Application of a modified distributed-dynamic erosion and sediment yield model in a typical watershed of hilly and gully region, Chinese Loess Plateau

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Abstract. Soil erosion not only results in the destruction of land resources and the decline of soil fertility, but also makes river channel sedimentation. In order to explore spatiotemporal evolution of erosion and sediment yield before and after returning farmland in a typical watershed of hilly and gully region, Chinese Loess Plateau, a distributed, dynamic model of sediment yield based on the Chinese Soil Loss equation (CSLE) was established and modified to assess effects of hydrological factors and human activities on soil erosion and sediment yield from 1995 to 2013. Results indicate that: 1) the modified model has characteristics of simple algorithm, high accuracy, wide practicability and easy expansion, and can be applied to forecast erosion and sediment yield of the hilly and gully region, Chinese Loess Plateau; 2) soil erosion gradations are closely related to spatial distributions of rainfall erosivity and land use patterns, the current soil and water conservation projects are not very ideal for high rainfall intensity; 3) the average sediment transport modulus before and after model modification in recent 5 years (in addition to 2013) is 4574.62 Mg/km^2 and 1696.1 Mg/km^2 respectively, it has decreased by about 35.4% and 78.2% compared with the early governance (1995-1998). However, in July 2013 the once-in-a-century storm is the most important factor causing the emergence of maximum value. Results may provide effective and scientific basis for soil and water conservation and ecological management of the hilly and gully region, Chinese Loess Plateau.

Key words: Soil erosion; Sediment yield; Dynamic model; Returning farmland; Spatio-temporal evolution

1. Introduction

Soil erosion is one of the main environmental disasters that restrict the survival and development of human beings (Ongley et al., 2010), it will bring disastrous land degradation and affect regular land development (Sun et al., 2012). Soil erosion of the Loess Plateau in China is serious (Miao et al., 2010), the annual average soil loss amount in this region is 1600 Gg, and the annual erosion amount of surface soil in most serious areas reaches 20 mm or more (Rudi & Victor, 2007). The recent studies on the Loess Plateau are mainly focused on the water erosion control in the water-wind crisscrossed erosion region, soil quality indicators in relation to land use and topography, overland flow on abandoned slopes, effects of long-term fertiliser applications on soil organic carbon and hydraulic properties, soil water content, interrill erosion on unpaved roads, and temporal variations of flow-sediment relationships (Zhao et al., 2015; Zhao et al., 2016a; Yu et al., 2016; Shi et al., 2016; Li et al., 2016a, 2016b; Cao et al., 2015; Yu et al., 2015; Gao et al., 2016). But there is little research on the dynamic simulation of soil erosion and sediment yield at watershed scales.

Majiagou River watershed belongs to a first grade tributary of the Yanhe River basin, it is located in the typical hilly and gully region of the Loess Plateau (Li, 2009), its topography and geomorphology have very strong representative, it is one of the most serious soil and water loss regions in the middle reaches of the Yellow River (Fu et al., 2010; Jia et al., 2014). Before the implementation of China's returning farmland policy to forest/grass in 1997 (Zhao et al. 2016b), the soil erosion area in Majiagou watershed reached 72.31 km^2, which accounts for 98% of the total watershed area, the soil erosion modulus was up to 8740 Mg/(km^2•a), it belongs to the serious soil erosion region (Dang et al., 2013); after the implementation of returning farmland to forest/grass project for nearly 10 years, the soil erosion modulus of the Majiagou River watershed decreased to 5700 Mg/(km^2•a) in 2008 (Wu et al., 2010). Therefore, it is necessary to study spatio-temporal characteristics of erosion and sediment yield in the Majiagou River watershed, and results may provide scientific references for optimized utilization of the land resource and reasonable formulation of soil and water conservation measures.

Under the international background of serious soil loss, the researches on monitoring, model and the most advanced technology have developed rapidly in the world (Chen & Cui 2006; Cui et al., 2013; Borrelli et al., 2015). In the field of experimental study, the earliest soil erosion quantitative observation occurred in 1912 (Meyer, 1984), the related scholars in the world carried out long-term experimental studies in the runoff plot under rainfall and natural status (Xia et al., 1998; Zhou et al., 2000; Yu et al., 2009; Chen et al., 2010), which provides the scientific basis for the study of soil erosion and the theoretical foundation for the factor analysis model. In the field of model study, based on the path process and the simulation method of the model, soil erosion model may be divided into factor analysis model (empirical statistical model) and physical process model (Zhou & Shangguan, 2004; Cao et al., 2015). The factor analysis model is simple and intuitive, and can be modified according to the specific application area. Its typical representative is the USLE and its modified form (Wischmeier & Smith, 1965, 1978; Renard et al., 1997; Xie et al., 2003; Wang & Lu 2004; Sadeghi & Mizuyama, 2007), which have been widely used in the world (Liu et al., 2001, 2002; Fu et al., 2001; Yin & Chen, 1989; Wang et al., 1996; Cheng et al., 2009; Arekhi et al., 2012; Ligonja & Shrestha 2015). In the field of physical model, the physical model of soil erosion will be divided into four main processes including precipitation sputtering, migration, runoff dispersing, and transport (Wang et al., 2008). Meyer established the theory of shallow gully erosion in 1972 (Meyer, 1984), Foster established soil erosion model based on physical process in 1980 (Foster, 1980), the United States Department of Agriculture introduced the WEPP model in 1995. At the same time in Europe and Australia there are some classic physical process models, such as the Holland

LISEM model, the British EUROSEM model and the Australian GUEST model. Since 1980, Chinese scholars have successively constructed the soil erosion prediction model with local characteristics (Mou & Meng, 1983; Yang et al., 2008; Tang, 1996; Cai et al., 1996; Fan, 1985; Yang et al., 2007). With the development of technology, distributed model and dynamic model have been applied gradually. In the field of distributed model, the typical soil erosion distributed models mainly include SHE model, IHDM model and EUROSEM model (Wang et al., 2003). In particular, some of the agricultural non point source pollution evaluation models such as SWAT and AGNPS also contains soil erosion evaluation module (Zhang et al., 2007; Li et al., 2009). Dynamic models for soil erosion of small-scale watershed system also have a wide range of application and value (Tang & Chen, 1997; Gao & Lei, 2010; Liao et al., 2012), the representative dynamic model is KINEROS model which simulates sediment process during storm event (Singh et al., 1999). In recent years, the research of soil erosion with the advanced technology such as GIS and RS, BP neural network, genetic algorithm and fruit fly algorithm has a rapid progress (Zhao et al., 2004; Dai et al., 2008; Ochoa-Cueva et al., 2015). They can achieve real-time simulation with high efficiency and high accuracy, forecast the occurrence of soil erosion, the temporal and spatial changes of the evolution process, the quantitative assessment of multi-scale soil erosion (Caro & Legarda, 2013). In short, with the development and popularization of computer technology, GIS/RS technology and information technology, the research on the distribution of watershed sediment yield has become an inevitable trend, and dynamic simulation has become necessary means to master temporal variations of soil erosion (Yao & Xiao, 2012).

However, the existing distributed dynamic model takes event based rainfall process as the research object, there is very little involved in inter-annual variability of erosion and sediment yield, there is still less scholar who in-depth considers effects of relationships between upstream and downstream within a watershed on dynamic changes of erosion and sediment yield. Therefore, the objectives of this study are to establish and modify a yearly distributed model of watershed erosion and sediment yield in the Majiagou River watershed, and to evaluate spatiotemporal evolution of soil erosion and sediment yield before and after returning farmland. Results may provide reliable scientific basis for the dynamic simulation of multi-scale watershed erosion and sediment yield, land use planning and watershed management.

