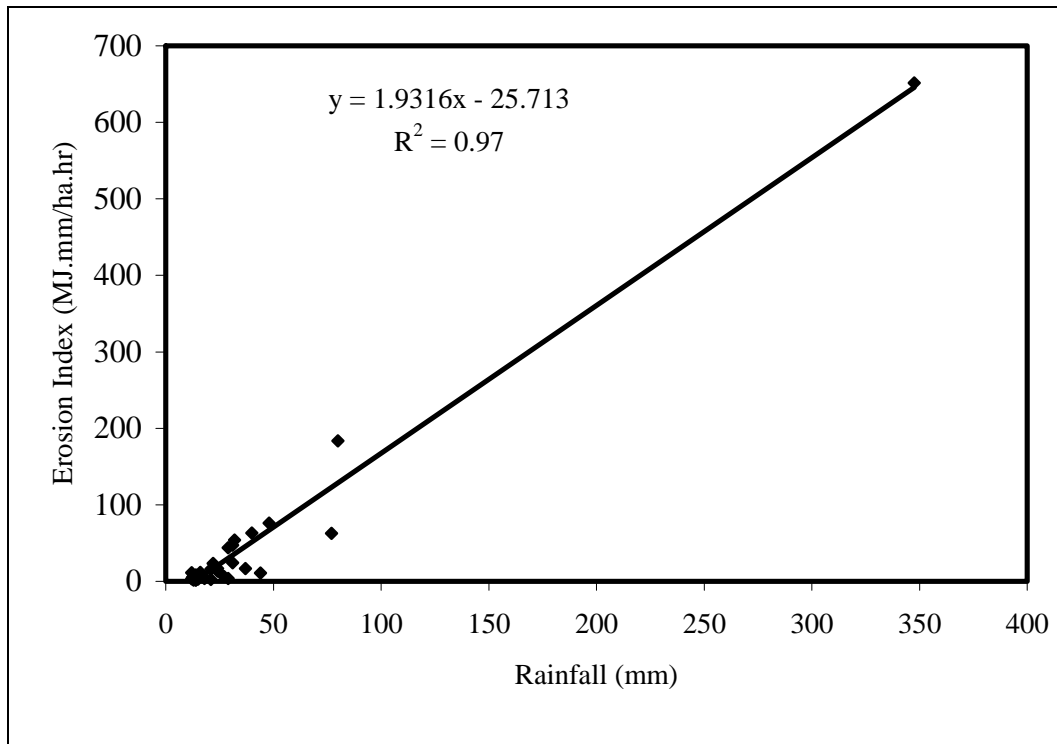


Figure 7: Relationship between Rainfall and Erosion Index (EI_{30})

