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Use of USLE/GIS Methodology for Predicting Soil Loss in a Semiarid Agricultural Watershed

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Abstract The Universal Soil Loss Equation (USLE) is an erosion model to estimate average soil loss that would generally result from splash, sheet, and rill erosion from agricultural plots. Recently, use of USLE has been extended as a useful tool predicting soil losses and planning control practices in agricultural watersheds by the effective integration of the GIS-based procedures to estimate the factor values in a grid cell basis. This study was performed in the Kazan Watershed located in the central Anatolia, Turkey, to predict soil erosion risk by the USLE/GIS methodology for planning conservation measures in the site. Rain erosivity (R), soil erodibility (K), and cover management factor (C) values of the model were calculated from erosivity map, soil map, and land use map of Turkey, respectively. R values were site-specifically corrected using DEM and climatic data. The topographical and hydrological effects on the soil loss were characterized by LS factor evaluated by the flow accumulation tool using DEM and watershed delineation techniques. From resulting soil loss map of the watershed, the magnitude of the soil erosion was estimated in terms of the different soil units and land uses and the most erosion-prone areas where irreversible soil losses occurred were reasonably located in the Kazan watershed. This could be very useful for deciding restoration practices to control the soil erosion of the sites to be severely influenced.

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1 Introduction

For nearly 40 years, the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) and its principal derivative, the Revised Universal Soil Loss Equation (RUSLE) (Renard, Foster, Weesies, Mccool & Yoder, 1997) have been used throughout the world to estimate average annual soil loss per unit land area resulting from rill and sheet erosion. The data required for the USLE calculations might be available in a geographic information systems (GIS) format so that GIS-based procedures can be employed to determine the factor values for predicting erosion in a grid cell via the USLE (Kinnell, 2001). The advantages of using GIS in environmental assessment were reported by Eedy (1995), and Burrough (1986) introduced the principles of GIS tools for collecting, storing, manipulating, and displaying spatial data. Therefore, estimation of soil erosion and its spatial distribution using remote sensing and GIS techniques could be performed with reasonable costs and better accuracy in larger areas (Millward & Mersey, 1999; Wang, Gertner, Fang, & Anderson, 2003). Ouyang and Bartholic (2001) developed an interactive Web-based approach to use RUSLE and GIS to predict soil erosion. Martin, Gunter and Regens (2003) used GIS/USLE model to estimate sheet erosion from a watershed. They illustrated the ease with which GIS could be integrated with the USLE to identify discrete locations with relatively precise spatial boundaries that have a high sheet erosion potential together with the areas where management practices might be suitable to prevent soils from eroding. Also it is recommended that the GIS/USLE modeling approach would offer quick and inexpensive tool for estimating sheet erosion within watersheds using publicly available information. Lu, Lı, Valladares and Batistella (2004) applied RUSLE, remote sensing, and GIS to the mapping of soil erosion risk in Brazilian Amazonia.

The USLE computes the average annual erosion anticipated on field slopes as a product of rainfall-runoff erosivity factor R, soil erodibility factor K, slope length factor L, slope steepness factor S, cover-management factor C, and support practice factor P. The USLE compares the calculated soil loss to the tolerable soil loss for a specific soil type, which is accepted as the maximum level of soil erosion that would still allow a high level of crop productivity in a sustainable and continuous way, in order to design the different land use systems and conservation practices. Soil loss was estimated by integrating a sample ground data set, TM images, and a slope map as a function of six input factors, including rainfall erosivity, soil erodibility, slope length, slope steepness, cover-management, and support practice (Wang et al., 2003). Authors compared two geostatistical methods and a traditional stratification to map the factors and to estimate soil loss and concluded that the two geostatistical methods performed significantly better than traditional stratification in terms of overall and spatially explicit estimates. As GIS tools usually facilitate derivation of the topographic factor from DEM data and computation of soil losses (Bartsch, van Miegroet, Boettinger & Dobrwolski, 2002; Cerri et al., 2001; Wang et al., 2003), remote sensing data help to develop the cover-management factor and land cover classifications (Ma, Xue, Ma & Wang, 2003; Millward and Mersey, 1999; Wang et al., 2003).