2. Material and Methods

2.1 Study area

Majiagou river, which is located in the western Ansai County of Yanan city, Northern Shaanxi Province, is one of the first grade tributaries of the Yanhe River (Fig.1). It flows into the Yanhe river in Ansai County from the northwest to the southeast, the main channel is about 17.4 km in length, the average gully slope is about 6.5‰. The watershed, with a total catchment area of 73.83 km^2, is situated on the typical hilly and gully region of the Loess Plateau (109°9′30″~109°18′59″E and 36°49′42″~36°56′42″N). The watershed belongs to a warm-temperature and semi-arid continental monsoon climate, the evaporation capacity is greater than 1000 mm, the annual average temperature is 6-11°C, the annual average precipitation is about 500 mm, the precipitation in 6-10 months accounts for about 80% of the total annual precipitation. The precipitation form is mostly heavy rainstorm with characteristics of high intensity and short duration, it easily produces a large number of surface runoff by mechanism for runoff yield under excess infiltration, and then leads to hyperconcentrated flood disaster under the action of water erosion.

2.2 Environmental database

The parameters included in this study include digital elevation model (DEM), daily precipitation data, runoff, soil properties, land use types (Figs. 2 and 3; Table 1).

2.3 Dynamic model of erosion and sediment yield

Soil loss is the comprehensive results of various natural factors and human factors (Fu et al., 2014; Tian et al., 2016). Climate, soil, topography and vegetation are the natural factors affecting soil loss (Zhao et al., 2013); the irrational land use, the destruction of forest and grass, excessive reclamation and overgrazing, cultivation on steep slopes, mining road and unreasonable waste soil and residue etc. are the main human factors affecting soil loss (Chen & Lv, 2012). Based on the USLE/RUSLE equations, the Chinese soil loss equation (CSLE) model put forward by Liu Baoyuan was selected and applied to quantitatively and dynamically evaluate soil erosion of the Majiagou River watershed. The basic expression is as follows,

$$Q = A \times R \times K \times L \times S \times B \times E \times T \tag{1}$$

where Q is the annual average soil erosion rate, ($t/hm^2 \cdot a$); A is the catchment area, hm^2; R is the rainfall erosivity factor, ($MJ \cdot mm/hm^2 \cdot h \cdot a$); K is the soil erodibility factor, ($t \cdot hm^2 \cdot h/hm^2 \cdot MJ \cdot mm$); L is the slope length factor; S is the slope gradient factor; B is the biological measure factor (equivalent to factor C of the RUSLE equation); E is the engineering measure factor; T is the tillage measure factor; L, S, B, E and T are all dimensionless.

Because not all eroded soil is actually delivered to the basin outlet, based on the equation (1) and the sediment delivery ratio factor, the annual average sediment yield can be estimated by the Eq. (2)

$$Q_s = A \times R \times K \times L \times S \times B \times E \times T \times \lambda \tag{2}$$

However, the Eq. (2) is the multi-year average sediment yield amount, it is not a dynamic changing expression. Furthermore, the dynamic-continuous modeling studies on the processes of sediment yield are very critical and necessary for accurately estimating annual changing trends of sediment (Gessesse et al., 2015). Rainfall runoff and human activity are two important factors affecting erosion and sediment yield (Mu et al., 2012; Liu et al., 2014; Lieskovský & Kenderessy 2014). According to the related study results (Long et al., 2008; Liu, 2009; Miao et al., 2012), the rainfall erosivity factor and the sediment delivery ratio factor affected by hydrological elements were designed into the dynamic hydrological factor; the biological measures, engineering measures, tillage measures and the sediment delivery ratio factor affected by human activities were designed the dynamic land management factor, so the dynamic equation of sediment yield suitable for the hilly and gully region of Loess Plateau was put forward as follows:

$$Q_{s,i} = A \times K \times LS \times (R_i \times \lambda_{q,i}) \times (B_i \times E_i \times T_i \times \lambda_{m,i}) \qquad (3)$$

where subscript i represents the i-th year, Supposing that the factor λ_i can be divided approximately into the product of $\lambda_{q,i}$ related only to hydrological conditions and $\lambda_{m,i}$ related only to land management measures.

Impacts of hydrological elements on sediment transport are mainly manifested in the moving action of sediment from erosion source to the river course by rainfall runoff (Mu et al., 2012). $\lambda_{q,i}$ can be estimated by the sediment transport capacity that is widely used in hillslope and fluvial geomorphology (Prosser & ustomji 2000). According to the definition for $\lambda_{q,i}$ and general situation of the study area, $\lambda_{q,i}$ can be supposed as follows: The widely used equation is:

$$\frac{\lambda_{q,i}}{\lambda_q} = \frac{TC_i}{TC} = \frac{k \times q_i^a \times s^b}{k \times q^a \times s^b} = \left(\frac{q_i}{q}\right)^{1.45} \qquad (4)$$

where *TC* is the average sediment transport capacity per unit width of slope (kg m^{-3}); *q* is the average runoff amount per unit width (m^{-3}); *k*, *a* and *b* are coefficients. Those coefficients and the surface gradient factor *S* are constants when there are no changes in underling surfaces of runoff.

Impacts of human activities on sediment transport are mainly demonstrated in water and sediment reduction effects by all kinds of water conservation measures (Schilling et al., 2011; Sarma et al., 2015). Under the annual changing conditions of $\lambda_{m,i}$, *B*, *E* and *T*, the dynamic land management factor was introduced and defined as,

$$\eta_i = \frac{B_i \times E_i \times T_i \times \lambda_{m,i}}{B \times E \times T \times \lambda_m} \qquad (5)$$

In order to quantitatively study impacts of human land management activities on the sediment transport process, according to Xu et al. (2012) research results of 1956-2009 runoff and sediment characteristics in the Yanhe River watershed, the year of 1956-1969 is a sporadic governance stage with little intervention of human activities, the intervention is only 0.9-3.9% and fluctuations of runoff and sediment are mainly caused by fluctuations of rainfall; after this stage, human land management activities gradually become the main driving force for changes of runoff and sediment, soil and water conservation are the main factors leading to reduction of runoff and sediment (Gao et al., 2010; Li et al., 2011). So this study will take the year of 1956-1969 as the base period, and the years after the 1970s will be defined as the governance period with the gradually increased impact of human activities (Wang *et al.,* 2015). Based on the related literatures (Wang & Fan, 2002), respectively, the fitting relationship expression (R^2=0.912) of runoff and sediment in Ganguyi hydrological station in 1954-1969 was taken as the denominator, and the fitting relationship expression (R^2=0.857) of runoff and sediment in 1954-1989 as the numerator, then the ratio of sediment during the governance period and the base period was defined as the dynamic influencing factor of human activities reflecting effects of human land management activities on yearly changes of the watershed sediment transport, the expression is,

$$\eta_i = \frac{y_{g,i}}{y_{b,i}} = \frac{0.449x_i - 5062.6}{0.4436x_i - 4559.9} \tag{6}$$

where x_i represents the runoff amount in the i-th year (10^4 m^3), n is the number of years, $y_{g,i}$ represents the sediment amount in the i-th year during the governance period (10^4 m^3), $y_{b,i}$ represents the sediment amount in the i-th year during the base period (10^4 m^3)

In summary, the dynamic model of erosion and sediment yield was determined as follows,

$$Q_{s,i} = \eta_i \times \left(\frac{q_i}{q}\right)^{1.45} \times R_i \times \lambda \times A \times K \times LS \times B \times E \times T \tag{7}$$

where $\lambda = \lambda_q \cdot \lambda_m$ represents the average sediment delivery ratio, B, E and T represent the average value of the watershed for many years.