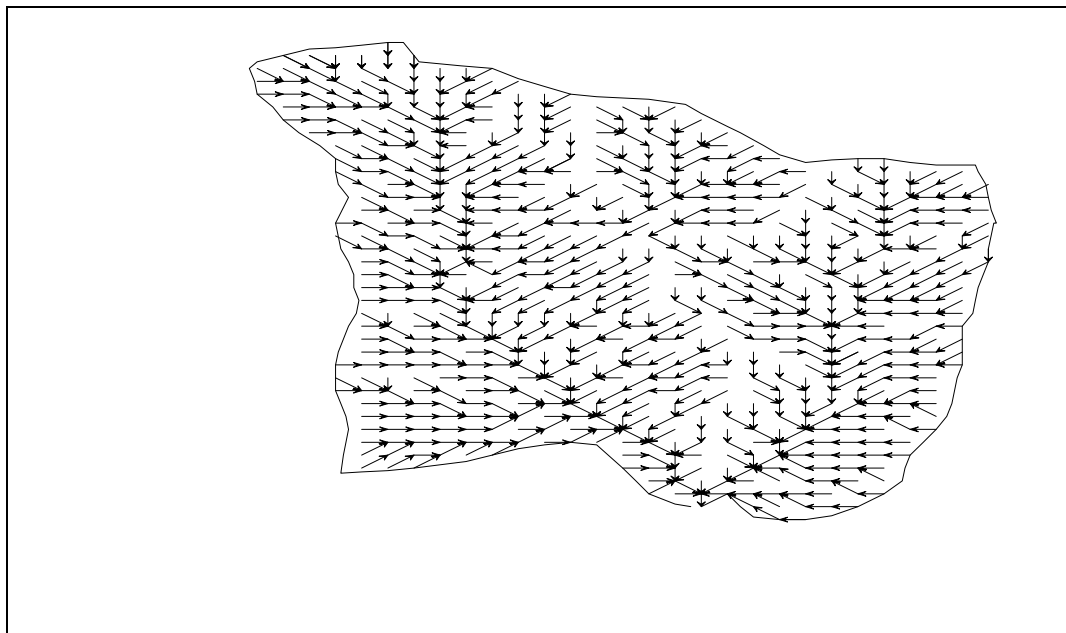


Figure 8: Drainage Map of Study Area Developed by Grid Elevation Data

Slope Length and Steepness Influence

About 7% area of the watershed has a gradient less than 10%, while 42% of the area has a gradient less than 30%. In the watershed, 46% of drainage area has gradient slope between 30 and 50% and only 5% is with a gradient more than 50%. The contour and slope steepness are shown in Figures 9 and 10, respectively. Except for

drainage channel and ridge of the mountain, the slope is generally very high. The altitude of the study area has variation ranging from 650 m above mean sea level, whereas about 52% of the area has an elevation between 700 to 900 m. This area is a good example representing more than 70% of the other watersheds, most of which have similar topography, vegetation, and climate conditions.