On the other hand, most attempts to use GIS in conjunction with the USLE to model spatial changes in soil loss have often proceeded without addressing the problems related to the assumptions that are incurred in scaling up the USLE applications from plots to large areas. The GIS/USLE application by Ventura, Chrisman, Conncrs, Gurda and Martin (1988) and Hession and Shanholtz (1988), for example, failed to mention a need of distinguishing areas that experience net erosion and net deposition before applying this equation. Difficulties and limitations experienced when applying erosion models together with GIS were broadly discussed by Wilson and Lorang (2000). Desmet and Govers (1996) reported that USLE was widely used because of its relative simplicity and robustness although it had many shortcomings and limitations.

This is a case study for application of USLE/RUSLE models by using erosivity map (Dogan, 2002) and soil and land use map of Turkey (GDPS, 1986) and an attempt to make use of the officially available data in order to perform erosion risk assessment at the watershed scale. This methodology of integrating GIS and USLE should offer useful insight to projects depending on more detailed data and being conducted at national and regional scales for evaluating erosion risk and planning conservation measures (Van der Kniff, Jones & Montanarella, 2000).

2 Materials and Methods

2.1 Study area

Study site is located in the Kazan watershed at an altitude of 1,450 m above sea level and approximately 47 km northwest of Ankara, Turkey. The Kazan watershed is in central Anatolia and covers an area of 6,000 ha. The region has terrestrial climate with annual precipitation of 350 mm with actual amounts determined by elevation, and average temperature is 22.7 °C in summer and 1.6 °C in winter. Selected site for this research contains cropland, dry fallow land, grassland, forestland, natural shrubs, and fruit orchards.

2.1.1 Procedure

A well-known Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) was used for this study because it is one of the most appropriate model-based approaches that could be applied to the authoritatively available data in Turkey. USLE quantitatively estimates soil erosion with the following empirical equation:

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

Where, A: mean annual soil loss (t ha^{-1} $year^{-1}$), R: rainfall erosivity factor (MJ mm ha^{-1} h^{-1} $year^{-1}$), K: soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), S: slope factor, L: slope length factor, C: cover management factor, and P: supporting practice factor. Assuming no support practice in the study area (P=1), it was not used in calculations.

Rainfall erosivity, defined as the potential ability of rain to cause erosion and given as the product (EI_{30}) of the total energy of rainstorm (E) and the maximum 30-min intensity (I_{30}) (Foster, MaCool, Renard & Moldenhauer, 1981; Wischmeier & Smith, 1958), was taken directly from isoerodent map of Turkey (Dogan, 2002), which gives erosive potentials of rainfalls and erosion index values of USLE for meteorological stations in the Kazan watershed:

$$E = 0.119 + 0.0873 \log_{10}(I) \quad (2)$$

And

$$E = 0.283 \quad (3)$$

Equations 2 and 3 are for the conditions where $I \leq 76$ mm h^{-1} and $I > 76$ mm h^{-1}, respectively, and E have units of megajoules per hectare per millimeter. This gives the energy per hectare per millimeter of rainfall. E has units of megajoules per hectare for total of P millimeter rainfall. Therefore, R $(= E \cdot I_{30})$ has units of megajoules per hectare per hour, for which I_{30} has units of millimeters per hour. By considering the effect of elevation on actual amount of precipitation (Toy & Foster, 1998), these point data were then applied to DEM of the study region to spatially create R surface:

$$R_{\mathrm{new}} = R_{\mathrm{base}} \left(\frac{P_{\mathrm{new}}}{P_{\mathrm{base}}} \right)^{1.75} \quad (4)$$

where, R_{new} is the new value for R at the desired new location, R_{base} is the R value at base location, P_{new} is the average annual precipitation at new location, and P_{base} is the annual precipitation at the base location. In the study area, there is a meteorological station at the altitude 1,215 m, but altitude distribution of the total area is between 790–1,405 m. R values of unknown elevations were computed by using DEM in Arcview 3.2 and Eq. 2, which assumed a 50 mm increase of precipitation with each 300 m increment in altitude. It should be noted that this study used Eqs. 2 and 3 to approximate the erosive powers of rainfalls in the watershed, and the applicability of these equations from data from other areas should be tested by validation of EI_{30} with the data set available in the area. Unfortunately, validation studies such as direct energy measurements of rains and estimation of rain energy from drop size distribution were not feasible for the Kazan watershed.