2.4 Determination of model factors

1) The rainfall erosivity factor

Rainfall erosivity refers to the potential capacity of soil erosion caused by rainfall. Scholars in the world have proposed simple algorithms of the rainfall erosivity in different forms, where the half-month rainfall erosivity model shows the seasonal distribution of rainfall erosivity by the period of half month. In this study, a half-month simple algorithm of rainfall erosivity established by Zhang et al. (2003) was used to calculate the monthly and/or annual rainfall erosivity, the half-month algorithm of rainfall erosivity estimated by daily precipitation is as follows:

$$R_i = \alpha \sum_{j=1}^{k} (P_j)^{\beta} \tag{8}$$

$$\beta = 0.8363 + \frac{18.144}{P_{d_{12}}} + \frac{24.455}{P_{y_{12}}} \tag{9}$$

$$\alpha = 21.586\beta^{-7.1891} \tag{10}$$

where R_i represents the rainfall erosivity value in i-th half-month period (MJ.mm.hm^{-2}h^{-1}), k represents the number of days within the half-month period, P_j is the rainfall in the j-th day during the half-month period (the erosive rainfall standard ≥12mm), P_{d12} represents the average daily rainfall when the daily rainfall ≥12mm, P_{y12} represents the average annual rainfall when the daily rainfall ≥12mm. In this algorithm, the half-month division standard is that the first 15 days of each month are used as the former half-month period, and the remaining days of this month as the other half-month period.

According to the above algorithm, the annual dynamic results of R factor in the Majiagou River watershed are determined in Table 2, and the spatial distributions of average annual rainfall erosivity are shown in Figure 4. Table 2 shows that most of the rainfall erosivity values in the hilly and gully region of Loess Plateau are below 2000 $\mathrm{MJ \cdot mm/hm^2 \cdot h \cdot a}$, which are consistent with the results of relevant scholars, so the algorithm and the calculation results are scientific and reliable. However, Yan'an suffered a once-in-a-century storm attack in July 2013, which is the key reason for abnormally large rainfall erosivity values of the Majiagou River watershed in 2013.

2) Soil erodibility factor

Soil erodibility is used to evaluate properties whether the soil is susceptible to erosion, it embodies the sensitivity of the soil to the separation and handling of erosion (Lu et al., 2011). The modified method presented by Zhang et al. (2007) was applied to calculate the factor K values, the formula is:

$$K = 0.74488K_n - 0.03336 \tag{11}$$

$$K_n = [2.1\times10^{-4} M^{1.14}(12 - OM) + 3.25(SSC - 2) + 2.5(PL - 3)]/100 \tag{12}$$

where M = Particle mass fraction of (0.002~0.1mm) × (particle mass fraction of (>0.002~0.05mm) + particle mass fraction of (>0.05~2mm)); OM is the soil organic matter content, g/kg; SSC is the structural coefficient; PL is the permeability level.

Based on soil properties of in the study area by soil survey results, the average K value of soil erodibility in the watershed was calculated as 0.0542 $\mathrm{Mg.h.MJ^{-1}.mm^{-1}}$, which is close to the research results by Li & Zheng (2012) in the Yanhe River basin. The spatial distribution map of soil erodibility factor in the Majiagou River watershed was also generated with the help of GIS technology (Figure 4).

3) Topography factor

Topography is an important factor affecting soil erosion. LS factor reflects the contribution degree of terrain factors to soil erosion, it can be divided into slope length factor and slope gradient factor. Many scholars have established empirical formulas used for quantitative analysis according to the standard definition and influence mechanism of LS factor (Wang, 2007). Through comprehensive comparison analysis, the slope length factor (L) in this study was estimated by the below equation,

$$L = \left(\frac{\lambda}{22.13}\right)^{\alpha} \tag{13}$$

$$\alpha = \frac{\beta}{\beta + 1} \qquad (14)$$

$$\beta = (\frac{\sin\theta}{0.0896}) / \left[3.0(\sin\theta)^{0.8} + 0.56 \right] \qquad (15)$$

where λ is the horizontal slope length; α is the slope length index; θ is the slope gradient (°).

The slope gradient factor (*S*) in this study was calculated using piecewise method, the gentle slope used the formula proposed by McCooL et al. (1987), and the steep slope adopted the formula proposed by Liu et al. (2010), the specific expressions are as follows,

$$\begin{aligned} S &= 10.8\sin\theta + 0.03 && \theta < 5^\circ \\ S &= 16.8\sin\theta - 0.05 && 5^\circ \le \theta \le 10^\circ \\ S &= 21.9\sin\theta - 0.96 && \theta > 10^\circ \end{aligned} \qquad (16)$$

where θ is the slope gradient (°).

Based on the above algorithm, the multi-year average *LS* value from the Majiagou River watershed is determined as 12.9, and the spatial distribution of LS factor in the study area is shown in Figure 4.

4) *BET* factor

Biological measure factor (*B* factor) refers to the ratio of soil erosion amount between the standard plot for growing crops and for continuous abandonment within a certain time under the same conditions (Wischmeier & Smith, 1965), its value changes between 0 and 1. Soil and water conservation engineering measure factor (*E* factor) is defined as the ratio of the soil erosion amount between engineering measures and non engineering measures (Qin, 2013). Tillage measure factor (*T* factor) is the ratio of the soil erosion amount between the certain tillage farmland and the continuous relaxation bare land under the same conditions, its value is also between 0 and 1 (Guo et al., 2013).

Considering the synchronization of human activities on underlying surface conditions between the Majiagou River watershed and the Yanhe River basin, based on the related research results of *B*, *E* and *T* factors in the Loess hilly area (Xie, 2008; Zhang *et al.,* 2012; Qin, 2013), the average *B*, *E* and *T* values of the Majiagou River watershed for many years were in turn assigned to 0.1562, 0.497 and 0.712. Besides, the spatial distribution of the average *BET* factor for many years is shown in Figure 4.

5) The sediment delivery ratio (*SDR*)

Reference to systematic research results of soil erosion in the Loess Plateau (Jing et al., 2005), there are different degrees of fluctuations for the annual *SDR* values of the Majiagou River watershed, the average value is around 0.9. Furthermore, considering the research results of the Yanhe River basin by Zhu et al. (2007), a *SDR* value of 0.92 for many years was determined as the average *SDR* value of the Majiagou River watershed.

3. Results and Discussion

3.1 Validation of erosion and sediment yield

Considering very similar climate and underlying surface conditions, the soil erosion modulus in the study area has some comparability with the Yanhe River watershed, the previous simulation results of Yanhe River waterhshed can be used to verify this results. According to Li & Zheng (2012) dynamic simulation results of soil erosion in the Yanhe River watershed from 2001 to 2010, the annual average erosion modulus of Yanhe River watershed is 5812.28 t/(km^2.a), it has little difference with the average simulated value of 5803.23t/ (km^2.a) in the Majiagou River watershed from 1995 to 2012, the relative error is very small; the annual erosion modulus of the Majiagou River watershed in 2008 is 2485.46 t/(km^2.a), the corresponding simulated value is 2278.2 t/(km^2.a), the relative error is 8.34%; this results demonstrate that the dynamic erosion and sediment yield model has scientific rationality and good reliability, the study results can be used for NPS pollution load estimation.