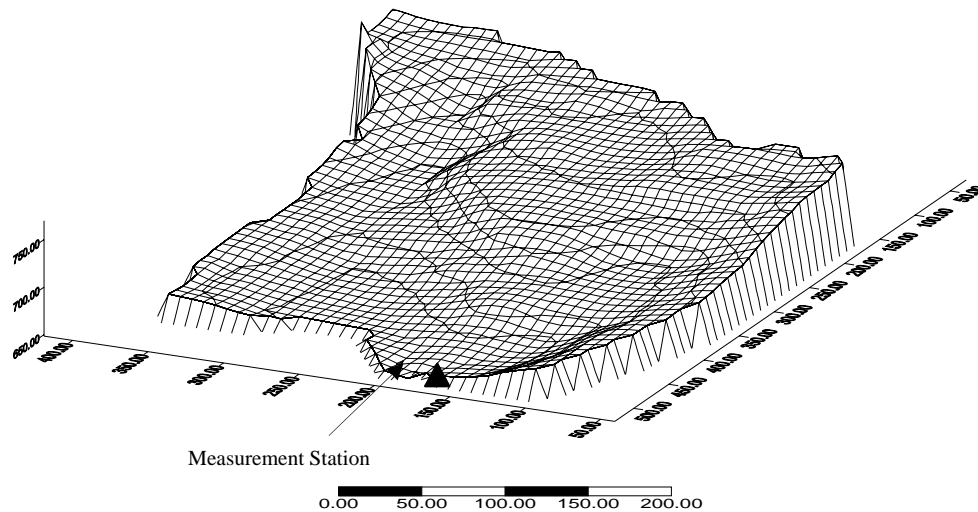


Figure 9: 3-D Contour Map Developed by Using Elevation Data of Each Grid

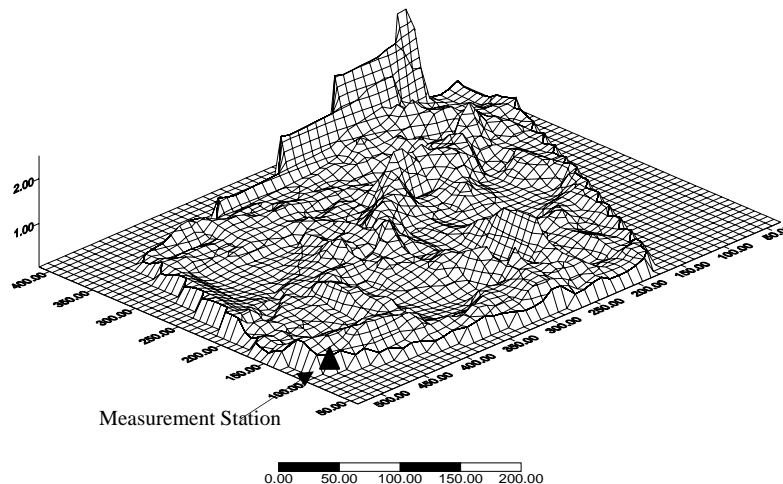


Figure 10: Slope Steepness Map by Using Elevation Difference Data

Soil Erosion Rate in the Watershed

It was found that topography and rainfall are the two most important factors affecting soil erosion. The variation in soil loss due to soil erodibility factor is much less compared with that due to these factors. The land cover factor has an important effect on the overall rate of soil loss, however, it was assumed to be constant for this study area. For any land cover, steep slopes have much higher rate of erosion compared with flat areas. Figure 11 shows the annual soil loss with respect to different topographic factors according to the slopes. The average rate of soil loss and the contribution to the total soil loss from steeper slope is tremendously higher compared with that of gentle slope.

GIS has been applied to calculate the potential erosion. The annual erosivity factor (R) and topographic factor (LS) for different slopes are presented in Figure 11. The practice factor in this study is assumed to be 1.0. Figure 12 shows that the soil loss was the highest (28 t/ha/yr) with steep slope. However, soil loss ranged from 0.1 to 8 t/ha/yr for flat soils. The average soil loss from the whole watershed is 19.13 t/ha/yr. The steep slope generates 74% of the total soil erosion.

Ahmad *et al.*, (1990) reported that for a slope of 1-10%, soil is being lost at a rate of 17-41 t/ha/yr under fallow conditions, and at a rate of 9-26 t/ha/yr under vegetative cover in the Fateh Jang watershed. Guobin *et al.*, (2006) found that at Pataha Creek Watershed USA, the crop lands exhibited much greater erosion rates and sediment yield to the stream channel than the non-cultivated lands. They concluded that soil loss and sediment yield could be reduced up to 78% when no till practices are implemented.

There is a considerable variation in rainfall within a year and that on a year-to-year basis. Despite these variations, the data derived from flume and sediment dried, show an excellent correlation with the input parameters. Using the parameters presented by Nasir *et al.*, (2002), it is possible to predict the soil loss with the application of RUSLE for verification. A comparison of predicted soil loss with measured monsoon soil loss shows that in this watershed soil loss is up to 18.6 ton/ha/yr (Shafiq *et al.*, 1998; Nasir *et al.*, 2002). The predicted soil loss with the application of RUSLE model is according to the variation of LS factor of each grid. Therefore, the RUSLE model predicted soil loss reasonably well during this study period.

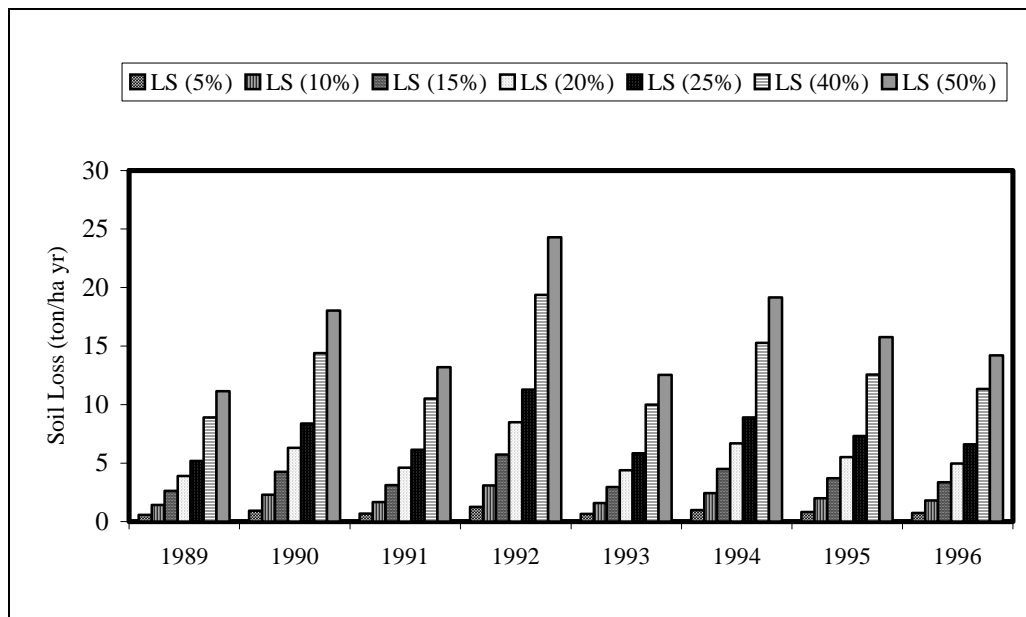


Figure 11: Soil Loss for Various Ranges of Slope and Topographic Factor

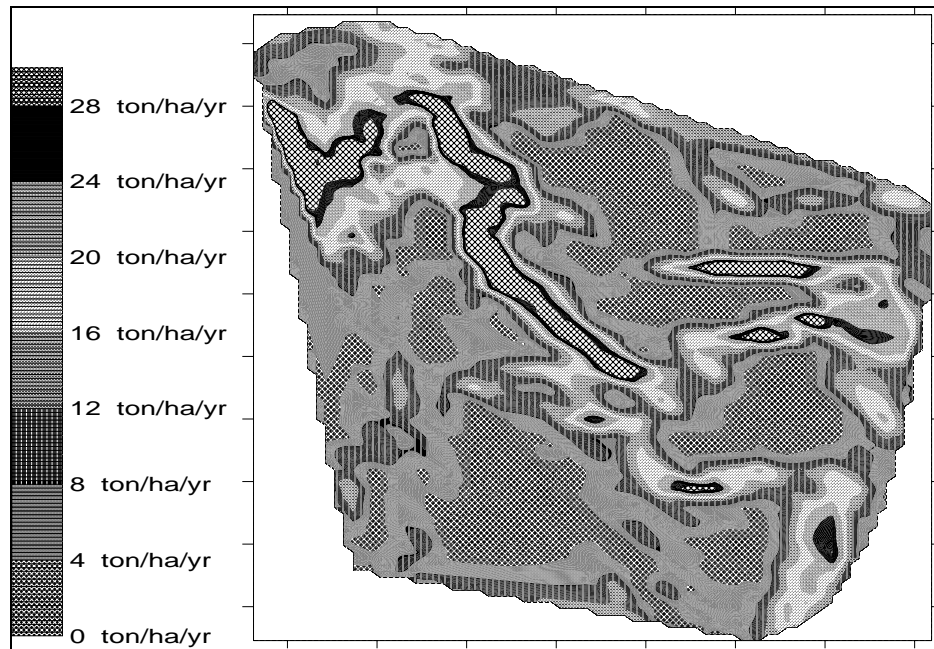


Figure 12: Predicted Soil Loss by Using Grid Mash Data of Satrameel Watershed

CONCLUSIONS

In the Satrameel watershed, significant amount of soil is being lost annually due to intense storms and poor or no land use planning. The topography and rainfall are the two most important factors affecting soil erosion. Over 203 runoff events were observed in which 131 runoff events had more than 25 mm rainfall. The predicted soil loss ranged from 0.1 to 28 t/ha/yr averaging 19.13 t/ha/yr. The soil loss was the highest (28 t/ha/yr) with steep slope. However, soil loss ranged from 0.1 to 8 t/ha/yr for flat soils. The steep slopes generated 74% of the total soil erosion. The RUSLE can be applied successfully in finding range of soil loss values in the watershed. However, accurate values of soil loss for individual locations can be obtained with the present state of development of the methodology, specially on the steep slopes.

ACKNOWLEDGEMENTS

The authors express their deep appreciation to Dr. M. Shafiq, WRRRI, NARC Islamabad, Pakistan,

for providing meteorological data for the Satrameel watershed.

REFERENCES

- Ahmad, S., Khan, M., M.A. Ikram, (1990). Soil and water conservation and integrated land use in Pothwar, Pakistan. In: Soil physics: applications under stress environments. Pakistan Agriculture Research Council, Islamabad. pp. 301-312.
- Ashraf, M. Fayyaz-ul-Hassan, M.A. Khan, (2000). Sustainable environment management: impact of agriculture. J. Sci., Tech. Develop. 19(4), 51-57.
- Belaud, G., Khan, A.K., G. Nabi, (1998). Sediment behaviour of Sangro distributary, Mirpurkhas sub-division, Sindh. International Irrigation Management Institute (IIMI) Report No. R-50. p. 69.
- Bhutta, I.A., (1999). Achievements and issues in 20th century in Small Dams (rainwater harvesting). In: Chandio B.A. (Ed),

- Proceedings of the national workshop on: water resources achievements and issues in 20th century and challenges for the next millennium. Pakistan Council of Research in Water Resources, Islamabad-Pakistan, pp.64-69.
- Biesemans, J.M., Meivenne V., D. Gabriels, (2000). Extending the RUSLE with the Monte Carlo error propagation technique to predict longterm average off-site sediment accumulation. *J. Soil Water Conserv.* 55, 35-42.
- Cuobin, F., Shulin, C., K.M. Donald, (2006). Modeling the impacts of no-till practice on soil erosion and sediment yield with RUSLE, SEDD, and ArcView GIS. *Soil Till. Res.* 85, 38-49.
- Foster, G.R., L.J. Jane., J.D. Nowlin, J.M. Laflen and R.A. Young., (1981). Estimating erosion and sediment yield on field size areas, *Trans. ASAE.* 24, 253-262.
- Jenson, S.K., and J.O. Domingue, (1988). Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogramm. Eng. Remote Sensing*, Vol. 11, pp. 1593-1600.
- Nasir, A. Uchida Kazunori, Shafiq, M., Khan, M., (2002). Monitoring soil erosion in a mountainous watershed under high rainfall zone in Pakistan, *J. Rural Environ. Eng.* 43, 23-30.
- Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C. (1997): Predicting soil erosion by water – a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE), USDA, Handbook No. 703, pp 404.
- Shafiq, M., Nasir, A., Ahmad, B., (1998). Hydrological characteristics and soil erosion from shrub forest watershed under high rainfall zone of Pothwar. *Agro-Environ International Symposium*, Faisalabad, Pakistan, 25-30 May, pp. 219-222.
- Shafiq, M., Ahmad, S. Nasir, A., Ikram, M.Z., Aslam M., Khan, M., (1997). Surface runoff from degraded scrub forest watershed under high rainfall zone. *J. Eng. Appli. Sci.* 16, 7-12.
- Wischmeier, W.H., Smith, D.D. (1978). Predicting rainfall erosion losses: a guide to conservation planning. U.S. Dep. Agric. Handbook No. 537.
- Wischmeier, W.H., Mannering, J.V., (1969). Relation of soil properties to its erodibility. *Soil. Sci. Soc. Am. Proc.* 33, 131-137.