The soil erodibility factor (K) describes the vulnerability of the soil to detachment and transport caused by raindrops and runoff. Soil database of Turkey (GDPS, 1986) at scale 1:25,000 was referred to map K values of the study area. A vector coverage that had polygons of soil classes was digitized and soil units which enclosed the combinations of texture and erosion were assigned to different classes of K using the following equation suggested by Romkens, Prasad, and Poesen (1986) and revised by Renard et al. (1997):

$$K = 0.0034 + 0.0405 \cdot \exp\left[-0.5 \left(\frac{\log D_g + 1.659}{0.7101} \right)^2 \right] \quad (5)$$

where, K is soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}) and D_g is geometric mean weight diameter of the primary soil particles (mm) and can be calculated by:

$$D_g = \exp\left(\sum f_i \cdot \ln\left(\frac{d_i + d_{i-1}}{2} \right) \right) \quad (6)$$

where, d_i is the maximum diameter (mm), d_{i-1} is the minimum diameter and f_i is the corresponding mass fraction for each particle size class of clay, silt, and sand. Finally, a rasterized layer of K was generated.

Slope-length factor (LS) relies on slope percentage and length of the slope. Slope percentage layer was derived from digital elevation model (DEM) of the study area. Slope length was assumed to be fixed as 15 m for each pixel (Ogawa et al, 1997), and LS factor was calculated by Eq. 7:

$$LS = \left(\frac{\chi\eta}{22.13} \right)^{0.4} \cdot \left(\frac{\sin\theta}{0.0896} \right)^{1..3} \quad (7)$$

