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Full Length Research Paper

Identification of critical source areas of soil erosion on moderate fine spatial scale in Loess Plateau in China

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Critical Source Areas (CSAs) are considered as priority areas for soil conservation and it is essential to identify CSAs for effective watershed management. Soil and water assessment tool (SWAT) model is a useful tool in identifying CSAs. Previous studies that used SWAT for CSAs identification were almost carried out on the basis of sub-watershed level which was too coarse to capture spatial detail of soil erosion. This research identified CSAs of soil erosion at a moderate fine spatial detail scale in a small watershed of Loess Plateau in China using SWAT model. CSAs were identified based on the 4-year average annual sediment yield of hydrological response units (HRU). The result shows that CSAs were mainly located in steep slope farmland areas and gully dominated areas. CSAs covered 10% areas of watershed, and contributed 30% sediment yield to the watershed. Such a trend is more obvious under larger storms. This could imply that CSAs identification on HRUs level is suitable for site-specific management design. This study also confirms that CSAs identification could be a potential approach assisting water quality control.

Key words: Soil conservation practices**,** soil and water assessment tool (SWAT), hydrological response units (HRUs), Loess Plateau, critical source areas.

INTRODUCTION

Soil erosion is a hazard to many countries and regions as it decreases soil fertility and increases sedimentation of rivers. With concerns of land degradation and water pollution problem, special attentions have been paid to soil and water control. Soil conservation practices are widely used to reduce soil erosion especially in agricultural watersheds (Morgan, 1986). However, due to the high cost associated with implementation of conservation practices and best management practices (BMPs), it is impossible to conduct practices over the whole watershed. Therefore, how to develop more effective soil conservation strategies has become one of the principal problems faced in watershed management. Soil erosion shows high spatial variability in watershed because a few critical areas are responsible for a disproportionate amount of sediment yield. Those areas could be the source or the transportation of sediment and other pollutants, which are referred to as critical source areas (CSAs), and have been recognized as the priority areas for the implementation of BMPs (Sivertun et al., 1998; Pionke et al., 2000; Gburek et al., 2002; White et al., 2009). Practices targeting CSAs could significantly influence their overall effectiveness (Gitau et al., 2004). Thus, identification of CSAs is a central issue to the effective and efficient implementation of soil conservation practices.

There have been many researches focusing on how to identify critical source areas. The identification methods ranges from manual overlay of spatially-index map to process-based distributed modeling (Tripathi et al., 2003). Erosion CSAs are originally delineated via evaluation by conservation planners based on professional judgment. With the support of geographic information system (GIS) in overlaying of soil erosion influencing factors such as slope, elevation, etc., some

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simple empirical derived methods have emerged and are widely used to identify critical source areas, including sediment yield index and universal soil loss equation (USLE) (Sivertun and Prange, 2003; Pandey et al., 2007). Though this kind of methods is simple and easy to carry out, the incapability in simulating soil erosion in details makes it ineffective for CSAs identification and watershed management. In addition, majority of these indices could only provide potential erosion prone areas but could not evaluate soil loss quantitatively (Sivertun and Prange, 2003).

Recently, processes based distributed models such as Areal Non point Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al., 1980), Agricultural Non-Point Source (AGNPS) Pollution Model (Young et al., 1995), European Soil Erosion Model [EUROSEM (Morgan et al., 1998)], and Soil and Water Assessment Tool (SWAT) (Anold et al., 1998) have been applied to evaluate spatial distribution of sediment yield and to indentify the CSAs. These models can not only quantify the sediment yield of watershed but also provide spatial variation of sediment (Strauss et al., 2007). Among these models, SWAT (Arnold et al., 1998) model has been widely used as an effective tool to evaluate the impact of watershed process (Gassman et al., 2007). Several studies have used SWAT model to identify the critical source areas in recent years (Tripathi et al., 2003; Ouyang et al., 2008; Busteed et al., 2009). However, due to the fact that earlier version of SWAT (SWAT 2000) did not locate the position of hydrological response units (HRUs), most of these studies were carried out on the basis of the sub-watershed level (Tripathi et al., 2003; White et al., 2003; Ouyang, 2008). Tripathi et al. (2003) used SWAT model to identify critical sub-watersheds out of 12 sub-watersheds. Ouyang et al. (2008) also focused on identifying the critical sub-watersheds of a mesoscale watershed, and 6 subbasin with large area were selected as CSAs. With such a coarse spatial scale, CSAs identified on sub-watersheds were insufficient to locate optimal spatial location for BMPs and thus were not suitable for precision site-specific BMPs deployment.

