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A GIS-based simulation study of the impact of land use change on the geological environment

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Abstract Land use change, as a concentrated manifestation of the disturbance of the natural environment by human activities, is an important factor affecting the geological environment. This study quantitatively extracts the land use change data of the study area with the help of GIS technology, and summarizes the trend of land use change in terms of change magnitude, change speed and transfer type. With the help of RULSE model, soil erosion is used to characterize the geological environment and analyze its response to land use change. The data show that during the period from 2000 to 2020, the overall land use structure of Daqing City has a small change amplitude, a fast change speed and a frequent land transfer. The arable land area of Daqing City expanded by 980.78 km², the grassland area shrank by 1273.64 km², and the value of the integrated land mobility changed from 0.43 (2000-2010) to 0.5 (2010-2020). Soil erosion in Daqing City was improved, and the average annual soil loss A was reduced from 88.28 in 2000 to 48.28 in 2020. The percentage of cultivated land area increased by a total of 4.63% during the study period, while the percentage of soil loss increased by 7.86%. The percentage of grassland area decreased by 6.01% while the percentage of soil loss increased by 11.78%.

Index Terms GIS, land use change, soil stability, geo-environmental

I. Introduction

Land use refers to the effective development and utilization of land resources by human beings, including various types of land such as arable land, urban land, forest land, grassland and water. And the change of land use will not only have a significant impact on the environment, but also have a far-reaching impact on the socio-economic development [1]-[3]. In recent years, with the continuous growth of population, the acceleration of urbanization and the continuous development of social economy, land use has undergone significant changes. With the rapid growth of urban population and the acceleration of industrialization, the demand for urban land has increased dramatically [4]-[7]. In order to meet the needs of urban residents, large-scale land has been used for the construction of residential, commercial and industrial parks, leading to large-scale forest destruction and ecological environment deterioration, grassland ecosystem deterioration, etc. [8], [9].

Land-use changes have had an irreversible impact on the geological environment. Urbanization has brought about a series of problems such as population growth, land development and resource depletion, which have had a far-reaching impact on the geological environment. Problems such as land use change, development and utilization of groundwater resources, pollution and degradation of soil quality, and the frequency and impact of natural disasters have all had a profound impact on the geological environment [10]-[13]. Therefore, in the process of urbanization, we should pay attention to the protection and sustainable development of the geological environment and take corresponding measures to reduce the irreversible impact on the geological environment. Only in this way can we realize the coordinated development of urbanization and geological environment [14]-[16].

Hunter, H.A. et al. studied the relationship between riverine vertebrates and land use in a region of New Zealand, and their results showed that the complex relationship between geology and land use has a greater impact on the riverine invertebrate community [17]. Gao, L. et al. emphasized the increasingly serious situation of human-land conflicts and ecological degradation in the Pearl River Delta. Through the analysis of the results of "comprehensive land use planning", and this result provides a geological basis for future land use planning [18]. Chen, G. used GIS to analyze the relationship between urban construction land and the geological environment and put forward a proposal for the rational use of urban land. The urban land was divided into residential land, facility land, industry, and ecological greening for research, and the results of the study are of great significance to China's urbanization [19]. Meer, M.S. et al. used remote sensing technology and GIS in the study of land use and land cover. Indicated that the changes in each factor lead to environmental changes in the study research area and their study report shows the variability which has a significant impact on the socio-economic and environmental of the study area [20].

Ibrahim, M. et al. indicated that the analysis of surface temperature has an important role in land use changes. And it has been shown that the detection of spatial and temporal changes in surface temperature can help to provide valuable information for environmental studies [21]. Long, L. et al. analyzed the risk of nonpoint pollution based on the evaluation of geo-environmental and theories related to land use and based on the results of the analysis, the zoning management in the area was carried out [22].

In this paper, Daqing City is taken as the study area to explore the spatial and temporal changes of land use types in the city within 2000 to 2020. And the soil erosion modulus is used to characterize the geo-environmental changes and analyze its response to the land use changes. GIS technology was used to study the spatial and temporal changes of each land use in Daqing City, and analyze the structural changes of its land use in terms of the magnitude of change, the speed of change and the type of transfer. The driving factors of soil erosion (rainfall, soil type, topography, vegetation cover, and land use) were explored with the help of geographic probes, and the factor values in different periods were calculated to quantitatively analyze the impact of land use changes on soil erosion in Daqing City.