In addition, the previous research results of sediment variations in Ganguyi hydrological station from 1961 to 2008 (Ren et al., 2012) and the simulation results of sediment yield in this study were comparatively analyzed that the sediment yield both showed a decreasing trend although there were fluctuations of different degrees in individual years (Fig. 5), it indicates that the overall changing trends of sediment yield in the study area are consistent with the background of returning farmland policy (Zhao et al., 2013), the current simulation accuracy basically meets the requirements of simulation and tendency Analysis. However, it can also be seen from Fig. 5 that the simulated values are largely different from the observed values, and the model fails largely for the individual events especially after 2006. The main reason can roughly be summed up that the sediment transport process in the established model may not clearly reflect spatiotemporal variations of the watershed underlying surface, especially for the physically-based complex sediment transport relationship between the upper and lower reaches after returning farmland.

Therefore, it is necessary to modify the established model, the influencing factor considering relationships between upstream and downstream within a watershed was introduced to further improve the accuracy of the established sediment yield model. According to the existing research results (Xie 2012; Xie & Li 2012), Eq. (7) can be changed into the following formula,

$$Q_{s,i} = \frac{Q_{w,i}}{Q_i - Q_{b,i}} \times \eta_i \times \left(\frac{q_i}{q}\right)^{1.45} \times R_i \times \lambda \times A \times K \times LS \times B \times E \times T \qquad (17)$$

where $Q_{w,i}$ is the annual saturated water when the saturated sediment transport is the observed sediment transport amount in a hydrological station, $Q_{b,i}$ is the annual base flow, Q is the observed annual runoff amount.

After modification, for Ganguyi hydrological station, the simulated value of the annual average sediment yield modulus from 1995 to 2012 is 5803.23 t/ (km^2.a) and 4510.66 t/ (km^2.a) before and after the modification, the observed value in Ganguyi hydrological station of the Yanhe River watershed is 3411.53 t/(km^2.a), the relative error of the improved model decreases by 30%~40% (Fig. 6). For Ansai and Zaoyuan hydrological station, the simulation results also improved a lot.

3.2 Spatiotemporal evolutions of soil erosion gradations

Figure 7 shows spatial distribution of soil erosion gradations of the Majiagou River watershed in 1995 and 2010. The annual average soil erosion modulus is 6307.86 t/ (km^2.a), based on standards for classification and gradation of soil erosion (SL 190-2007), the soil erosion of the Majiagou River watershed belongs to is the intensive erosion, it confirms the grim diagnosis of soil and water loss in the study area, it also shows that it is vigorously necessary for the protection and management of soil and water resources.

Although the overall spatial distribution patterns of soil erosion modulus in two typical years of 1995 and 2010 are generally the same, there is a little different for the gradation distribution of soil erosion (Table 3). Compared with 1995, the occurrence area of micro and mild erosion of the Majiagou watershed in 2010 decreased slightly, the reducing area accounts for 8.48% of the catchment area. However, the soil erosion area of moderate and above moderate erosion in 2010 increased by 8.48% than that in 1995, among them the area of intensive soil erosion increased more obviously and the corresponding increased amplitude was 4.22%, this indicates that spatiotemporal evolutions of soil erosion intensity in the watershed are closely related to temporal and spatial distributions of rainfall intensity, rainfall duration, rainfall amount and land use patterns; meanwhile, the long-duration concentrated rainfall in steep easily-eroded sloping land results in the erosion intensity is a little higher than that in 1995, it also shows that the current water and soil conservation projects are not very ideal for high rainfall intensity, and the results potentially emphasize the necessity of making further efforts on soil and water conservation measures.

3.3 Temporal evolutions of sediment yield

Figure 8 shows that the sediment transport amount in the study area has an overall decreasing trend from 1995 to 2012, the average sediment transport modulus before and after model modification in recent 5 years (in addition to 2013) is 4574.62 Mg/km^2 and 1696.1 Mg/km^2 respectively, it has decreased by about 35.4% and 78.2% compared with the early governance (1995-1998). Results show that the modified model is more accordant with practical circumstances. For the occurrence of non conventional heavy rainfall in the watershed, the main reasons for the decreasing sediment mainly result from water and soil conservation measures. Since the late 1990s, China has gradually carried out construction projects of returning farmland to forest and grass, beautiful mountains and rivers, and soil and water conservation of Yanhe River by World Bank loan in Northern Shaanxi. A lot of targeted soil and water conservation measures were implemented for coping serious soil and water loss situation of the Yanhe River basin, it continues to improve underlying surface conditions and soil erosion disasters. Especially after 2003, the sediment transport in the study area not only has an overall decrease trend, but also the tendency of inter-annual fluctuations is small and the whole sediment transport level is low. It also fully shows that the continuous improvement of the underlying surface conditions and implementation of standardized and effective water and soil conservation measures in recent years have significant reduction benefits of water and sediment.

Soil and nutrient loss in the Loess Plateau is mainly caused by few transient rainstorms (Zhang *et al.,* 2004; Austin *et al.,* 2004). But the serious soil erosion hazards in the study area due to the once-in-a-century storm encountered in 2013 can not reflect the general sediment yield evolutions. Figure 9 shows the monthly erosion dynamics in 2013, it can be seen that the monthly distribution of sediment transport in the basin is very uneven, and the maximum values of runoff and sediment both occurred in July, the sediment transport capacity only in July accounted for 96.18%. The reasons are that the rainfall erosivity value in July accounted for 80.49% of the whole year, and it is 3.11 times more than the average simulation value for many years, a powerful hydraulic erosion force was formed due to the once-in-a-century storm; the corresponding monthly runoff in the basin also accounts for 56.22% of the total annual runoff, it accounts for 76.79% of the multi-year average runoff amount in the Majiagou River watershed; and the corresponding monthly erosion modulus reached 44.5 times more than the average annual erosion modulus. Therefore, the once-in-a-century storm in July 2013 is the most important factor for the maximum sediment yield, it also shows that rainfall plays a very important role on the evolution process of soil erosion under non conventional storm.

The theory analysis of the sediment transport indicates that rainfall and human activity are two main factors affecting dynamic changes of soil erosion. Rainfall is the promotion factor for erosion evolution, it can affect the formation and development of soil erosion process by splash effects of raindrops and erosion moving of rainfall runoff; The positive human activities are the restraining factors for erosion evolution, they can increase vegetation cover, improve water and soil measures, consolidate soil, weaken soil erosivity, and strengthen effects of the interception and hindrance.

3.4 Spatial evolutions of sediment yield

Figure 10 shows spatial distributions of the sediment transport modulus in the Majiagou River watershed in 1995 and 2010. Due to more sloping farmland, stream mapping indicated that streambank erosion dominated sediment sources in the watershed, and peak values of the sediment transport modulus also mainly occurs along the banks of the main river running through the whole Majiagou watershed from northwest to southeast. Spatiotemporal variations of sediment transport in the whole watershed are largely related to spatial distribution of land use types. The large spatial variations of sediment transport are also closely related to spatial changes of topography and soil.