The Loess Plateau is the most severe soil erosion areas in China, with an average erosion rate of 150000 kg ha^{-1} per year, which is among the highest soil erosion rates in the world (Kang et al., 2001; Miao et al., 2010). How to establish an effective conservation practices is an urgent issue facing the regional sustainable development. However, limited research work on identification of critical source areas in the Loess Plateau conditions has been reported.

The overall objective of this study was to identify the critical source areas of soil erosion on a moderate spatial detail level (with a spatial unit of HRUs which is more detailed than subbasin and less detailed than cell) in a small watershed of Loess Plateau in China. The SWAT model was used to simulate hydrological and sediment yield processes and delineate CSAs in the Losses Plateau watershed.

MATERIALS AND METHODS

Description of study area

The study area, Yangdaogou, is a tributary of Yellow River, located in Lishi County, Shanxi province, China (Figure 1). The whole area is about 0.2 km^2. Annual temperature is about 9°C. Annual precipitation is about 505.7 mm. Precipitation occurs mainly in summer, from May to September, and accounted for 80.6% of the annual precipitation. Soils in this area are mainly Loess soil with red clay soil in the valley.

The watershed is considered as a representative small watershed of Loess Plateau for severe soil erosion (ISSCR, 1982). Annual soil erosion is about 20811 t km^{-2}. The area remains in natural state, meaning that no soil erosion control efforts have been made in this area. The study watershed is characterized by high mountains and steep slopes with an average slope of 31° and it is crisscrossed by gullies and ravines (Figure 2). Approximately 58% of the watershed is under intensive cultivation, and the rest of the watershed is steep ravines and not suitable for agriculture, remaining barren land (Figure 3). Agricultural activities have seriously led to soil loss. Soils in this area are mainly cultivated Loess soils with little red clay (Figure 4).

SWAT model input data

The basic data sets required to develop the model input are topography, soil, land use and climatic data (Table 1). The digital elevation model (DEM), soil type map and land use maps of 1968 were provided by the Environmental and Ecological Science Data Center for West China. Soil properties were obtained from the Chinese Soil Database of the Institute of Soil Science, and land use properties such as Manding's n value for overland flow were directly from the SWAT model database. The reason for using the period of 1965 to 1970 was that the observed data for 1965 to 1970 is of the highest quality.

The climate data include precipitation, daily data of maximum and minimum temperature, solar radiation, humidity, and wind speed. Precipitation data were collected from the measured data in the Yangdaogou watershed, while the rest are from Lishi weather station near Yangdaogou watershed collected from the China Meteorological Administration (CMA).

Observed daily stream flow and sediment discharges at basin outlet were extracted from the experimental data provided by the Institute of Shanxi soil and conservation research. These data were used for model calibration and validation.

Description of the model

SWAT, developed by United States Department of Agriculture (USDA), is a semi-distributed, physically based, watershed-scale model to predict long-term impact of land management practices on water, sediment and agricultural yields (Arnold et al., 1998). It is a continuous model running on a daily time step. The major components simulated by SWAT include hydrology, erosion, crop growth, weather, agricultural management practice, and nutrients and pesticide fate.

SWAT model is selected for this study because it has gained international acceptance as a robust interdisciplinary watershed modeling tool. It can be used to describe the spatial variability of sediment yield and is widely used to assess the effect of conservation practices on water resources. For example, most of