II. Method

II. A. Geographic Information System

Geographic Information System (GIS), a new technology for geographic research that began to develop rapidly in the 1960s, is a product of the intersection of many sciences. As a product of the combination of traditional science and modern technology, GIS provides new methods for various disciplines involved in the analysis of spatial data. GIS is a technology for comprehensively processing and analyzing geospatial data, and it is an information system that collects, stores, manages, analyzes, and describes a variety of data related to geographic distribution.

GIS has two distinctive features: one is that it can manage not only digital and textual information like a traditional database management system (DBMS), but also spatial information. The second is that it can make use of various methods of spatial analysis to synthesize many different kinds of information, seek interrelationships among spatial entities, and analyse and deal with phenomena and processes distributed in a certain area.

II. B. Methods for analyzing land-use change

The impact of human production activities on the ecological environment is huge, the change of land use type can intuitively reflect the transformation of human beings on the land resources, the change of land use type can also react to the degree of transformation of human beings on the nature, so through the change of the characteristics of the land use type to react to the human-land relationship and the state of the ecological environment [23].

II. B. 1) Magnitude of change

The magnitude of change is used as a metric and is calculated as:

$$P = \frac{U_1 - U_0}{U_0} \times 100\% \quad (1)$$

II. B. 2) Rate of change in land-use types

The rate of change is an indicator of the change in land use type over a time period and is calculated by the formula:

$$R = \frac{U_i - U_0}{U_0} \times \frac{1}{T} \times 100\% = \frac{P}{T} \quad (2)$$

II. B. 3) Bidirectional attitude modeling

The formula for calculating the attitude of a land use type i to a given length of time is:

$$S = \frac{\Delta S}{S} \times \frac{1}{T} \times 100\% \quad (3)$$

The regional differences describing the rate of land use change can be measured by the combined land use dynamics, which is calculated by the formula:

$$S = \left[\sum_{ij}^2 \left(\frac{\Delta S_{ij}}{S_i} \right) \right] \times \frac{1}{T} \times 100\% \quad (4)$$

Only the area converted from land type i to non-type i land types is considered, ignoring the new area added by reverse conversion. Therefore, a two-way momentum attitude is introduced into the above equation as a measure of the rate of change, calculated as:

$$S = \left[\sum_{j'}^{\pi} \left(\frac{\Delta S_{i\Omega} + \Delta S_{j/2}}{S_j} \right) \right] \times \frac{1}{T} \times 100\% \quad (5)$$

ΔS_{ij1} and ΔS_{ij2} represent the area of interconversion of i land use types and non- i land types, respectively. The bi-directional attitude combines the processes of transfer and addition.

II. B. 4) Comprehensive utilization of kinetic attitudes

The integrated land use momentum attitude is used to describe the rate of land use change in the study area and is expressed by the formula:

$$LC = \left[\frac{\sum_{i=1}^n \Delta LU_{i-j}}{2 \sum_{i=1}^n LU_i} \right] \times \frac{1}{T} \times 100\% \quad (6)$$

II. B. 5) Transfer matrix for land-use types

Markov transfer matrix can further quantitatively analyze the structure, area and proportion of the transformation of different land use types. It is expressed as the process of transformation of land use dynamic transformation from T to $T+1$ time state within a specific time period. The application of Markov model in the dynamic change of land use types can not only reflect the structure and composition of land use within the time period of the study, but also reveal the rate of transfer between the land use types, whose matrix is based on the transfer probability of area as an element, and the expression of the transfer matrix is:

$$P_{ij} = \begin{pmatrix} P_{11} & P_{12} & P_{13} & \cdots & P_{1n} \\ P_{21} & P_{22} & P_{23} & \cdots & P_{2n} \\ P_{31} & P_{32} & P_{33} & \cdots & P_{3n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{n1} & P_{n2} & P_{n3} & \cdots & P_{nm} \end{pmatrix} \quad (7)$$

P_{ij} is the transferred area of land use type i converted to type j .