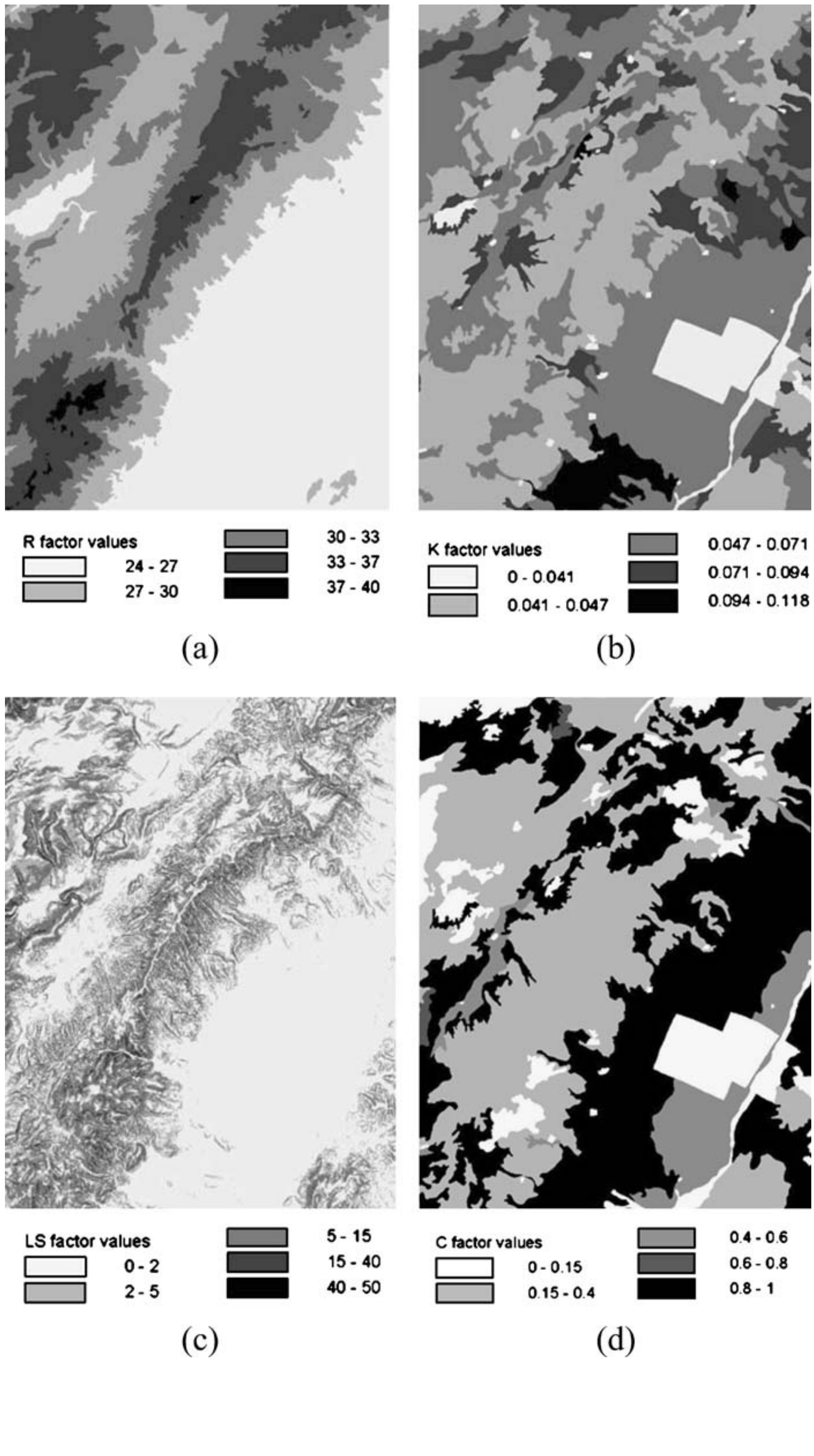

Figure 1 USLE factor layers.

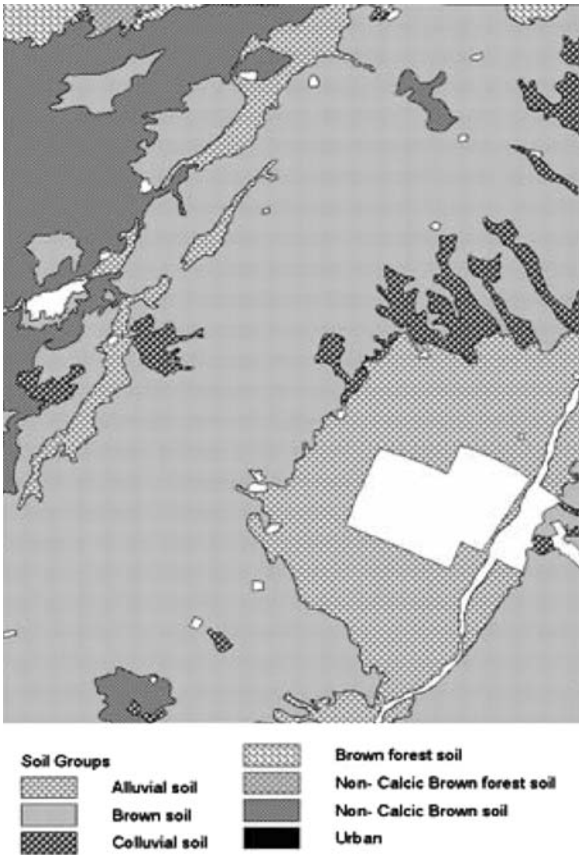

Figure 2 Soil map of Kazan watershed.

Where, χ is flow accumulation and is derived from DEM using a GIS accumulation algorithm (Lee, 2004), η is cell size, and θ is slope in degrees. As in Eq. 7, LS factor was estimated based on the flow accumulation and slope steepness (Moore and Bruch 1986a, 1986b). Flow accumulation was computed using the watershed delineation tool of Arcview 3.2. Since USLE is only suitable for estimating erosion due to interrill and rill processes, there is an upper bound on the slope length that should be used. To enforce an upper bound using the above approach, we needed to modify the flow accumulation map.

