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ASSESSMENT OF SOIL EROSION AT LARGE WATERSHED SCALE USING RUSLE AND GIS: A CASE STUDY IN THE LOESS PLATEAU OF CHINA

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ABSTRACT

Soil erosion is a serious problem in the Loess Plateau of China, and assessment of soil erosion at large watershed scale is urgently need. This study used RUSLE and GIS to assess soil loss in the Yanhe watershed. All factors used in the RUSLE were calculated for the watershed using local data. RUSLE-factor maps were made. The mean values of the *R*-factor, *K*-factor, *LS*-factor, *C*-factor and *P*-factor were 970 209 MJ km^{-2} h^{-1} a^{-1}, 0·0195 Mg h MJ^{-1} mm^{-1}, 10·27, 0·33359 and 0·2135 respectively. The mean value of the annual average soil loss was found to be 14 458 Mg km^{-2} per year, and the soil loss rate in most areas was between 5000 and 20 000 Mg km^{-2} per year. There is more erosion in the centre and southeast than in the northwest of Yanhe watershed. Because of the limitations of the RUSLE and spatial heterogeneity, more work should be done on the RUSLE-factor accuracy, scale effects, etc. Furthermore, it is necessary to apply some physical models in the future, to identify the transport and deposition processes of sediment at a large scale. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: soil erosion; watershed scale; RUSLE; GIS; China; Loess Plateau

INTRODUCTION

Soil erosion has increased throughout the 20th century (Angima *et al.*, 2003), and is becoming an extremely serious environmental problem, if not a crisis (Stanley and Pierre, 2000). Much effort has been put into understanding the mechanism of soil erosion and predicting soil loss, and several empirical or process-based models have been constructed around the world (Merritt *et al.*, 2003; Russell and William, 2001). More attention is being paid at the large scale (David and David, 2003; De Jong *et al.*, 1999; Chris and Jon, 2002), and the results will provide useful information for decision-makers and planners to take appropriate land-management measures. To date, most studies of soil erosion at the large scale have followed two general approaches: (1) evaluation by the regional erosion factors or available models (David and David, 2003; Bissonnais *et al.*, 2002; Wang and Yang, 2003); (2) evaluating soil loss by extrapolating from plot and micro-catchment scales to catchments, watersheds and regional scales (Zhang *et al.*, 2002a; Chris and Jon, 2002; Brazier *et al.*, 2001; Zobeck *et al.*, 2000). Both of the approaches have the substantial obstacle of spatial heterogeneity at the large scale, and more methods need to be tried for different areas.

The Chinese Loess Plateau suffers some of the highest soil erosion rates in the world (Fu, 1989), about 5000–10 000 Mg km^{-2} per year in most areas, and even higher than 20 000 Mg km^{-2} per year in some areas (Chen *et al.*,

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2001). The problem receives a lot of attention from the Chinese Government (Chen *et al.*, 2001). Much work has been done on soil erosion evaluation at plot or catchment scale (Kang *et al.*, 2001; Zhang, 2001; Fu *et al.*, 2004), and some at a regional scale (Qiao and Qiao, 2002; Yang *et al.*, 2002). However, the current knowledge at the regional scale is far from perfect, and more work should be done on the topic (Yang *et al.*, 2002).

The Revised Universal Soil Loss Equation (RUSLE; Renard *et al.*, 1997) is an empirical model, designed for use at runoff plot or single hillslope scales. However, erosion rates of ungauged catchments can also be predicted using RUSLE by using knowledge of the catchment characteristics and local hydroclimatic conditions (Angima *et al.*, 2003), though sediment yield cannot be estimated (Renard *et al.*, 1997). In this study, the RUSLE has been applied at large watershed scale, and some methods (including the upscaling method) of calculating the factors of RUSLE were also attempted.

The region of China with the highest erosion rates is generally considered to be the hilly part of the Loess Plateau, which is mostly located in the northern part of Shanxi and Shaanxi Provinces. This paper took one watershed (the Yanhe watershed) in northern Shaanxi as a cased study. The objectives were:

(1) To test some methods for calculating the factors of RUSLE at large watershed scale; and
(2) To assess soil erosion for the Yanhe watershed.

MATERIALS AND METHODS

The study area (7725 km^2) is the Yanhe watershed (108° 38′-110° 29′ E, 36° 21′–37° 19′ N), which lies in the middle part of the Loess Plateau in Northern Shaanxi Province in China (Figure 1). The elevation varies from 495 m to 1795 m, and the slope varies from 0 to 54·6 degrees, which is derived from 1:50 000 DEM. The region has a semiarid continental climate, with annual precipitation averaging 520 mm. Rainfall in July, August and September accounts for 60–70 per cent of the total annual precipitation, and markedly affects runoff and soil erosion. Land use in this area comprises slope farmland, terrace farmland, orchard, sparse forestland, forestland, residential land, water body, etc. The most common soil in the watershed is loess, a fine silt soil. Loess is weakly resistant to erosion (Fu, 1989; Fu and Gulinck, 1994).