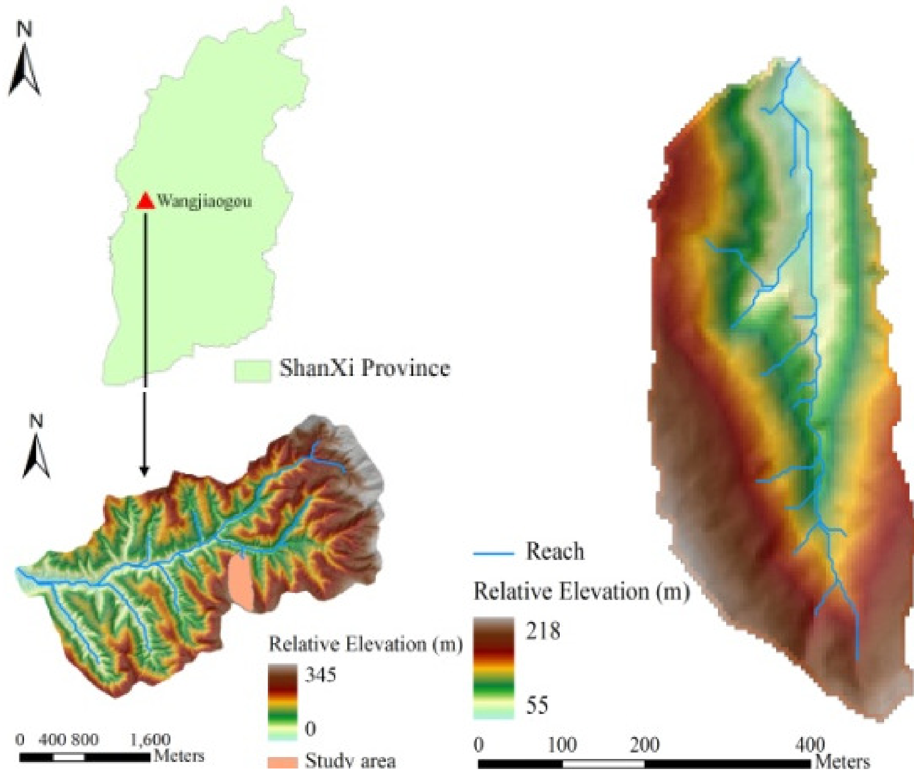

Figure 1. Location of the study area.

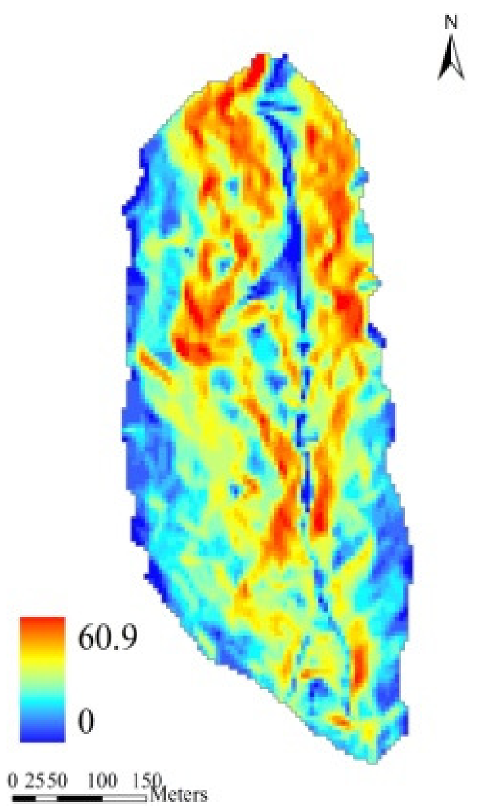

Figure 2. Slope of study area.

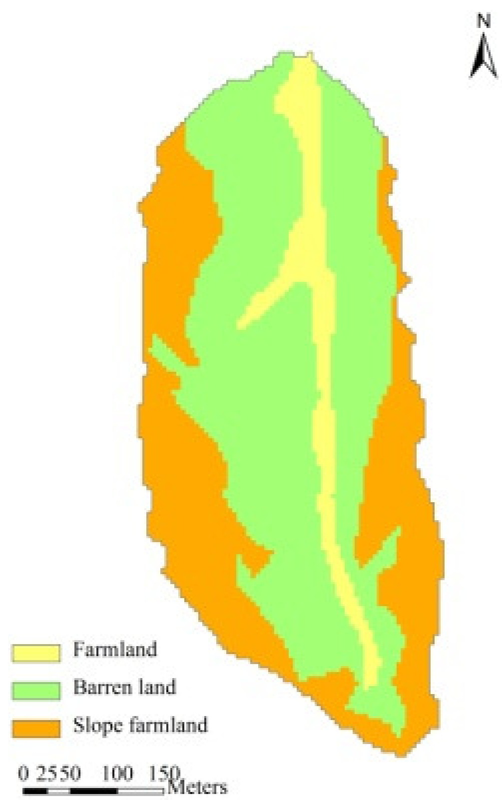

Figure 3. Land use of study area.

Table 1. Input data for hydrological modeling.