Crop management factor depends on vegetation cover, which dissipates the kinetic energy of the raindrops before impacting soil surface. Therefore, vegetation cover and cropping systems have a large influence on runoff and erosion rates. Soil erosion can be limited with proper management of vegetation, plant residue and tillage (Lee, 2004). C values were decided with the use of land cover data described in the map of land use/land cover of Turkey (GDPS, 1986). A map of C was generated through reclassification of each land-use/land-cover type into its corresponding C values. Finally, a map showing potential soil erosion was produced using USLE and integrating layers of R, K, LS, and C with ArcView 3.2 software (Wall, Coote, Pringle & Shelton, 1997).

3 Results and Discussion

The USLE factor layers of R, K, LS, and C are presented in Figure 1a–d, respectively. From R layer (Figure 1a), it was evident that most of the area had R values of 24–37 MJ mm ha^{-1} h^{-1} year^{-1} and to great extent, the values were within the range of 24–27 MJ mm ha^{-1} h^{-1} year^{-1}, having a climatologically low erosion potential. However, in spite of showing a very low erosivity values, it has been long recognized that the climatic characteristics of these regions together with topographic, soil, and land use factors have escalated water erosion. The substantial sign of the potential risk in these semiarid regions of Central Anatolia is very high climatic unevenness in which extreme events occur and rainy and vegetative seasons hardly concur.

The soil map of the Kazan watershed is given in Figure 2. Brown soils covered 58.9% of the study area and their K values mostly varied from 0.041 to 0.047 t ha h ha^{-1} MJ^{-1} mm^{-1} depending on the texture of the surface horizons (Eqs. 5 and 6) (Figure 1b). Respectively, alluvial soils and Noncalcic Brown soils extended over 17.6% and 12.4% of the area, having a range of K values from 0.047 to 0.071 t ha h ha^{-1} MJ^{-1} mm^{-1}. In other words, 88.9% of the watershed soils had the K values between 0.041 and 0.071 t ha h ha^{-1}

Table I Crop management factor for different land-use/land cover type

Land-use/Land-cover type	C factor
Fallow	1.00
Dry fallow	1.00
Agricultural crop (wheat)	0.40
Agricultural crop (corn)	0.45
Poorly managed pasture	0.25
Settlement	0.10
Dense forest	0.15
Natural shrubs	0.15
Water bodies	0.10
Fruit orchards	0.40

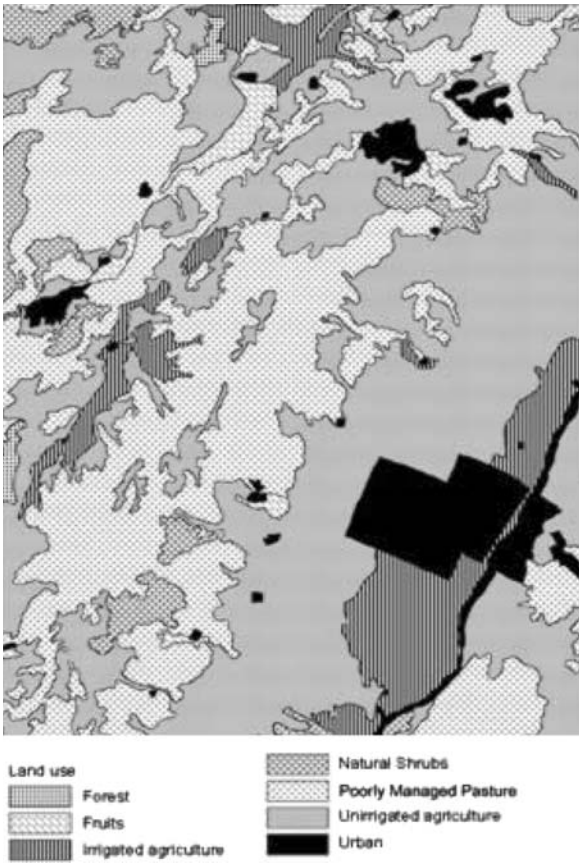

Figure 3 Land use map of Kazan watershed.