4. Conclusions

A distributed-dynamic sediment yield model based on the CSLE equation was verified and modified to investigate impacts of returning farmland on erosion and sediment yield in the Majiagou River watershed from 1995 to 2013. Results indicate that the overall status of the watershed belongs to intensive erosion, spatiotemporal evolutions of soil erosion intensity in the watershed are closely related to distributions of rainfall intensity, rainfall amount, and land use patterns; the multi-year average sediment yield modulus before and after modification in the Majiagou River watershed was 5803.23 Mg/(km^2.a) and 4510.66 Mg/(km^2.a) respectively, the overall annual sediment transport tracked to a decreasing trend from 1995 to 2012. Especially after 2003, the annual sediment transport in the study area was diminishing year after year, and the fluctuation trend is very weak and the overall sediment transport level is relatively low, the average sediment transport modulus before and after model modification in recent 5 years (in addition to 2013) is 4574.62 Mg/km^2 and 1696.1 Mg/km^2 respectively, it has decreased by about 35.4% and 78.2% compared with the early governance (1995-1998). Results also show that the implementation of large-scale soil and water conservation projects in the late 90's of the last century has continuously improved soil situation of the watershed, but the situation is still grim and needs to continue increasing the governance intensity. In particular, the extreme storm will lead to large fluctuations of sediment transport, for example, the once-in-a-century storm of Yan'an city in July 2013 is the most important factor for the maximum erosion and sediment yield of the watershed. Therefore, the current soil and water conservation measures are not very ideal for high rainfall intensity in July 2013, and the results potentially emphasize the necessity of making further efforts on soil and water conservation measures in steep easily-eroded sloping land of the hilly and gully region, Chinese Loess Plateau.

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Table 1: Descriptions and sources of the environmental database for the Majiagou River watershed

Data layer	Format	Description	Source
DEM	Raster	30 m spatial resolution DEM data of the Majiagou watershed	Computer Network Information Center, Chinese Academy of Sciences

			http://datamirror.csdb.cn/index.jsp
Land use	Raster	Farmland, grassland, forest land, residential area, water area, sand	Data Center for Cold and Arid Region Sciences http://westdc.westgis.ac.cn/
precipitation	DBF	Daily values in Ansai and Yanan rain-gauge stations (1957-2013)	China Meteorological Data Sharing Service Network http://www.cdc.sciencedata.cn
Soil	DBF	Physical and chemical properties	National Science & Technology Infrastructure of China， Data Sharing Infrastructure of Earth System Science (http://www.geodata.cn)
Runoff and sediment	Excel	Time series of daily observed values in Ganguyi hydrological stations (1954-1989)	

Table 2: The annual dynamic values of *R* factor (MJ·mm/hm^2·h·a) in the Majiagou River watershed from 1995 to 2013

Year	*R* value	Year	*R* value	Year	*R* value	Year	*R* value
1995	1240.416	2000	759.223	2005	1573.623	2010	1235.926
1996	1046.692	2001	2004.196	2006	1957.735	2011	1904.582
1997	1253.405	2002	1856.162	2007	1515.931	2012	1470.239
1998	1804.647	2003	1890.972	2008	937.696	2013	5644.205
1999	849.033	2004	1166.029	2009	1797.271		

Table 3 Classification and gradation of soil erosion, percentage in the Majiagou River watershed in 1995 and 2010

Erosion gradation	Erosion modulus （t/hm^2·a）	1995		2010	
		Ratio (%)	Area (hm^2)	Ratio (%)	Area (hm^2)
micro	<5	11.60	856.17	9.55	704.85
mild	5~10	8.85	653.08	8.01	591.36
mild	10~25	34.96	2581.46	29.37	2168.31
moderate	25~50	37.35	2757.67	40.63	2999.59
intensive	50~80	6.12	451.98	10.34	763.59
Very intensive	80~150	1.12	82.63	2.06	152.32
severe	>150	/	/	0.04	2.99
sum		100	7383	100	7383

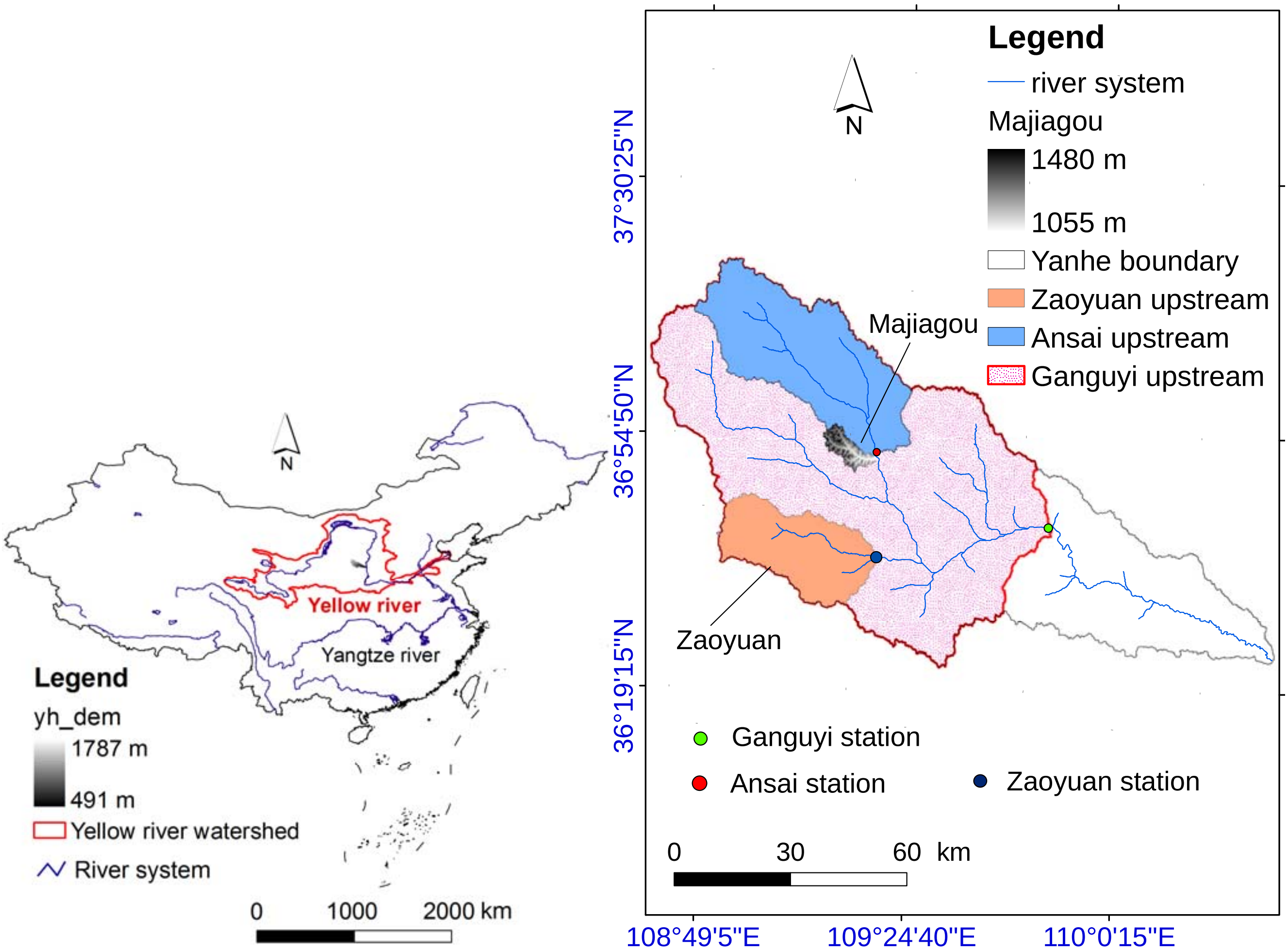

Figure 1: The relative location between the Yanhe River watershed and the Yellow River/Yellow River Basin, the geographical location sketch of the Majiagou River watershed, Zaoyuan upstream, Ansai upstream, Ganguyi upstream in the river system of Yanhe River watershed