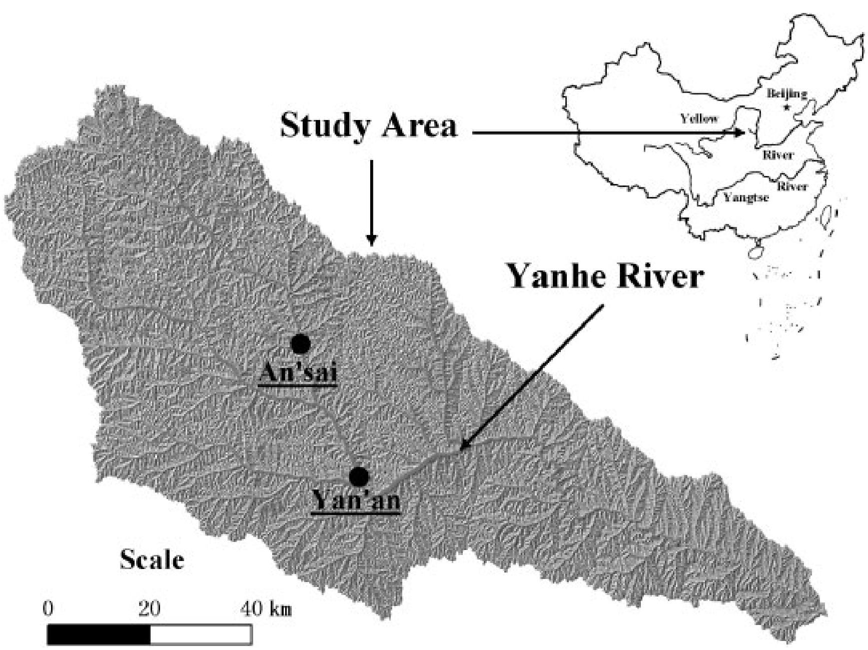

Figure 1. The location of the study area.

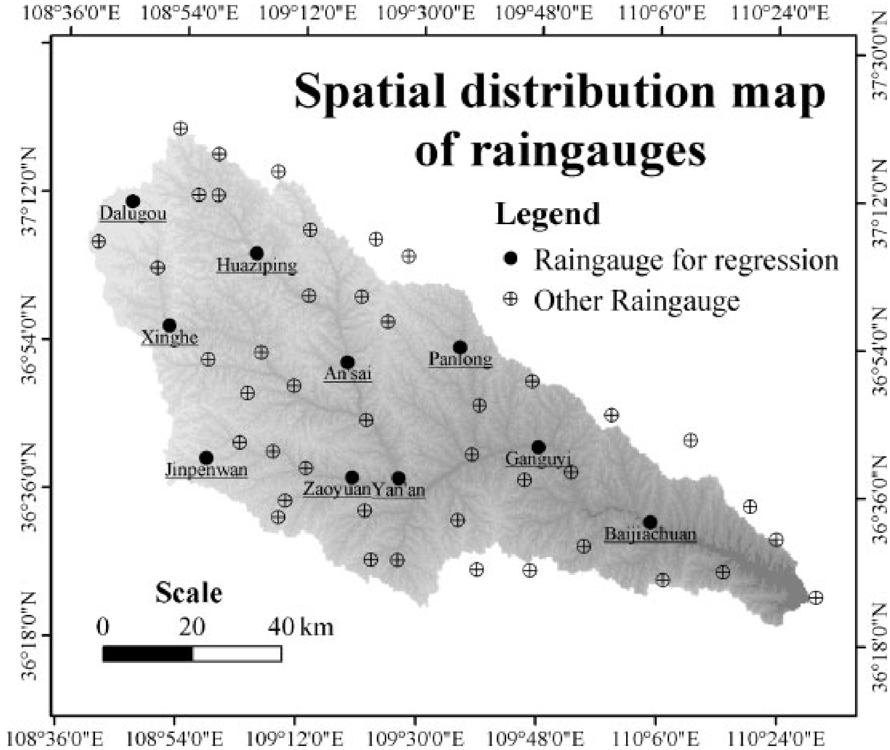

Figure 2. Spatial distribution of raingauges in the Yanhe watershed.

The average soil loss (A) due to water erosion per unit area per year was quantified using RUSLE by the following equation (Renard *et al.*, 1997):

$$A = R \times K \times L \times S \times C \times P \tag{1}$$

where A is the average soil loss due to water erosion (Mg km^{-2} per year), R the rainfall–runoff erosivity factor (MJ mm km^{-2} h^{-1} per year), K the soil erodibility factor (Mg h MJ^{-1} mm^{-1}), L the slope length, S the slope steepness, C the cover-management practice factor, and P the support practice. Every factor was calculated by a GIS, and multiplying factor map layers in the GIS gave the spatial distribution of the soil loss of Yanhe watershed.