MJ^{-1} mm^{-1}. This also indicated that these soils had high soil erodibility, mostly comprising the textures of very fine sand, fine sand, very fine sandy loam and silt loam (K≥0.04 t ha h ha^{-1} MJ^{-1} mm^{-1}).

Dimensionless LS layer calculated by Eq. 7 (Figure 1c) showed that the Kazan watershed had LS values which ranged from 0–2 to 15–40. Coverage areas were 51.5%, 23.6%, 22.7%, and 2.2%, respectively, for the ranges of LS values 0–2, 2–5, 5–15, and 15–40. This suggested that topography of the watershed mostly favored less erosion, and only for 2.2% of the watershed steeper and longer slopes were combined to result in the accumulated water amounts with higher velocities and greater erosion.

Figure 1d reveals the map of C generated by reclassification of each land-use/land-cover type using C values given in Table I. Land use map of Kazan watershed (GDPS, 1986) is presented in Figure 3. A total of 77.5% of the watershed was covered by dry fallow and natural shrubs (43.4% and 34.1%, respectively) (Figure 3) while pasture and open and dense forests totally covered 5.3% (0.4%, 4.2%, and 0.7%, respectively). Regardless of the fallow, agricultural crops, corn and wheat entirely enveloped 7.4% of the watershed (2.1% and 5.3%, respectively). Therefore, C layer of the watershed (Figure 1d) mainly comprised of values of 1 and 0.15, respectively for the dry fallow and natural shrubs. On the other hand, it was obvious from C and LS layers (Figure 1c and d, respectively) that relatively flat areas with lower LS values of corresponded to the dry fallow while areas with the steeper slopes, where higher water velocities were expected, matched with the natural shrubs.

The map of the potential soil losses predicted by the USLE as a product of R, K, LS, and C is shown in Figure 4, and annual soil losses in ton per hectare per year with respect to the different soil units and land-use/land-cover types are given in Tables II and III, respectively. In determining the soil loss classes the amount of 1 ton ha^{-1} $year^{-1}$ was taken as an upper

Figure 4 Map of soil loss.

Table II Annual soil loss predicted for the different soil units of Kazan Watershed

Soil unit	%						
	Covarege	Soil loss (t ha^{-1} year^{-1})					
		0–1	1–2	2–4	4–6	6–11	11<
Alluvial soil	17.6	16.2	1.0	–	–	–	–
Brown soil	59.0	15.7	12.7	16.3	7.2	5.2	1.6
Colluvial soil	4.2	1.4	1.0	1.1	–	–	–
Brown forest soil	1.0	–	–	–	–	–	–
Noncalcic brown forest soil	0.3	–	–	–	–	–	–
Noncalcic brown soil	12.4	3.4	2.7	3.4	1.6	1.1	–
Urban	5.1	5.3	–	–	–	–	–

limit of soil erosion rate still tolerable to sustain the soils of the watershed since the rate of soil formation was expected to be so slow in semiarid environments like Central Anatolia of Turkey and any soil loss of more than 1 ton ha^{-1} year^{-1} over 50–100 years was considered as irreversible (EEA, 1999; Renard et al., 1997).

Most of the irreversible soil losses occurred in the Brown soils since they were medium-textured (K≥ 0.04 t ha h ha^{-1} MJ^{-1} mm^{-1}) and covered a greater area of steep slopes (5 ≥LS ≥40). Also, the fact that pastures in the watershed were overgrazed and poorly managed led to the greater soil erosion rates in this soil unit. Similarly, in Noncalcic Brown soils spreading over summits and back slopes of mountains there appeared the irreversible soil losses. In fact, percentages of soil losses more than 1 ton ha^{-1} year^{-1} were 43% and 8.8% for Brown and Noncalcic Brown soils covering 58.9% and 12.4% of the total area of the watershed, respectively (Table II). Alluvial and Colluvial soils did not have as much erosion risk as Brown and Noncalcic soils and percentages of soil losses more than 1 ton ha^{-1} year^{-1} were 1.0% and 2.1%, respectively, considering their coverage of 17.6% and 4.2%.