II. C. Characterization indicators and calculations of the geological environment

The RUSLE model was used to quantify soil erosion in the study area [24], which was expressed as shown in Eq:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (8)$$

II. C. 1) Rainfall erosivity factor R

Rainfall is the external camping force of soil erosion, in this paper, the annual and monthly rainfall data from meteorological stations around Daqing City are used as the basis for the monthly rainfall model proposed by Wischmeier and Smith, and the calculation formulas are as follows:

$$R = \sum_{i=1}^{12} 1.735 \times 10^4 \left[\left(1.5 \times \lg \frac{P_i^2}{P} \right)^{-0.8188} \right] \quad (9)$$

where, R is the erosive power of rainfall (MJ·mm/km²·h·a), P_i is the amount of rainfall in month i (mm), P is the amount of annual rainfall (mm), and $P \geq 12.7$ mm.

II. C. 2) Slope Length Gradient Factor LS

Slope length L factor and slope S factor are important topographic factors affecting soil erosion, in this paper, the L factor calculation method proposed by Wischmeier et al. and the S factor calculation method proposed by Liu Baoyuan et al. are used respectively, and their calculation formulas are as follows:

$$L = \left(\frac{\lambda}{22.13} \right) \quad (10)$$

$$\alpha = \frac{\beta}{1 + \beta} \quad (11)$$

$$\beta = \frac{\sin \theta}{0.0896 \times [3.0(\sin \theta)^{0.8} + 0.56]} \quad (12)$$

$$S = \begin{cases} 10.8 \sin \theta + 0.03 & (\theta \leq 5^\circ) \\ 16.8 \sin \theta - 0.5 & (5^\circ \leq \theta \leq 14^\circ) \\ 21.9 \sin \theta - 0.96 & (14^\circ \leq \theta) \end{cases} \quad (13)$$

II. C. 3) Soil erodibility factor K

Soil erodibility reflects the degree of sensitivity of soil to erosion, is the internal comping force of soil erosion, there is a close connection between soil erodibility K factor and soil type, this paper adopts the EPIC model proposed by Williams to calculate the K factor, the calculation formula is as follows:

$$K = \left\{ 0.2 + 0.3 \exp \left[-0.0256 SAN \left(1 - \frac{SIL}{100} \right) \right] \right\} \times \left(\frac{SIL}{CLA + SIL} \right) \times \left[1 + \frac{0.25C}{C + \exp(3.72 - 2.95C)} \right] \times \left[1 - \frac{0.7SNI}{SNI - \exp(-5.51 + 22.9SNI)} \right] \quad (14)$$

$$SBI = 1 - \frac{SNI}{100} \quad (15)$$

II. C. 4) Vegetation cover and management factor C

Vegetation cover has an inhibitory effect on soil erosion, the C factor is closely related to the degree of vegetation cover, it has been shown that the state of vegetation growth and spatial density can be expressed by the normalized vegetation index (NDVI), based on the results of the normalization process of the remote sensing images obtained by the ENVI software, and adopting the model of calculating the C factor and FVC proposed by Cai Chongfa et al [25], which is given in the following formulas:

$$NDVI = \frac{NIR - R}{NIR + R} \quad (16)$$

$$FVC = \left(\frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \right) \quad (17)$$

$$C = \begin{cases} 1 & FVC = 0 \\ 0.6508 - 0.3436 \lg FVC & FVC < FVC \leq 78.3\% \\ 0 & FVC > 78.3\% \end{cases} \quad (18)$$

II. C. 5) Soil and water conservation measures factor P

The soil and water conservation measure factor P is the ratio of the amount of soil loss under a given erosion control measure to the amount of soil loss without the control measure, reflecting the inhibiting effect on soil erosion. The P factor is a dimensionless number that takes values between 0 and 1. The values of the P factor for each land type are, watersheds 0, woodlands 0.75, grasslands 0.75, cropland 1, building land 0, and unutilized land 1. The land use data can be assigned a value by the use of GIS technology. GIS technology can be used to assign values to land use data.