Rainfall-runoff Erosivity R-factor

There are 52 raingauges in or near the Yanhe watershed (Figure 2). It is an exhausting task to get the rainfall–runoff erosivity (R-factor) map layer by calculating the value of EI (storm energy times intensity) for every individual rainfall event during the period from 1981 to 1989. In order to get the R-factor map from the raingauge more efficiently, the calculation equation of the R-factor at watershed scale should be derived, which is based on individual rainfall data and can be called a kind of upscaling method. For each erosive storm that occurred between 1981 and 1989, over the selected ten raingauges (Figure 2), EI_{30} values were computed according to RUSLE handbook instructions, and monthly EI_{30} values were computed as the sum of EI_{30} for each erosive storm that occurred during the month. $Rain_9$ (the monthly rainfall for days with $\geq 9{\cdot}0$ mm) was also derived from the raingauge data. Different models were tested and the regression equation of R-factor and $rain_9$ was derived (Eq. 2; $R^2 = 0{\cdot}626$; Zhao *et al.*, 2004).

$$R = 8{\cdot}3462\ \mathrm{rain}_9^{1{\cdot}2570} \tag{2}$$

Using Eq. 2, the *R*-factor value for raingauges of the Yanhe watershed were computed, and the *R*-factor map layer was made by Kriging interpolation in GIS.

Soil Erodibility K-*factor*

Soil erodibility (*K*-factor) is the rate of soil loss per rainfall erosion index unit as measured on a unit plot, and often determined using inherent soil properties (Parysow *et al.*, 2003). The data on soil mechanical composition were collected from Yan'an soil (Zhao *et al.*, 1989) and the value of the *K*-factor was calculated using the following equation (Renard *et al.*, 1997; Liu *et al.*, 2001):

$$K = 7{\cdot}594\left\{0{\cdot}0034 + 0{\cdot}405\exp\left[-\frac{1}{2}\left[\frac{\log(Dg) + 1{\cdot}659}{0{\cdot}7101}\right]^2\right]\right\} \quad (3)$$

where $Dg = \exp(0{\cdot}01\sum f_i \ln m_i)$, and Dg = geometric mean particle diameter. Here, f_i is the primary particle size fraction in percent, and m_i is the arithmetic mean of the particle size limits of that size.

Soil information data were put into the attribute database of the soil map, and the *K*-factor was computed in GIS. The results of the soil erodibility map were converted into grid format for further analysis.

Slope Length and Steepness LS-*factor*

A limitation of using the RUSLE soil-erosion models at regional scales has been the difficulty in obtaining an *LS*-factor grid suitable for use in GIS applications (Van Remortel *et al.*, 2001). Different methods or models have been tried to solve this problem (Hickey, 2000; Kinnell, 2001). The algorithms adopted in this paper to estimate slope length and steepness were the raster grid cumulation and maximum downhill slope methods, which were developed by Van Remortel (Van Remortel *et al.*, 2001); the Arc Macro Language (AML®) program can be downloaded from his website. The basic input for generating a *LS*-factor grid map in GIS is a 25 m DEM dataset of the Yanhe watershed, which was integer formatted, having been derived from a 1:50 000-scale contour map. In the AML program, the RUSLE algorithms were used for calculating *L* and *S* constituents after deriving slope length and slope steepness (Van Remortel *et al.*, 2001). *L* is equal to: $(\text{HPSL/RSL})^{\text{m}}$, where HPSL is the horizontally projected slope length derived, and RSL is the 22·1 m reference slope length. For slopes of less than 9 per cent gradient, *S* is equal to: $10{\cdot}8 \times \sin(\text{slope\_angle}) + 0{\cdot}03$; for slopes of 9 per cent or steeper, *S* is equal to: $16{\cdot}8 \times \sin(\text{slope\_angle}) - 0{\cdot}50$.

Cover and Management Practices C-*factor*

The *C*-factor is calculated on the basis of soil-loss ratios for the different crop-growth stages (Gabriels *et al.*, 2003), and to measure *C*-values for specific crop rotations is time-consuming at plot scale. At big watershed scale, it is very difficult or impossible to measure every plot to get the *C*-factor map layer. The reasonable methods to compute *C*-factor for large scale are extrapolating from the plot scale if there are basic data for plots, or evaluating qualitatively if there are no basic data. In the Loess Plateau of China, there are some experiments that have allowed the calculation of *C*-factor for cultivated land (Zhang *et al.*, 2001; Zhang *et al.*, 2002b), but few for other land-use types, at the plot scale. Therefore, in this study, one upscaling method was used for cultivated land at watershed scale, and for other land-use types, qualitative data were adopted based on some research papers (Wang and Jiao, 1996a).

The basic method of upscaling the *C*-factor from plot scale to watershed scale comes from the equation for calculating *C*-factor ($C = (\text{SLR}_1\text{EI}_1 + \text{SLR}_2\text{EI}_2 + \cdots + \text{SLR}_n\text{EI}_n)/\text{EI}_t$). The basic data for up-scaling are: (1) spatial distribution of rainfall–runoff erosivity in different months (SDRE); (2) The spatial composition of planting area for different crops (SCPA); and (3) soil-loss rate in different months for different crops (SLRM). By multiplying SCPA and SLRM, the value of regional soil loss rate (RSLR) in different months can be calculated. Using raster calculator in GIS will then get the spatial distribution map of *C*-factors; the equation is:

$$C = \sum_{i=1}^{n} RSLR_i\ SDRE_i \Big/ \sum SDRE \quad (4)$$

Support Practice P-*factor*

At the large watershed scale, the differences in support practices, such as terracing, contour tillage, and so on, cannot be reflected from a land-use map. Also, the possible method for calculating *P*-factor is by means of an empirical equation. In this study, the Wener method (Lufafa *et al.*, 2003) was used to determine the value for the *P*-factor, and the equation was:

$$P = 0{\cdot}2 + 0{\cdot}03 \times S \qquad (5)$$

where S is the slope grade (%).