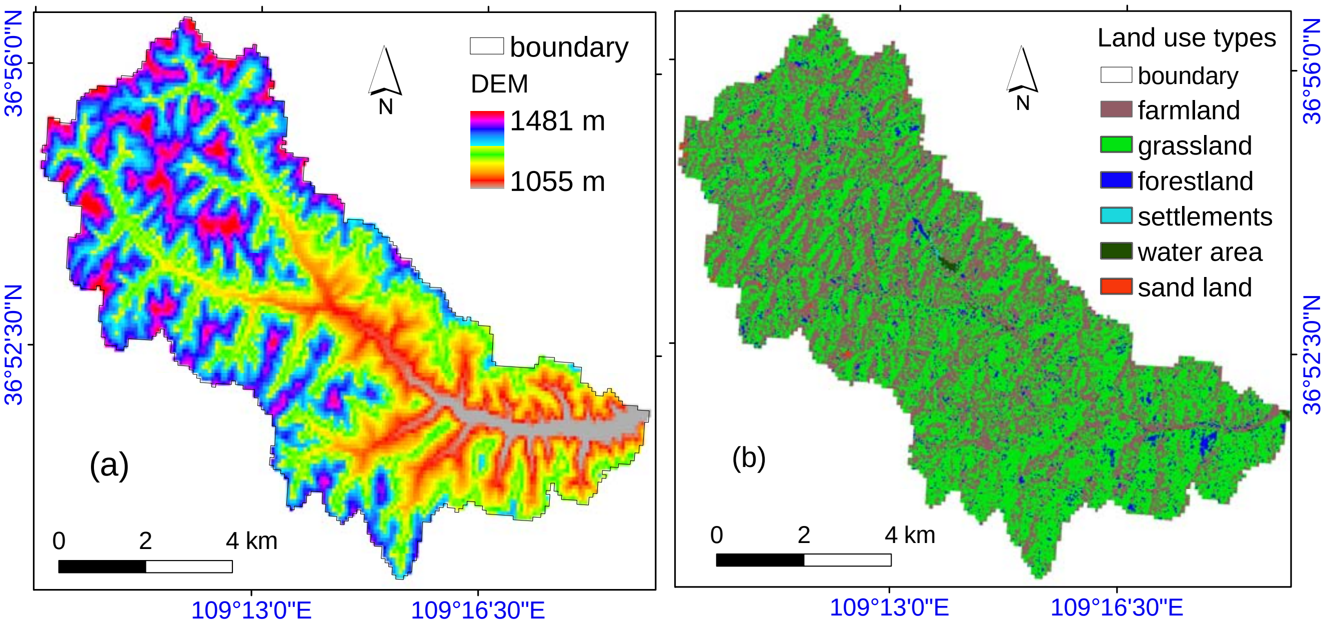

Figure 2: Longitude and latitude coordinates of the study area, digital elevation model (DEM) data, reclassified land use types of the Majiagou River watershed

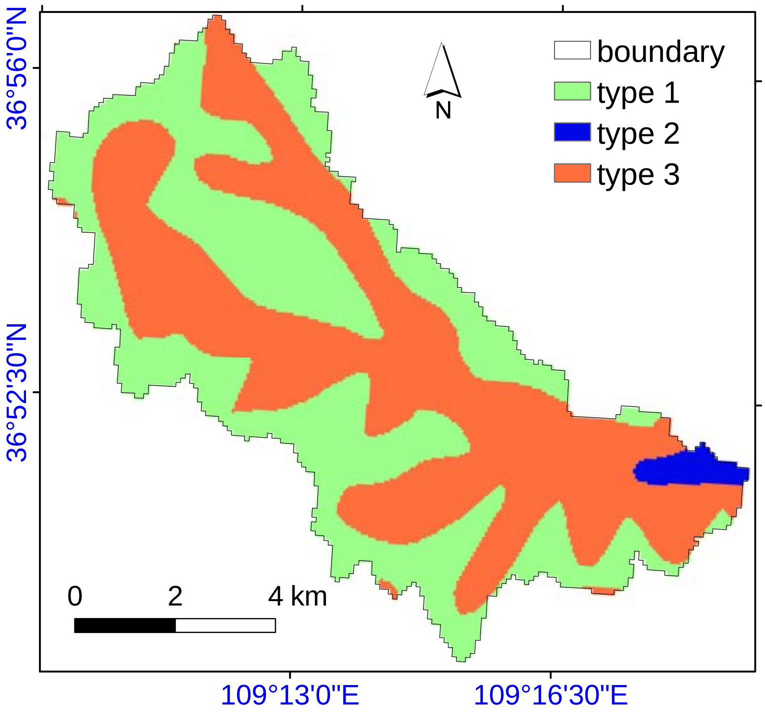

Figure 3: Soil types of the Majiagou River watershed (Legend notes: Type 1: Tillage erosive loessal soil (80%) + Erosive loessal soil (20%); Type 2: Tillage erosive loessal soil (80%) + Calcareous alluvial soil (20%); Type 3: Erosive loessal soil (80%) + Tillage erosive loessal soil (20%)).

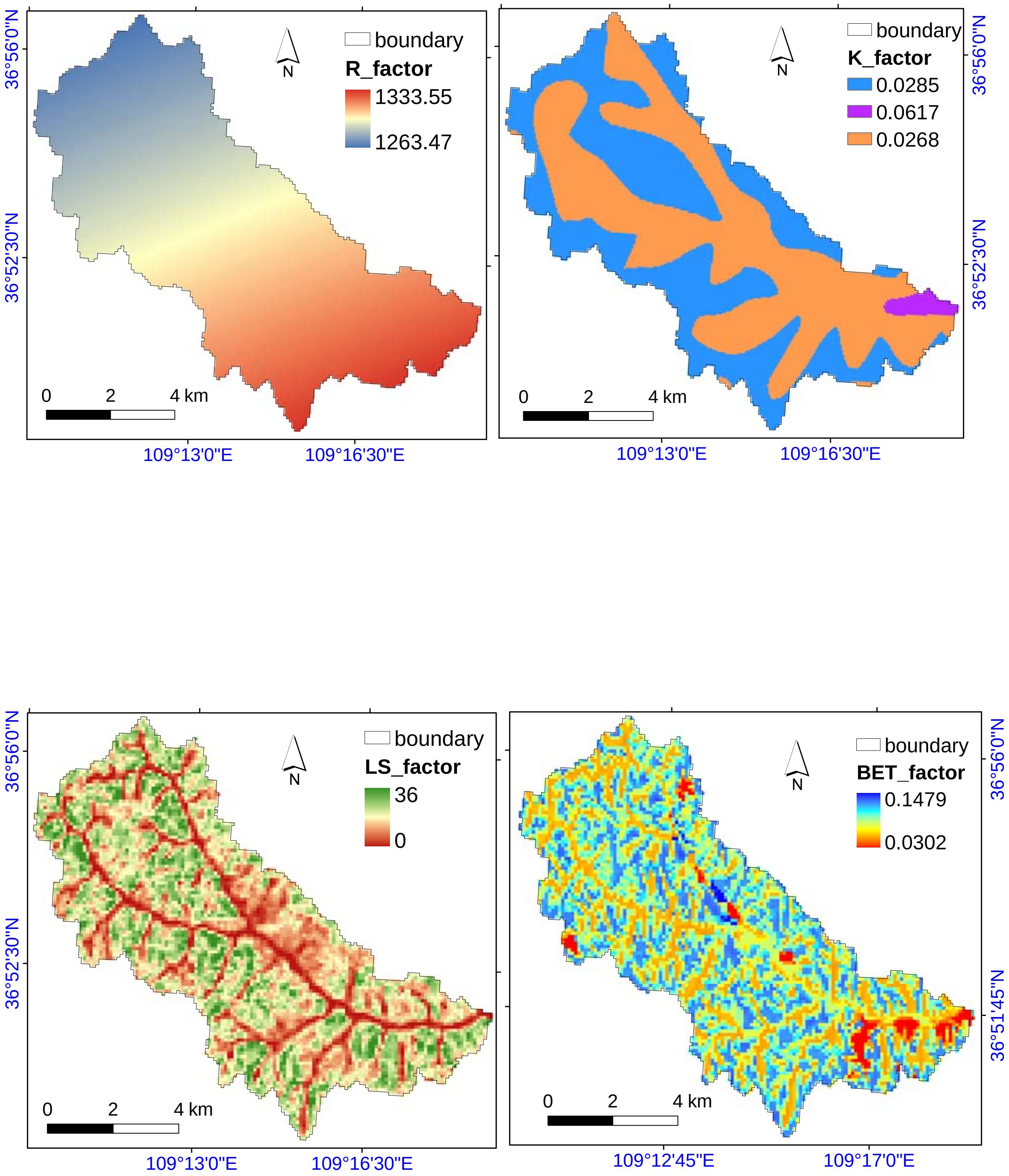

Figure 4: Spatial distributions of annual average R factor, K factor, LS factor and BET factor in the Majiagou River watershed

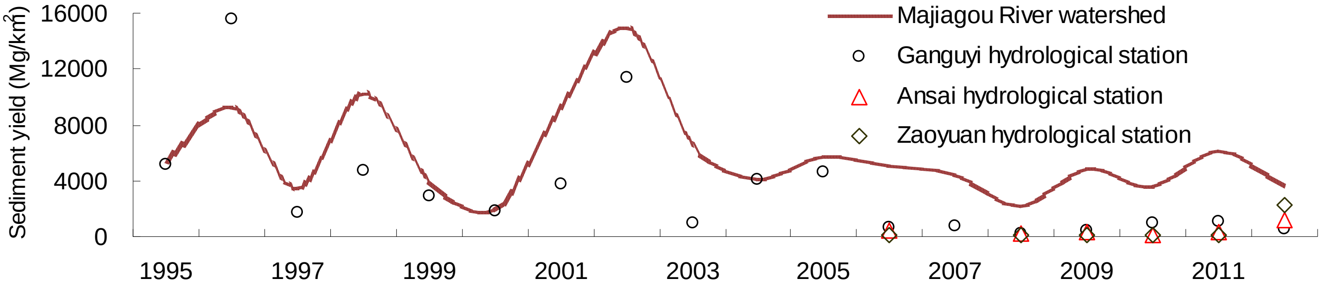

Figure 5: Validation of sediment yield modulus between Ganguyi, Ansai, Zaoyuan hydrological stations and Majiagou River watershed based on the established model

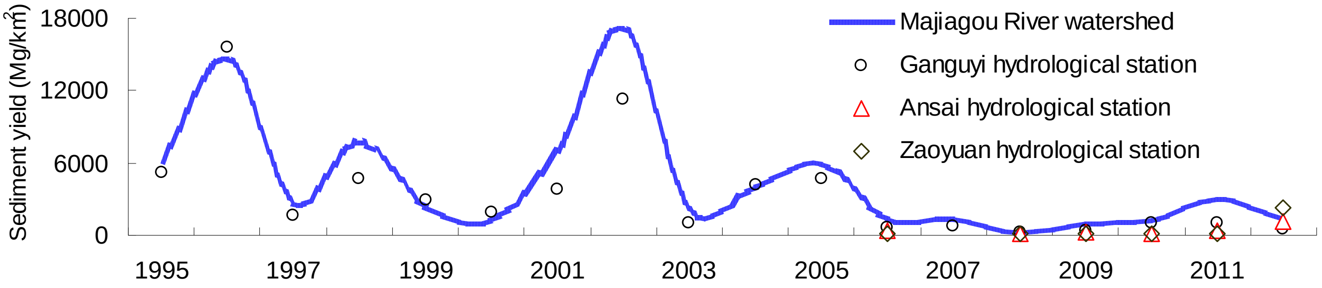

Figure 6: Validation of sediment yield modulus between Ganguyi, Ansai, Zaoyuan hydrological stations and Majiagou River watershed based on the modified model

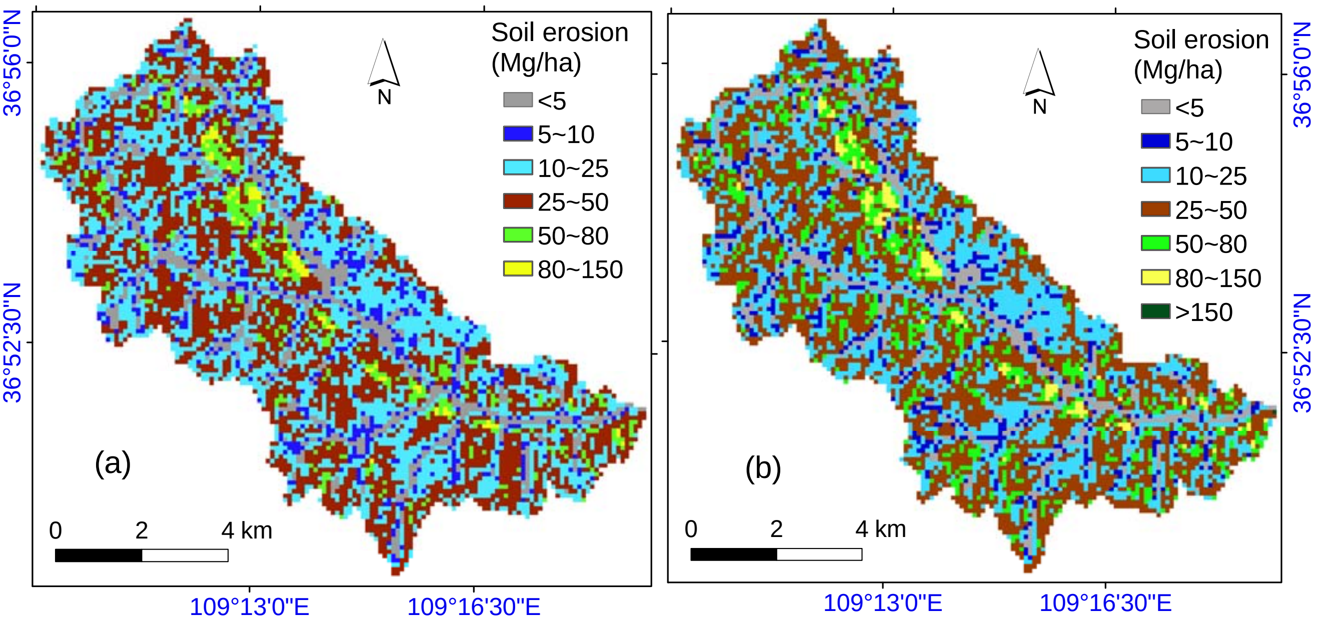

Figure 7: Spatial distribution of soil erosion gradations of the Majiagou River watershed: (a) 1995; (b) 2010

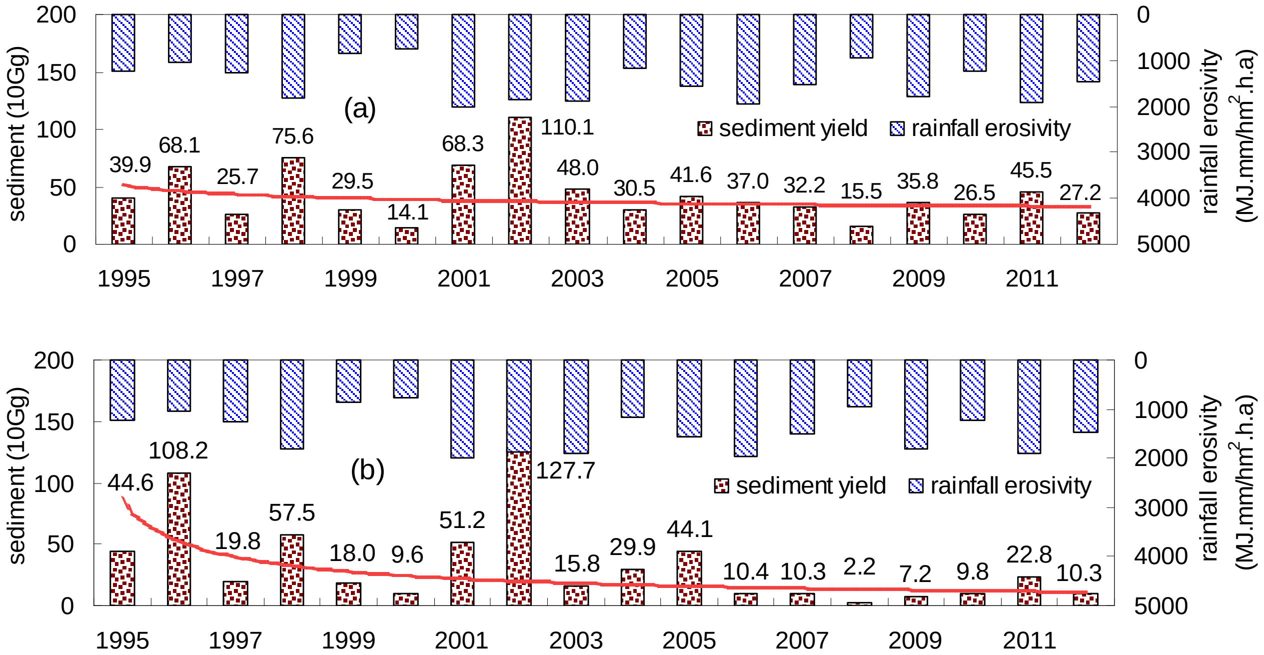

Figure 8: Comparative variations of sediment yield and rainfall erosivity in the Majiagou River watershed from 1995 to 2012: (a) the established dynamic model, (b) the modified dynamic model

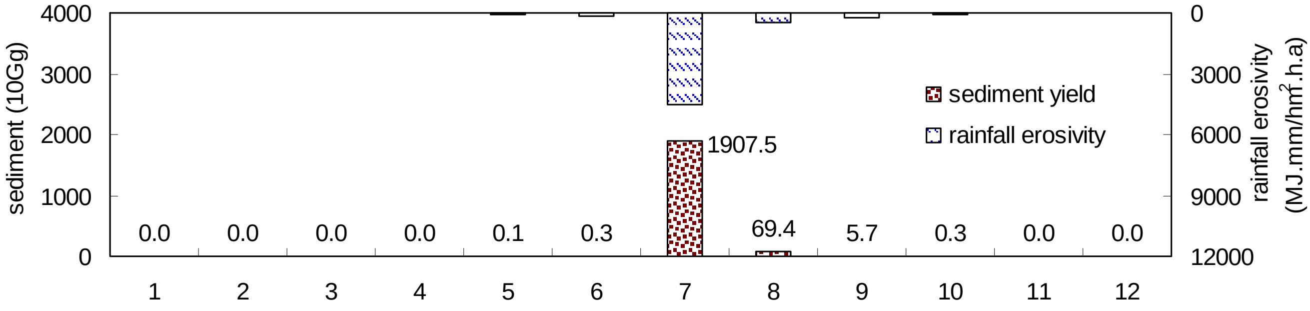

Figure 9: Comparison of monthly sediment yield and rainfall erosivity in the Majiagou River watershed in 2013

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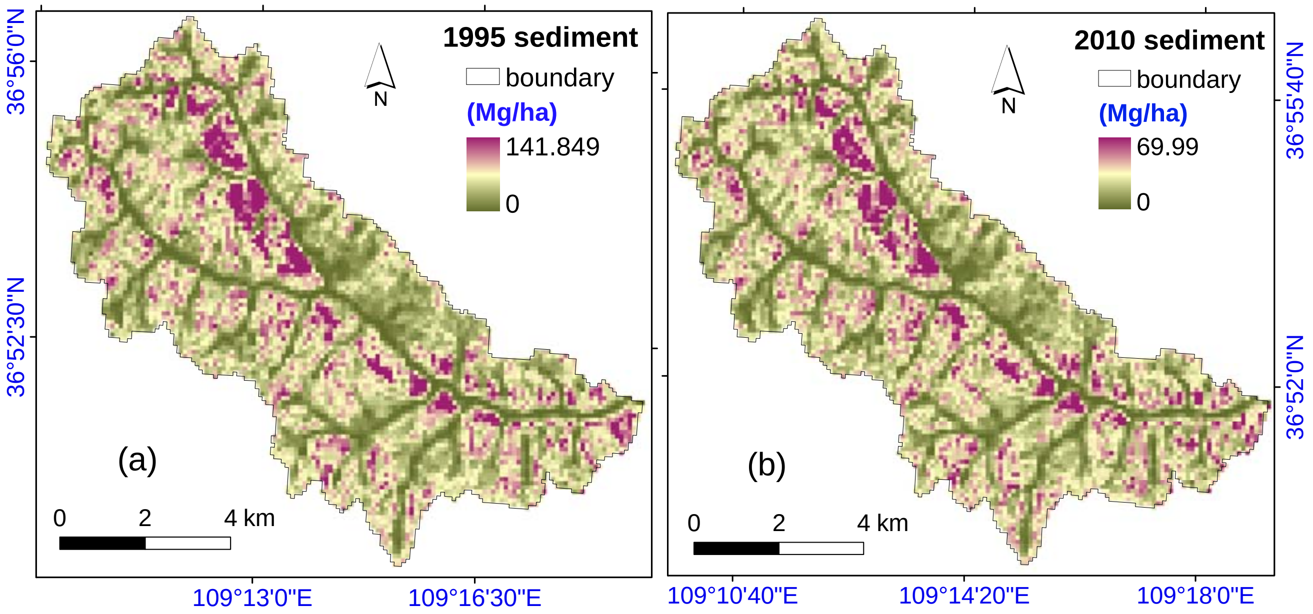

Figure 10: Spatial distribution of sediment yield ratio of the Majiagou River watershed: (a) 1995; (b) 2010