III. Result and discussion

III. A. Physical and geographic conditions of the study area

The study area of this paper is Daqing City, which is located between 45°46'-46°55' N latitude and 124°19'-125°12' E longitude. It is in the Songhua River basin, and the city has a flat terrain with low elevation, which is part of the

Songnen Plain. The total area of the city is 21,195.18 square kilometers, of which the urban area is 5,107 square kilometers. The city is rich in natural wetlands, which account for 1/3 of the known wetland area in China, and the altitude is generally between 106m-165m above sea level. Influenced by natural erosion, the high terrain shows a wind-eroded landform type with poor vegetation cover, which also forms a diffuse granite landform. The flat terrain is mostly characterized by a unique landscape of wetlands and saline soils interspersed between arable land and grassland, and many of the lower areas have become large and small lake bubbles.

III. B. Land use analysis of the study area

In this paper, taking into account the characteristics of land types in Daqing City and the purpose of the study, the land classification standard of grassland, forest land, water, wetland, construction land, unutilized land, etc. in the study area is divided into seven major categories.

III. B. 1) Analysis of the magnitude of change

Based on the GIS system to calculate the data of land use types in Daqing City for three periods in 2000, 2010 and 2020, the area of land use types in different periods and the change of the area during the 20-year period are shown in Figure 1. It can be seen that during the period from 2000 to 2020, the areas of cropland, forest land and construction land expand, while the areas of grassland and wetland shrink. Cultivated land and grassland are still the main land use types in Daqing, with the area of cultivated land increasing by 980.78 km² from 9,652.9 km² in 2000 to 10,633.68 km² in 2020, while the area of grassland shrinking by 1,273.64 km² from 4,268.77 km² in 2000 to 2,995.13 km² in 2020. During the period from 2000 to 2020, the areas of forest land, water area, construction land and unutilized land showed an overall growth, expanding by 202.27km², 102.4km², 235km², and 297.5km², respectively, except for the wetland, which shrunk from 2,348.85km² in 2000 to 1,804.54km² in 2020, with a total reduction of 544.31km².

In summary, the land use structure of Daqing City has a small change, the most important is the expansion of cultivated land area and the reduction of grassland area. As of 2020, the structure of land use types in Daqing City is: cropland>grassland> water>wetland>unutilized land>construction land>forest land.

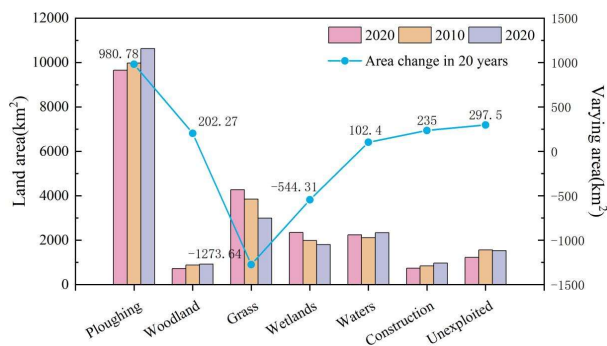


Figure 1: Land use type area from 2000 to 2020

III. B. 2) Analysis of the rate of change

The results of calculating the motivation of each land use type in Daqing City are shown in Table 1. The R value indicates the annual rate of change of a single land use type, while the LR value indicates the combined motivation of land use types. The data show that from 2000 to 2010, the single dynamics of cropland, forest land, construction land and unutilized land is positive, of which the single dynamics of unutilized land is 2.74%, growing faster than other land use types. From 2010 to 2020, the single dynamics of cropland, forest land, water and construction land is positive, of which the single dynamics of construction land is 1.57%, growing faster than other land use types. Grassland has the greatest rate of change, with a single dynamic value of -2.21%, indicating a rapid decrease in grassland area between 2010 and 2020.

During the study period, the absolute values of the single land use motivation attitude of the seven land types, from low to high, are, respectively, waters (0.23%), cropland (0.51%), wetland (-1.16%), unutilized land (1.21%), forested land (1.4%), grassland (-1.49%) & built-up land (1.59%). It can be seen that land transformation in Daqing City is diverse and at different rates, and the rate of land change during the study period was relatively smooth.

III. B. 3) Land transfer analysis

Based on GIS technology, the land use transfer matrix for the period from 2010 to 2020 can be calculated by intersecting the land use data of two adjacent periods, and the data results are shown in Table 2. The land transfer in Daqing City during the study period mainly consists of the transfer in of arable land area and the transfer out of

grassland area. The area of grassland transferred out was 888.88km², and the areas converted into cropland, forest land, wetland, construction land and unutilized land were 467.12km², 31.43km², 22.98km², 89.19km² and 278.16km², respectively. The transferred area of arable land is 931.97km², and the main sources of replenishment include forest land, grassland, wetland, water, construction land and unutilized land, with a transferred area of 82.68km², 467.12km², 71.06km², 84.86km², 65.12km², and 161.13km², respectively.