RESULTS AND DISCUSSION

Rainfall–Runoff Erosivity Map Layer

Using Eq. 2 and rainfall amount data ($rain_9$) of the 52 raingauges (Figure 2), the average annual rainfall–runoff erosivity from 1981 to 1989 was calculated. In addition, four multivariate geostatistical methods were used for interpolation of *R*-factor values. By comparing prediction errors in different methods, it was found that the mapped surfaces by simple Kriging and disjunctive Kriging give more accurate predictions of rainfall–runoff erosivity than that by ordinary Kriging and universal Kriging (Table I), though the prediction errors are not perfect.

The rainfall–runoff erosivity map was interpolated by disjunctive Kriging and the *R*-factor map layer was obtained (Figure 3). The average annual *R*-factor value varied from 670 852 MJ km^{-2} h^{-1} a^{-1} to 1 198 968 MJ km^{-2} h^{-1} a^{-1} and the mean value was 970 209 MJ km^{-2} h^{-1} a^{-1}. With respect to the anisotropies of rainfall–runoff erosivity, the major axis of average annual rainfall–runoff erosivity lay in the NNW–SSE, and the major range was approximately 100 km, the minor 46 km. There is more rainfall–runoff erosivity in the centre and southeast of the watershed than that in the northwest. The spatial distribution of the *R*-factor has a close relation with the decreasing trend of rainfall from southeast to northwest and non-uniformity of spatial distribution of rainfall in the Loess Plateau (Wang and Jiao, 1996b).

In order to calculate the *C*-factor map later, the spatial distribution maps of the *R*-factor values in different months were also interpolated (Figure 3). It can be found from the maps that *R*-factors in July and August were higher than in June, September and other months. The spatial distribution character of *R*-factors varies in different months, with more rainfall–runoff erosivity in the centre and southeast of its area.

Soil Erodibility Map Layer

The main soil type in the Yanhe watershed is loess soil, and the soil textures are sandy, light or medium-loamy in general. At the soil genus level, the soil in the Yanhe watershed was divided into sixteen types, of which cultivated loess soil and eroded loess soil occupy 32 per cent and 29·61 per cent respectively (Table II). Using Eq. 3 and the soil properties data from Yan'an Soil (Zhao *et al.*, 1989), the *K*-factor value in the Yanhe watershed was calculated (Table II), and the spatial distribution map of soil erodibility in the Yanhe watershed was also made (Figure 4). The

Table I. Prediction errors of average annual rainfall–runoff erosivity by different Kriging methods

Algorithms[a]	Prediction errors			
	Mean	Root-mean-square	Average standardized error	Root-mean-square standardized
Ordinary Kriging	−8·206	802·3	818·5	0·982
Simple Kriging	−0·6769	940·8	732·3	1·365
Universal Kriging	−18·95	922·6	738·3	1·305
Disjunctive Kriging	−0·1784	910·3	714	1·332

[a]Kriging is a method of interpolation based on statistical models that can predict unknown values from data observed at known locations.

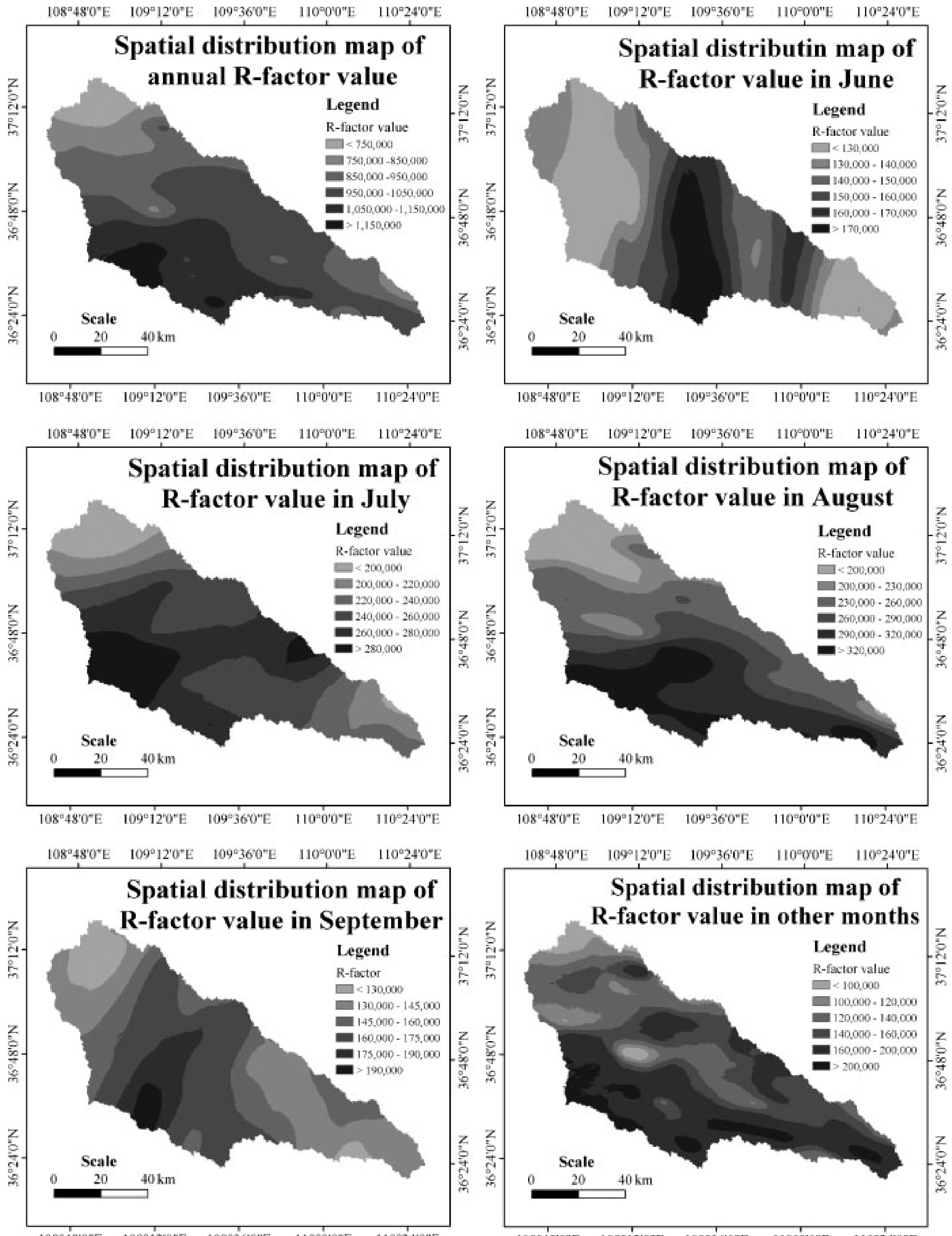

Figure 3. Spatial distribution map of *R*-factor values in the Yanhe watershed.

Table II. The *K* value for different soils in the Yanhe watershed

Soil type	*K*-factor value	Area (%)
Eroded loess soil	0·01621	29·61
Cultivated loess soil	0·0191	32
Mature loess soil	0·0248	0·77
Hipparion laterite soil	0·03224	3·99
Calcareous skeletal soil	0·0292	0·12
Loamy calcareous alluvial soil	0·03205	3·76
Cultivated sandy loess soil	0·01649	7·91
Eroded sandy loess soil	0·01747	7·21
Chalk loess soil	0·02026	0·66
Eroded chalk loess soil	0·02229	2·52
Cultivated chalk loess soil	0·01824	2·46
Grey loess soil	0·02394	3·31
Degraded grey loess soil	0·02633	4·22
Cultivated grey loess soil	0·02154	0·89
Eroded dark-purple loess soil	0·02262	0·01
Covered dark-purple loess soil	0·02292	0·55

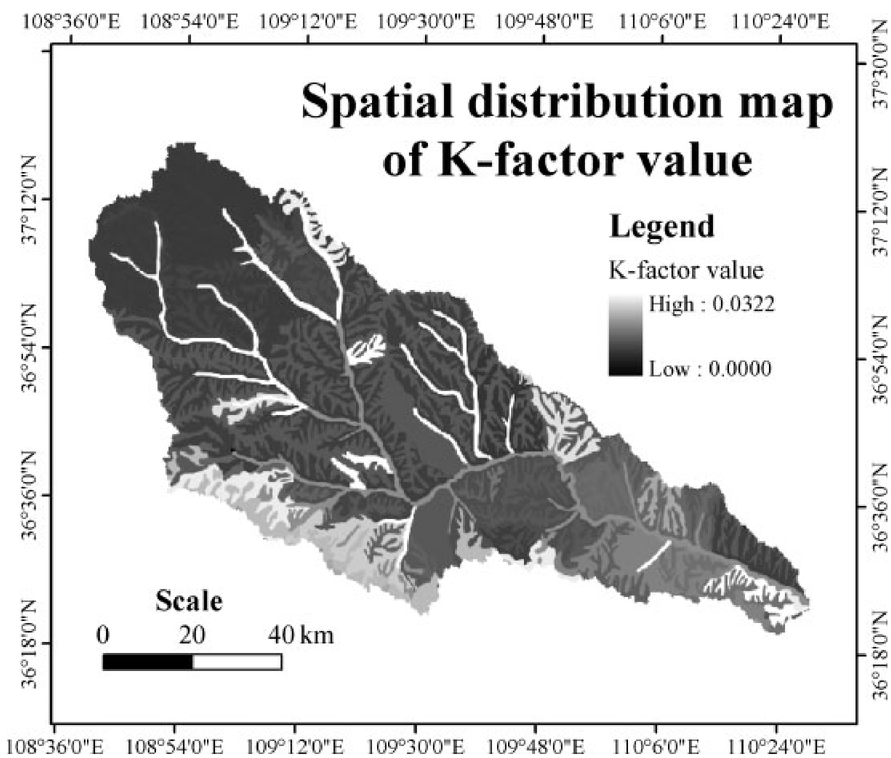

Figure 4. Spatial distribution map of *K*-factor values in the Yanhe watershed.