Data type	Data description/properties
Topography	Digital elevation model with a grid size of 5 × 5 m
Soil	Soil type and soil physical properties including texture, saturated conductivity, etc., with a grid size of 5 × 5 m
Land use	Land use classifications, with a grid size of 5 × 5 m
Climate data	Temperature, precipitation, wind speed, humidity (Lishi station, 1965-1970)

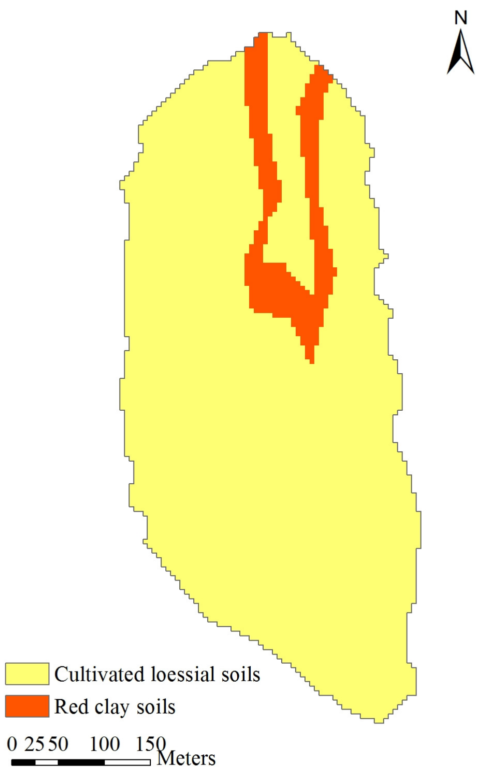

Figure 4. Soil of study area.

the Conservation Effects Assessment Project (CEAP) projects in USA use the SWAT model for their watershed water quality studies. To represent the spatial variability of the watershed, SWAT model first subdivides watershed into sub-basins based on the number of tributaries. Each sub-basin is then further disaggregated into HRUs, which is considered homogeneous in terms of land use and soil, as the basic modeling unit. Stream flow and sediment is calculated for each HRU, and then added to channel and routed to the outlet. The SWAT model used Soil Conservation Service Curve Number (SCS-CN) method to estimate stream flow and Modified Universal Soil Loss Equation (MUSLE) to estimate sediment yield.Stream flow and sediment are calculated in each HRU and then aggregated for each sub-basin, and finally routed to the outlet of the watershed.

Model parameterization

In this study, the Yangdaogou watershed was subdivided into sub-basins on the basis of DEM and stream network. The threshold for HRU definition was set to 0% both for land use and soil so as to achieve the most detailed distribution of HRUs. The watershed was discretized into 28 sub-basins and 307 HRUs as shown in Figure 5.

The watershed parameterization and the model input were derived using the SWAT2005 for ArcGIS 9.2, which provides a graphical support to the watershed disaggregation scheme and the derivation of model parameters from digital maps. Model simulations were conducted on daily time steps from January 1965 to December 1970.

Model calibration and validation

After an initialization run, the model was then calibrated and validated with observed daily runoff and sediment discharges at basin outlet using a split sample procedure. Data from the period of 1965 to 1966 was used for calibration, while data from 1967 to 1970 was used for validation.

Model calibration and validation were conducted in order to make sure the prediction is reliable. Model calibration was accomplished by two procedures. First, the auto-calibration and uncertainty analysis are conducted to achieve the sensitive parameters and their reasonable ranges.

The Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992) method which is integrated into the SWAT-CUP software (Abbaspour et al., 2008) was applied to the sensitivity analysis. The curve number (CN2), available water content (AWC), soil evaporation compensation factor (ESCO), slope (SLOPE), slope length (SLSUBBSN), USLE_K, USLE_C were selected as the sensitive parameters for calibration. Second, manual-based calibration method known as 'Trial and Error' method was conducted by varying the sensitive parameter values to achieve a simulated result which is more in line with observed data.

Model validation is conducted by evaluating the model performance after calibration. Model performance was evaluated by Nash-Sutcliffe coefficient recommended by ASCE Task Committee (Nash and Sutcliffe, 1970).

Critical source areas identification

The verified model was then applied for the CSAs identification. The SWAT model generates the spatial distribution of sediment yield on sub-basin-level and HRU-level. We used HRU-level sediment yield to identify CSAs because significant detailed distribution of critical source areas could be captured using HRUs predictions.

It required a threshold unit load to identify CSAs. Most of the researches directly defined the threshold unit load from soil erosion classes when previous studies have been carried out. However, White et al. (2009) recommended that the threshold unit area load at which a discrete unit was categorized as CSAs depended on the characteristics of watershed. An appropriate threshold should be defined by ranking each discrete unit within a watershed based on the predicted sediment yield and regarded the highest ranking fraction as the threshold.