Table 1: Land utilization dynamics from 2000 to 2020

Type	2000-2010		2010-2020		2000-2020
	R (%)	LR (%)	R (%)	LR (%)	R (%)
Ploughing	0.33	0.43	0.66	0.5	0.51
Woodland	2.21		0.49		1.4
Grass	-0.99		-2.21		-1.49
Wetlands	-1.56		-0.9		-1.16
Waters	-0.58		1.1		0.23
Construction	1.4		1.57		1.59
Unexploited	2.74		-0.25		1.21

Table 2: Land use transfer matrix from 2000 to 2020 (km²)

In Out	Ploughing	Woodland	Grass	Wetlands	Waters	Construction	Unexploited	Transfer out
Ploughing	8769.74	34.98	133.37	39.95	14.97	69.66	148.65	441.58
Woodland	82.68	514.16	0.00	0.00	0.00	20.28	0.00	102.96
Grass	467.12	31.43	2491.01	22.98	0.00	89.19	278.16	888.88
Wetlands	71.06	41.23	18.18	1547.24	190.93	0.00	79.41	400.81
Waters	84.86	27.48	11.89	51.43	1805.42	16.22	24.74	216.62
Construction	65.12	15.58	13.55	0.00	18.70	415.91	47.87	160.82
Unexploited	161.13	53.40	75.07	14.29	43.22	82.97	368.24	430.07
Transfer in	931.97	204.10	252.06	128.65	267.82	278.32	578.82	

During the study period, the confusion diagram of the conversion ratio of land use types in Daqing City is shown in Figure 2. It can be seen that the conversion between various land use types of cropland, grassland, unutilized land and construction land is obvious. Cultivated land is the main transformation direction of forest land (80.3%), grassland (52.55%), watershed (39.18%), construction land (40.49%) with unutilized land (37.47%). The conversion of cultivated land to grassland and unutilized land is also obvious, with the conversion ratio of 30.2% and 33.66% respectively, which means that Daqing has achieved some success in returning farmland to grassland. The conversion of wetland and water land use types is frequent, with 47.64% of the wetland transferred to water, and 23.74% of the water transferred to wetland. Besides, the conversion rate of each land use type to construction land is maintained at about 10% to 20%, and the degree of urban construction and development is reasonable.

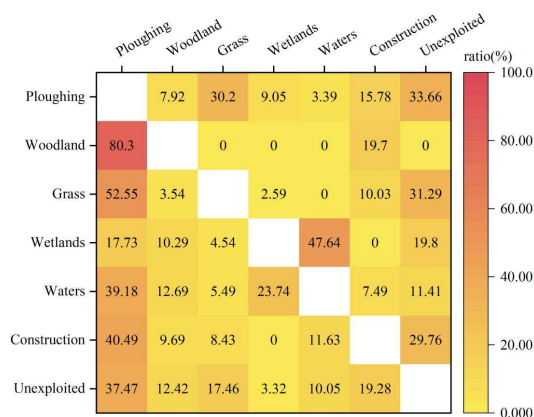


Figure 2: Land use transfer probability heat diagram from 2000 to 2020

III. C. Impact of land-use change on the geological environment

III. C. 1) Analysis of changes in soil erosion factors

The values of soil erosion factors in Daqing from 2000 to 2020 are shown in Table 3. The average annual rainfall erosivity factors in Daqing were 2008.9, 2078.4 and 2376.5 MJ·mm/km²·h·a in 2000, 2010 and 2020, respectively. The factors of vegetation cover and management, C, and soil and water conservation measures, P, are dimensionless factors. The factors C and P showed a decreasing trend during the study period, which means that the vegetation cover and conservation measures in Daqing City are getting better and better. The mean value of the slope length and slope gradient factor, which is used to characterize the topography of Daqing, was 12.7, and the mean value of the soil erodibility factor, K, which reflects the sensitivity of soil to erosion, was 0.0831t·h/MJ·mm. The average annual soil loss, A, was reduced from 88.28 in 2000 to 48.28 in 2020, which indicates that the soil erosion situation in Daqing has been improved.

Table 3: Rslc factor value of Daqing city from 2000 to 2020

Year	R (MJ·mm/km ² ·h·a)	LS	C	P	K (t·h/MJ·mm)
2000	2008.9	12.7	0.1536	0.2711	0.0831
2010	2078.4		0.1005	0.2553	
2020	2376.5		0.0895	0.2151	

III. C. 2) Response of soil erosion to land use type

Soil loss under different land use types in Daqing City during the study period is shown in Figure 3. Changes in the area of cultivated land had a significant effect on soil loss, and the percentage of cultivated land in Daqing City was 45.54% in 2000, and soil loss on cultivated land accounted for 61.21% of the total soil loss in the city. By 2020, the area of cultivated land in Daqing City increased by 4.63%, while the percentage of soil loss on cultivated land increased by 7.86%. It shows that the increase in the area of cultivated land worsens the soil loss within Daqing City. In addition to this, the decrease of grassland also directly led to the worsening of soil erosion in Daqing City, and the percentage of grassland area decreased from 20.14% in 2000 to 14.13% in 2020, while the percentage of soil loss on grassland increased from 4.46% in 2000 to 16.24% in 2020. Since the area of other land use types is smaller in the study area, their impact on soil loss is also smaller.

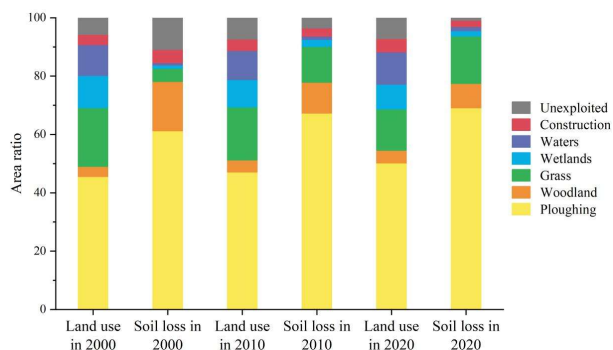


Figure 3: Soil loss in the land use type

IV. Conclusion

This study takes Daqing, a resource city, as the study area, and analyzes the spatial and temporal land use changes in Daqing from 2000 to 2020 in terms of land change magnitude, change rate and type transfer with geographic information data. The RUSLE model is used to evaluate the soil stability in Daqing, and analyze the connection and influence between land use change and geological environment.

The changes in land use structure in Daqing City were small, most notably the expansion of cultivated land area and the reduction of grassland area, with the cultivated land area increasing by a total of 980.78 km² during the study period and the grassland area shrinking by a total of 1,273.64 km². The mutual transformation between land types in Daqing City is frequent and in an accelerated stage, and the value of the comprehensive land movement attitude changes from 0.43 (2000-2010) to 0.5 (2010-2020). The land transfer in Daqing City is mainly the transfer of arable land area and grassland area, 80.3% of forest land, 52.55% of grassland, 39.18% of water, 40.49% of construction land and 37.47% of unutilized land are converted to arable land. In addition to cultivated land, the other main direction of conversion of grassland is unutilized land, with a conversion rate of 33.66%.

Soil erosion in Daqing City was improved. During the study period, the values of the average annual rainfall erosivity factor in Daqing City showed an increasing trend, while the vegetation cover and management factor C and the soil and water conservation measures factor P showed a decreasing trend. Between 2000 and 2020, the average value of the slope length gradient factor in Daqing was 12.7, and the average value of the soil erodibility factor K was 0.0831t·h/MJ·mm. The average annual soil loss A decreased from 88.28 in 2000 to 48.28 in 2020.

Land use change is the main factor affecting soil erosion, which varies greatly under different land use types. The increase in the area of cultivated land and the decrease in the area of grassland are important factors leading to an increase in the amount of soil loss. The percentage of cultivated area increased by 4.63% during the study period, while the percentage of soil loss increased by 7.86%. The percentage of grassland area decreased by 6.01% while the percentage of soil loss increased by 11.78%. Since the area of other land use types is relatively small in the study area, their impact on soil loss is also small.

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