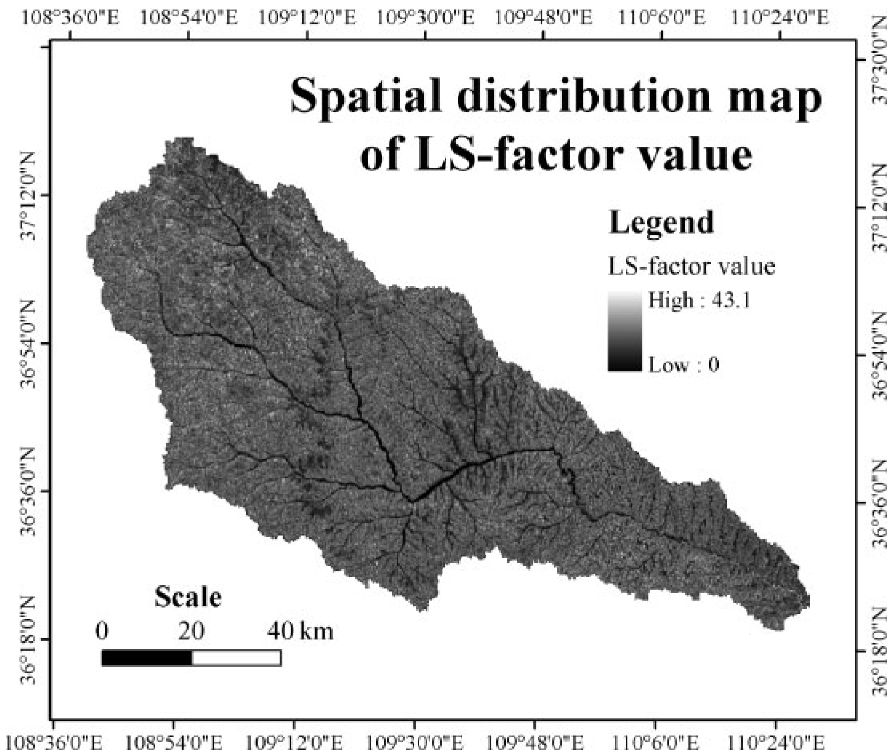

Figure 5. Spatial distribution map of *LS*-factor values in the Yanhe watershed.

K-factor value for eroded loess soil is lowest (0·01621 Mg h MJ^{-1} mm^{-1}), and that for Hipparion laterite soil is highest (0·03224 Mg h MJ^{-1} mm^{-1}). At the watershed level, the mean *K*-factor value is 0·0195 Mg h MJ^{-1} mm^{-1}, and the *K*-factor value is generally higher in the southeast than in the northwest, except for some particular places along rivers.

Slope Length and Steepness Map Layer

The AML program for calculating the *LS*-factor was downloaded from the website http://www.cwu.edu/~rhickey/slope/slope.html, and carried out in the workstation environment of ArcGIS®. Long time and fast local hard drives are needed because of the drawback of the *LS*-factor grid iteration process (the AML program runs are extremely resource-intensive) and the higher resolution DEM. From the calculations, we obtained the *LS*-factor map in the Yanhe watershed (Figure 5), and the min, mean and max values for the *LS*-factor were also calculated (0, 10·27 and 43·1). The lowest values for the *LS*-factor occurred along rivers, which is possibly because of the low slope. The higher values for *LS*-factors were scattered, but more in the northwest than in the southeast.

Cover and Management Practices Map Layer

The calculation process for the *C*-factor was divided into two parts; one used the upscaling method for cultivated land, and the other used the existing research results for forestland, sparse forestland, and other land types. The *C*-factor for cultivated land was calculated from the predominant crops (winter wheat, millet, beans, maize, potato, broom corn millet, etc.), and soil loss rate in different months (Table III) was obtained from published sources (Zhang *et al.*, 2002; Jiang *et al.*, 1996). Because there was only one crop per year, the effect of crop rotation on the *C*-factor was not taken into account. Using spatial composition of crops and soil-loss rate in different months for

Table III. Soil loss rates for some crops in the Yanhe watershed

	Area (%)	SLR in June	SLR in July	SLR in August	SLR in September	SLR in other months
Winter wheat	22·75	0·17	0·19	0·21	0·50	0·23
Millet	15·97	0·54	0·52	0·52	0·52	0·94
Beans	15·66	0·68	0·54	0·46	0·46	0·64
Maize	10·24	0·45	0·40	0·39	0·41	0·59
Potato	7·74	0·84	0·51	0·41	0·3	0·75
Other grain crops	4·50	0·63	0·56	0·54	0·58	0·82
Setaria italica	4·40	0·58	0·52	0·50	0·54	0·76
Other crops	18·74	0·51	0·45	0·44	0·47	0·66
Cultivated land	100	0·49	0·42	0·40	0·47	0·62

Table IV. *C*-factor values for some land use types in the Yanhe watershed

Land-use type	*C*-factor value
Forestland	0·09
Sparse forestland	0·15
Shrub forestland	0·22
Higher coverage grassland	0·12
Medium coverage grassland	0·18
Lower coverage grassland	0·32
Residential and built-up land	0·2
Water body	0

the different crops, the area-weighted average SLRS for cultivated land in different months were calculated (Table III). The annual *C*-factors are listed in Table IV, taken from Chinese papers (Zhang *et al.*, 2002b; Cai *et al.*, 2000).

Using Eq. 4 and raster calculator in ArcGIS, the spatial distribution of *C*-factors for cultivated land was derived by integrating the *R*-factor and soil-loss rate in different months. Combined with *C*-factors of other land-use types, a spatial distribution map of *C*-factor values in Yanhe watershed was drawn (Figure 6). *C*-factor values in the Yanhe watershed vary from 0 to 0·52, and the mean value is 0·3359. Because of the large area of cultivated land in the centre part, the higher *C*-factor happens also in that area.

Support Practice Map Layer

The lower the *P*-factor value, the better the practice is for controlling soil erosion (Angima *et al.*, 2003). Accurate *P*-factors are good indicators for support practice. However, because of the difficulty in identifying different support practices at large watershed scales, only a rough *P*-factor value for the Yanhe watershed could be calculated using Eq. 5. The *P*-factor map (Figure 7) was made from the spatial analysis program in GIS; the mean value of *P*-factors of Yanhe watershed is 0·2135 and the max is 0·2436. It can be seen from the map that the *P*-factor value is lower in some places in the centre and higher in some places in the northwest. This is connected with topographical features. The slope in areas around the river source is in general steeper than that around the river outlet, which leads to the spatial variety of *P*-factors at watershed scale.

Average Annual Soil Loss in Yanhe Watershed

Using Eq. 1, the average annual soil loss in the Yanhe watershed was computed by overlaying the five factor maps. As seen in Figure 8, average annual soil loss in most of the area is between 5000 and 20 000 Mg km^{-2} per year, and

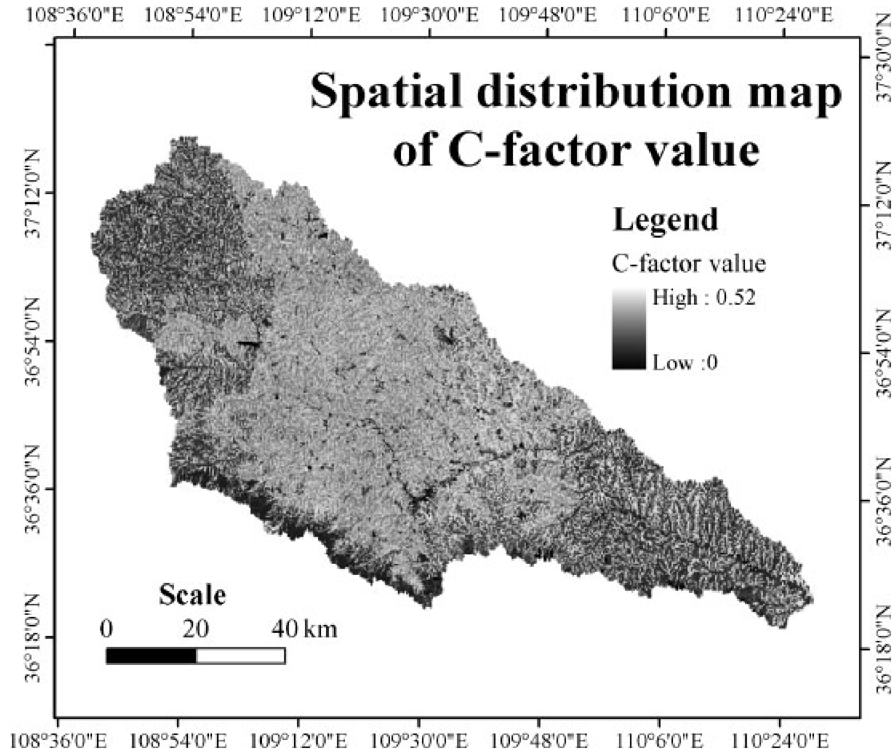

Figure 6. Spatial distribution map of *C*-factor values in the Yanhe watershed.

the mean value is 14 460 Mg km^{-2} per year. These results compare well with other studies and local data (GCSNU, 1983; Fu, 1989; Liu *et al.*, 2000). With regard to the spatial variation, the middle and southeast parts of the Yanhe watershed has more erosion than the northwest part. The main reason for soil loss is the close relationship with land use and rainfall–runoff erosivity.

CONCLUSIONS

Soil erosion is a serious problem in the Loess Plateau of China, and attempting different methods to evaluate soil loss at large watershed scale is necessary for sustainable land use and comprehensive region management. The RUSLE model is a statistical and relatively simple soil erosion model, which is easy to parameterize and thus requires less data and time to run. With some upscaling methods, this paper attempts to evaluate soil loss in Yanhe watershed by integrating RUSLE and GIS, and obtain a gross amount and spatial distribution of soil loss for the watershed.

The process of calculating RUSLE-factors, especially the upscaling methods for *R*-factor and *C*-factor, may be helpful for the relative studies. The predicted amount of soil loss and its spatial distribution can provide a basis for comprehensive management and sustainable land use at watershed scale. But, because of the limitation of RUSLE, spatial heterogeneity in the watershed and use of empirical data, there are uncertainties in the predicated value. In further studies, more attention should be paid to the accuracy of RUSLE-factors, scale effects, data precision, etc. Some physical models may need to be tried for the large scale also, which will identify the transport and deposition process of sediments at large watershed scale.

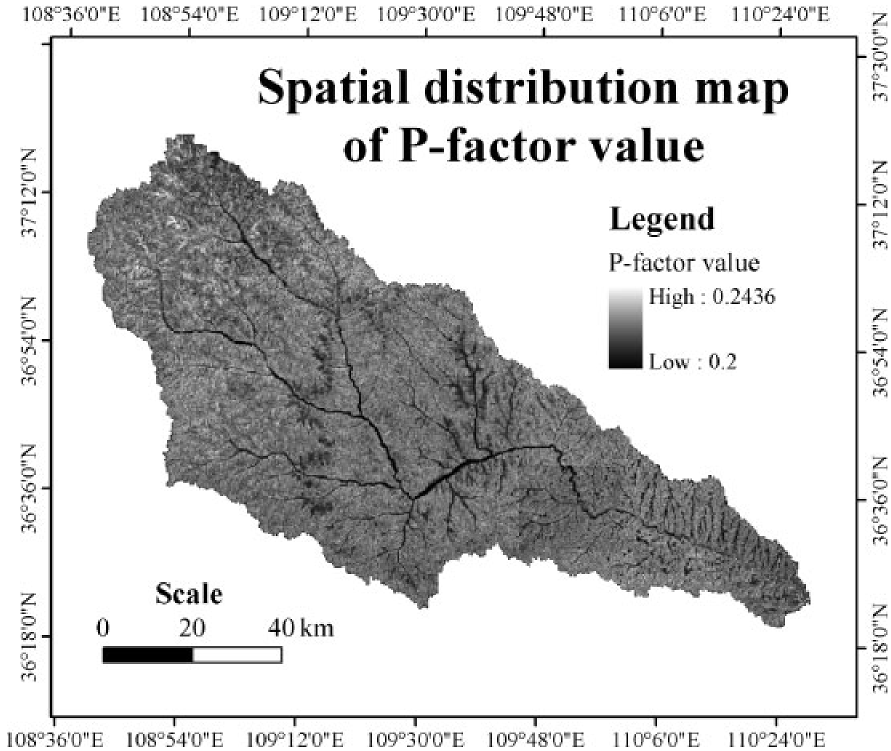

Figure 7. Spatial distribution map of *P*-factor values in the Yanhe watershed.

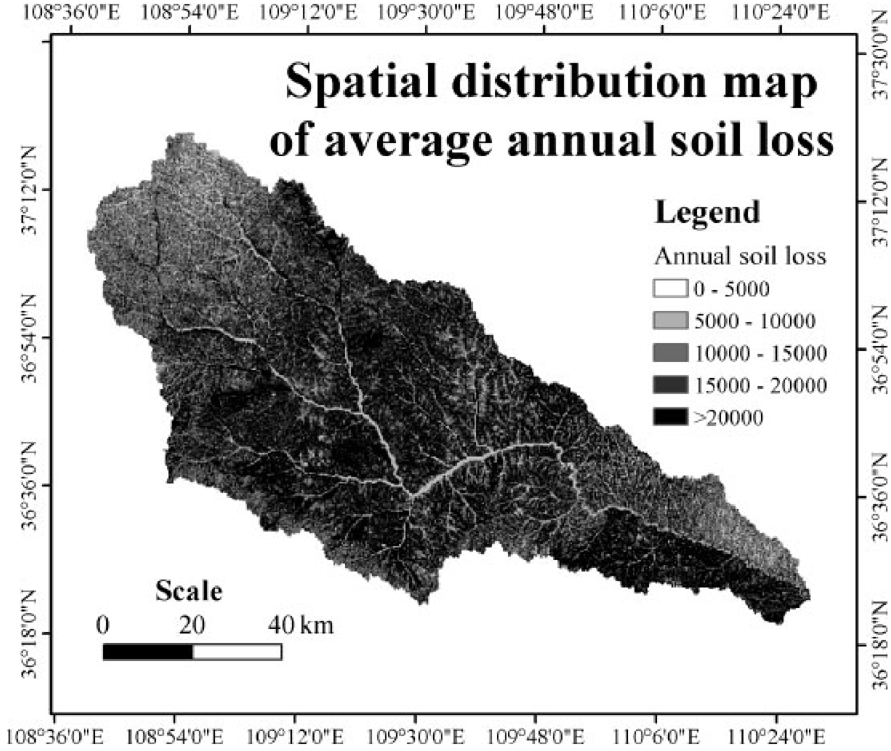

Figure 8. Spatial distribution map of average annual soil loss in the Yanhe watershed.

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