As there is no previous study in the Loess Plateau about the

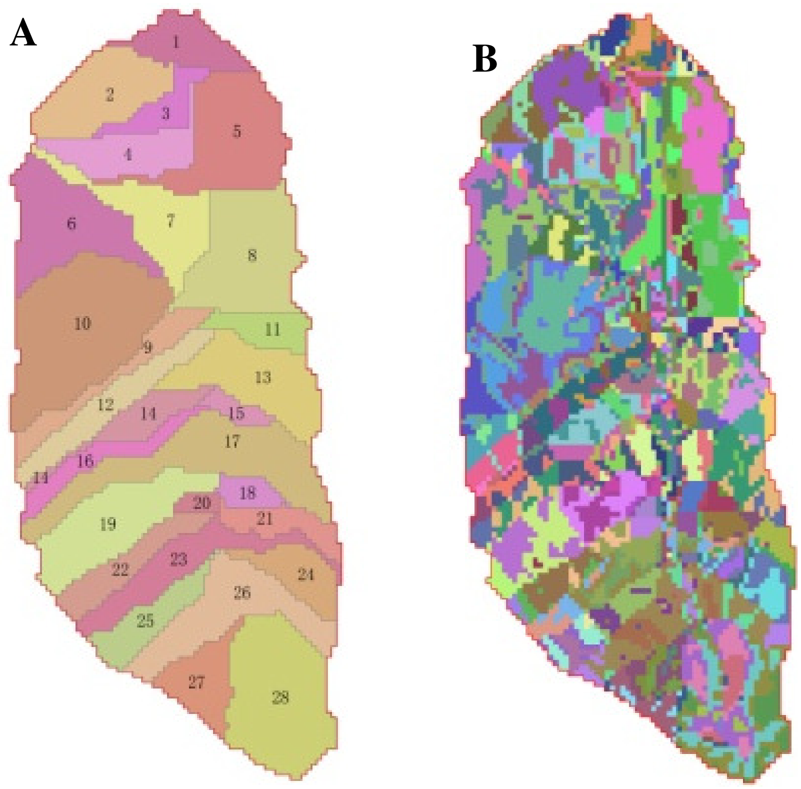

Figure 5. Discretization of Yangdaogou watershed; A) Subbasins and B) HRUs.

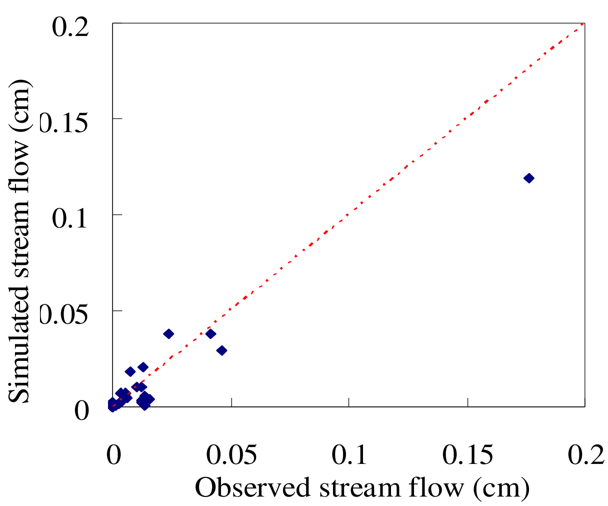

Figure 6. Simulated observed stream flow of 1967-1970.

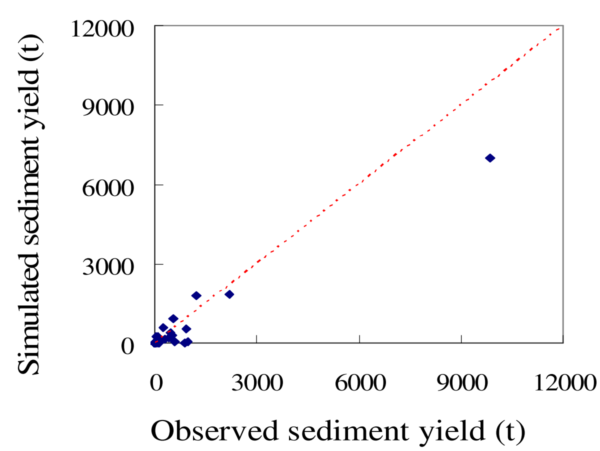

Figure 7. