Study on soil erosion Simulation in Tianshui Maiji district based on InVEST-SDR model with GIS and RS

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Abstract: The Maiji district of Tianshui city locates in the transition regions of semi-arid and semi-humid with fragile ecosystems, so it is of great scientific and practical significance to analyse and study its characteristics and influencing factors of soil erosion. Based on GIS, RS and InVEST-SDR model, this paper simulations the soil erosion in 2015 and analyses the effect of different influencing factors on soil erosion. The results showed that: 1) In 2015, the soil erosion in the study area was mainly slight and light erosion, in spatially, the north-western part of the study area was more eroded than other regions; 2) The effect of vegetation cover on soil erosion presented bimodal pattern mode; 3) The effects of elevation and slope on soil erosion had a critical value of 1300 m and 30 degree; 4) Forestland was the main type of land use that produced the largest amount of soil erosion in the region, followed by cropland and grassland.

1. Introduction

Soil erosion is one of the global environmental problems that limits the survival and development of human beings, which seriously affects the sustainable development of soil productivity, ecological environment, social and economic development and ecosystem. Many soil erosion models with various characteristics have played an important role in the field of soil erosion research [1], of which, the general soil loss equation USLE (The universal soil loss equation) and its later correction model RUSLE model, proposed by the United States in 1965, have been widely used in all over the world [2,3]. As an empirical model, the USLE method can accurately reflect the soil erosion condition of the region, but it ignores the sediment retention ability of the plot when calculating the soil retention quantity and there are some deviations [4]. In recent years, the InVEST-SDR (Sediment Delivery Model) model which based on the USLE model, made up for the above defects of USLE. It has been used for the calculation of soil retention function quality by many researchers. Cheng et al. (2016) evaluated and analyzed the spatial heterogeneity of the ecological service functions of land retention, soil erosion and soil conservation by using the InVEST-SDR model for Shangluo which locates in the areas of the Project of Water Diversion from South to north project[5]. Oleson et al. (2016) used the model to examine trade-offs among possible agricultural road repair management actions (water bars to divert runoff and gravel to protect the road surface) across the landscape in West Maui, Hawaii, USA [6]. In addition, Bouguerra et al. (2017) calculated the soil loss and sediment yield by the InVEST-SDR model and identified and prioritized critical sub-catchments were based on average annual soil loss in Rmel river basin, Tunisia [7]. Compared with the USLE model, the use of InVEST-SDR model was relatively few on its application in soil loss. In particular, there was a relative lack of applications in climate transition regions.

Therefore, the present study uses Maiji District as our study area, which is a typical climate transition regions of semi-arid and semi-humid, the InVEST-SDR model combined with GIS and RS technology are utilized to estimate the locational soil erosion condition in 2015, to analyse the distribution pattern
of soil erosion, and identify the crucial area for the overall management of soil erosion. It can provide a reference to implement the effective management of soil and water conservation in the transition region.

2. Study Area and data source

2.1 Study Area
The Maiji District of Tianshui city is located between the coordinates 105°25′–106°43′ E and 34°06′–34°48′ N, with an area of ~3480 km² (Fig. 1). It belongs to Gansu Province of China. The whole region is cool and humid, belonging to the continental semi-humid monsoon climate with moderate rainfall that averages 600 mm yearly, gradually decreasing from south to north. The soil is classified into seven types, namely cinnamon soil, loessial soil, dark loessial soil, red clay soil, anthropogenic-alluvial soil, fluvo-aquic soil, alluvial soil, and brown soil. In particular, the area with cinnamon soil is the largest. The Weihe River System (a tributary of the Yellow River) lies north of this mountain range, while the Jia Lingjiang River (a tributary of the Yangtze River) is south of this region. There has two geomorphological parts of Qinling Mountains and Loess Plateau. The Qinling Mountains bisect the southern part of this region, running from west to east at an average elevation>2000m and featuring moderately-to-deeply incised, medium-sized, stony mountains. In the north-western part, the Loess Plateau is criss-crossed by ridges, gullies, and hills.

2.2 Data Sources
In this study, several types data from different sources are used, all the requirement data, sources and its usages are listed in Table 1.

| Data requirements          | Data sources                                                                 | Data usage                                  |
|----------------------------|------------------------------------------------------------------------------|---------------------------------------------|
| Daily rainfall data        | The China Meteorological Data Network (http://data.cma.cn/)                  | Calculate R factor                          |
| Soil attribute data        | 1:100,000 soil map of Maiji district from the Countywide Cultivated Land     | Provide Soil Species Patches for calculating K factor |
|                           | Fertility Evaluation Project                                                 |                                             |
|                           | The Report on the Second Soil Survey (1981) in Tianshui City from the         | Supply the soil mechanical composition and  |
|                           | Countywide Cultivated Land Fertility Evaluation Project                      | organic matter content of the corresponding |
|                           |                                                                               | soil species for calculating K factor       |
| DEM                       | 1:100,000 the topographic map of Maiji district                             | Calculate LS factor                          |
| Land cover data           | Landsat8 TM image from the Geospatial Cloud (http://www.gscloud.cn/)         | Calculate C and P factors                   |
| Vegetation coverage       | The Report on the Second Soil Survey (1981) in Tianshui City                | Calculate C factor                           |
| Sediment retention        | InVEST model database                                                        | Calculating SE factor                       |
3. Model and parameter calculation

3.1. InVSET-SDR model

The InVSET-SDR model is a spatially-explicit model working at the spatial resolution of the input DEM raster. For each cell, the model first computes the amount of eroded sediment, then the sediment delivery ratio (SDR), which is the proportion of soil loss actually reaching the catchment outlet. The amount of annual soil loss on pixel is given by the revised universal soil loss equation (RUSLE) [8]:

\[ A = R \cdot K \cdot L \cdot S \cdot C \cdot P \]

(1)

where \( A \) is the mean annual soil loss per unit area \([t/(hm^2 \cdot a)]\); \( R \) is the rainfall erosivity factor \([MJ \cdot mm/(hm^2 \cdot h \cdot a)]\); \( K \) is the soil erodibility factor \([t \cdot h/(MJ \cdot mm)]\); \( L \) is the slope length factor (dimensionless); \( S \) is the slope steepness factor (dimensionless); \( C \) is the crop cover management factor (dimensionless), and \( P \) is the soil conservation practice factor (dimensionless).

3.2. Rainfall Erosivity Factor (R)

Based on the daily rainfall of 1951–2015 at 21 meteorological stations near the Maiji District, the \( R \) for our study region is calculated by using the rainfall erosivity estimation method (Eqs. 2–5) of Zhang et al. (2002) [9]. Then, the Kriging interpolation in the Geostatistical Analyst toolbox of ArcGIS v10.2 is used to generate a spatial distribution map of the \( R \) factor in the study region for 2015 based on these discrete meteorological stations (Fig.-2).

\[ R = \sum_{i=1}^{24} R_i \]

(2)

\[ R_i = a \sum_{j=1}^{k} p_j^{\beta} \]

(3)

where \( R_i \) is the erosivity value in the \( i \)-th half-month period \([MJ \cdot mm/(hm^2 \cdot h \cdot a)]\); \( k \) is the number of days in this half-month period; \( P_j \) is daily rainfall in the \( j \)-th day of the half-month period (daily rainfall \( \geq 12 \) mm, otherwise set to 0; this 12-mm threshold corresponds to the erosive rainfall standard); \( a \) and \( \beta \) are model parameters, both estimated from regional rainfall characteristics as follows:

\[ a = 21.586 \beta^{-7.1891} \]

(4)

\[ \beta = 0.8363 + 18.177 \frac{P_{d12}}{P_{d12}} + \frac{24.455}{P_{y12}} \]

(5)

where \( P_{d12} \) is the mean daily rainfall (mm) of \( \geq 12 \) mm daily rainfall, namely the sum of \( \geq 12 \)-mm daily rainfall in a year divided by the corresponding number of days; \( P_{y12} \) is the mean annual rainfall of \( \geq 12 \)-mm daily rainfall, namely the annual mean of total erosive rainfall per year.

3.3. Soil Erodibility Factor (K)

According to the soil map of Maiji district, and the soil mechanical composition and organic matter content of the corresponding soil species from the Report on the Second Soil Survey (1981) in Tianshui City, the \( K \) value of each soil species vector patch is calculated according to formula 6[10], and then the \( K \) vector map is converted to the grid data with 30×30m spatial resolution.

\[ K = 0.1317 \times 0.2 + 0.3 \exp \left[ -0.02568 \times \left( 1 - \frac{S_{10}}{100} \right) \right] \times \left( \frac{S_{10} - S_{h}}{C_{h} + S_{h}^{0.1}} \right) \times \left[ 1.0 - \frac{0.25C}{C + \exp \left( 3.72 - 2.95S_{N} \right)} \right] \times \left[ 1.0 - \frac{0.7S_{N}}{S_{N} + \exp \left( -5.51 + 22.9S_{N} \right)} \right] \]

(6)
where $S_{AN}$ is the sand content (%); $S_{IL}$ is the silt content (%); $C_{LA}$ is the clay content (%); $C$ is the organic content (%), and $SN_1 = 1 - S_{AN} / 100$.

3.4 Topographic Factor (LS)
In this paper, the LS factor is calculated from the method developed by Desmet and Govers (1996) for two-dimension surface by the InVEST-SDR model [11]. The detail calculation method can be found in the users’ guide of the InVEST model.

3.5 Crop Cover Management Factor (C)
Based on monthly TM remote-sensing images, firstly the normalized difference vegetation index (NDVI) are calculated, then the vegetation coverage are calculated in January through December using Eq. 7, and at last the annual mean vegetation coverage is obtained. In addition, the land cover data is arrived at by using ENVI software supervision classification based on the Landsat8 TM images and regional high-resolution images, the Kappa coefficient of classification is 86.25% that achieves the classification accuracy requirements. So, combining the data of vegetation coverage and land cover types, a spatial distribution map of C according to the calculation method (Eq. 8) proposed by Jiang et al (1996) [12] is obtained.

$$\begin{align*}
\text{V} &= \frac{\text{NDVI} - \text{NDVI}_{\text{min}}}{\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}}} \\
\text{C} &= \begin{cases} \\
0.0085 v & \text{forestland} \\
0.00418 v & \text{grassland and farmland} \\
0 & \text{build-upland and wetland} \\
1 & \text{bareland} \\
\end{cases}
\end{align*}
$$

where $v$ is the vegetation coverage; NDVI is the normalized difference vegetation index, defined as the ratio of the difference between the values in near-infrared and infrared bands to the summed values of both bands; $\text{NDVI}_{\text{max}}$ is the NDVI value of a pure vegetation pixel, and $\text{NDVI}_{\text{min}}$ is the NDVI value of bare land or a non-vegetated pixel.

3.6 Soil Conservation Practice Factor (P)
The P factor conveys the difference in soil erosion which is relation to different crop cover management practices. Based on the slope data obtained through the DEM and the land cover data from images above calculated, the P factor are given (table2), which reference the method of Lu et al. (2011)[13].

| Landuse type | Slope (%) | P value |
|--------------|-----------|---------|
| Agriculture  | 0–5       | 0.11    |
|              | 5–10      | 0.12    |
|              | 10–20     | 1.14    |
|              | 20–30     | 0.19    |
|              | 30–50     | 0.25    |
|              | >50       | 0.33    |
| Forest       | 0–200     | 0.8     |
| Others       | 0–200     | 1       |

3.7 Sediment retention (SE)
The Invest soil conservation model, based on the ability of each vegetation cell to capture and hold soil erosion, estimates how many of the objects in the cell will be intercepted by vegetation in the
downstream area. In the InVEST model database includes 66 kinds of sediment retention efficiency of different land use types, which can be assigned respectively according to the actual situation of the local area. So, according to InVSET model database, the sediment retention value for each LULC class in this paper is showed in Table 3.

### Table 3. Sediment Retention Value for Each LULC Class

| LULC Class   | Wet land | bare land | Crop land | Build-up land | Forest land | Grassland |
|--------------|----------|-----------|-----------|---------------|-------------|-----------|
| SE Value     | 2        | 2         | 50        | 5             | 60          | 40        |

4. Results and discussion

4.1 Spatial distribution pattern of soil erosion

In the InVEST-SDR model, the spatial maps of DEM, K and land cover, the biophysical table with c, p and SE value, are integrated to estimate the soil erosion. In 2015, the area of soil erosion in the study region was 3421.51 km², accounting for 98.3% of the total area of the whole region. According to the “Soil Erosion Classification and Grading Standard” (SL 190–2007) formulated by the Ministry of Water Resources of China in 2007, our study region soil loss is divided into six classes—slight, light, moderate, severe, more severe, and extremely severe—with 10, 25, 50, 80, and 150 t/hm²·a used as their corresponding dividing points (Fig. 2).

#### Fig.2. Spatial distribution of soil erosion area in different erosion classes

In 2015, the sum of the areas under slight and light erosion respectively accounted for 42.0% and 23.01% of the total study area, making them the most prevalent form of erosion throughout the study area. The area of moderate, severe, more severe, and extremely severe erosion were generally decreasing (Table 4). As regard to the gross amount of soil loss, about 5.13% of the total soil loss occurred in the area of minimal to low erosion and nearly 42.62% occurred in the area of high to extreme erosion. Spatially, slight and light erosion mainly occurred in the southern region bisected by the Qinling Mountains from west to east. Higher classes of erosion were relatively concentrated on the northwestern region.

### Table 4. The statistical value of erosion on different erosion classes in 2015

| Soil erosion classes | Eroded area (km²) | Average soil erosion modulus | Soil loss amount (10⁴t) | Occupying ratio of total erosion area (%) | Occupying ratio of total erosion amount (%) |
|----------------------|-------------------|------------------------------|-------------------------|------------------------------------------|-------------------------------------------|
| Slight Erosion       | 1461.38           | 4.89                         | 219.18                  | 42.72                                    | 5.13                                      |
The influence of elevation and slope on the soil erosion showed a bimodal pattern with vegetation coverage (Fig. -3-a). The first and second peaks of soil loss respectively appeared in classes 40–50 and 80–90 of vegetation coverage. When the vegetation cover was located between 0–40% and 60–80%, the amount of soil erosion increased with the increase of vegetation cover, and when the vegetation cover was located in other intervals, the amount of soil erosion decreased with the increase of vegetation cover. Elevation and slope influence on soil erosion showed a parabolic trend obviously. Changed in soil loss with different elevation classes followed a trend of first rapidly increasing and then slowly decreasing, with 1300 m the critical threshold level for these shifts. Within the range of 1300–1500 m, the soil loss was considerably higher than the other classes (Fig. -3-b). Importantly, soil loss increased rapidly when the slope level was less than 30°, however, slow decreases were observed in soil loss with an increasing slope above this 30°-level (Fig. -3-c). The influence of the two topographic factors (elevation and slope) on soil erosion was not showed a simple linear effect, but had a critical value. Since these two factors are static factors that are not easy to change, so both two factors had relatively fixed impacts on soil erosion .The results obtained from regions with different thresholds for the impact of elevation and slope on soil erosion are different [14, 15], and the two key thresholds for this study were 1300 m and 30°.

The types of land cover in the study areas were dominated by three main types of forestland and crop land, of which woodland accounted for 68.99% and 26.75% of the total area. As shown in Fig. -3-d, the distribution characteristics of soil erosion on different land cover types were different, the soil loss on forestland was the highest, the crop land and grass land was the second in turn. Among them, the forest land was the main land use types for the study area erosion. This result are consistent by the Wang et al. [16].

According to the topography and vegetation cover of the study area, the high vegetation cover area in the study area was mostly located in the southern region, which covered by the forest and with the high elevation and steep slope, and the vegetation cover increased gradually. So the increasing vegetation cover could effectively inhibit the occurrence of soil erosion, but at the same time it was affected by rainfall erosion force. The rainfall erosion force in the southern region was obviously higher than that in the northwest, and there was also a large precipitation erosion force in the area with high vegetation coverage. Thus, under the interaction between the different factors, the region presented existing erosion pattern.

|                | Light Erosion | Moderate Erosion | Severe Erosion | More Severe Erosion | Extremely Severe Erosion |
|----------------|---------------|------------------|----------------|----------------------|--------------------------|
| Erosion Amount | 800.69        | 507.88           | 230.97         | 220.97               | 176.62                   |
| Loss           | 17.44         | 36.47            | 64.06          | 108.92               | 336.31                   |
| Rate           | 428.51        | 568.22           | 499.14         | 738.42               | 1822.25                  |
| Percentage     | 23.40         | 14.85            | 7.42           | 6.46                 | 42.62                    |

Fig. 3. Changes of soil loss with different influencing factors in 2015
5. Conclusions
Maiji district is located in the climate transition zone, the difference of geomorphological types from North to south is obvious, the analysis on the soil erosion research situation in this area is helpful to understand the local soil erosion situation, adjust the soil protection plan in time, improve the local soil productivity, and provide some guarantee for the socio-economic sustainable development. In this paper, based on the soil erosion simulation of INVEST-SDR model, according to the previous research results, the rainfall erosivity(R), soil erodibility factor (K), crop cover management factor(C) and soil conservation practice factor(P) in the model are localized. According to the simulation results, the soil erosion in the study area was mainly slight and light erosion in the study area in 2015, the influence of elevation and slope on soil erosion had a critical value, the effect of vegetation cover on soil erosion presented bimodal pattern mode, the soil erosion loss on regional woodland was the largest, and the relevant areas should be focused on the management of regional soil and water treatment in the future.

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