With respect to the land uses, areas of natural shrubs and dense forest had the most irreversible soil losses, and percentages of soil losses more than 1 ton ha^{-1} year^{-1} were 27.8% and 24.8%, respectively (Table III). When their coverages in the watershed were considered, 34.1% and 0.7%, respectively, it appeared that in the areas of the natural shrubs irreversible erosion was a serious problem that should be dealt with conservation measures. This was attributed to the fact that the natural shrubs occurred on the slopes with the range of K value between 0.047 and 0.071 t ha h ha^{-1} MJ^{-1} mm^{-1}). In the land of the dry fallow, corn, and wheat the soil erosion potential was not as critical as in the land of the natural shrubs and dense forest. This was due to, although they had the relatively higher C values than those of natural shrubs and dense forest (1.0, 0.45, and 0.40, respectively), the fact that the land of the

Table III Annual soil loss predicted in the land uses of the Kazan Watershed

Land use	%						
	Covarege	Soil Loss (t ha^{-1} year^{-1})					
		0–1	1–2	2–4	4–6	6–11	11<
Settlement	8.2	5.2	–	–	–	–	–
Fruit orchards	1.4	7.9	0.2	0.1	–	–	–
Poorly managed pasture	0.4	1.2	0.2	0.1	–	–	–
Open forest	4.2	0.4	0.0	0.0	–	–	–
Dry fallow	43.4	1.1	1.3	1.2	0.5	0.2	
Natural shrubs	34.1	15.6	6.6	9.1	5.1	5.1	1.9
Dense forest	0.7	9.4	9.0	10.7	3.8	1.3	
Agricultural crop (corn)	2.1		0.0	0.2	0.1	0.2	0.2
Agricultural crop (wheat)	5.3	1.6	0.3	0.1	–	–	–
TOTAL (%)		42.3	17.7	21.4	9.5	6.8	2.1

agricultural crops was situated in the areas where the range of LS was between 0 and 2 (Figure 1c) and deposition occurred.

Finally, the application of the USLE/GIS methodology resulted in a consistent pattern of soil erosion among different land uses, slope positions and soil groups and reasonably predicted the annual soil losses, locating the erosion-prone areas where the concentrated flow created the irreversible soil losses in the Kazan watershed. Particularly, rather than land-use/land-cover type, soils and topographical properties of the watershed had a greater influence on the magnitude of soil losses since R factor did not changed significantly in the study area.

4 Conclusion

The USLE/GIS technology was used to predict potential soil erosion in the semiarid Kazan watershed located in the Central Anatolia, Turkey. Model parameters R, K, and C were respectively computed from the erosivity map, soil map, and land use map of Turkey. Additionally, in view of the effect of elevation on actual amount of precipitation, R values were site-specifically corrected using DEM and the climatic data. The topographical and hydrological effects on the soil loss were characterized by LS factor evaluated by the flow accumulation tool using DEM and watershed delineation techniques of Arcview 3.2. By assuming no support practice in the study area (P=1), the annual soil losses in ton ha^{-1} $year^{-1}$ with respect to the different soil units and land-use/land-cover types of the watershed were estimated as a product of R, K, LS, and C layers. With the use of the USLE/GIS methodology spatial distribution of different erosion-prone areas were identified in the Kazan watershed to successfully take erosion control measures in the severely affected areas. However, since there were no direct field measurements of soil erosion in the watershed, it was not practical to confirm the results of USLE prediction. Therefore, future works are needed for monitoring of sediment load in rivers and measurement of sediment deposition in lakes and reservoirs that exist in the watershed. The use of reference areas where this kind of data is available would provide several advantages in upscaling.

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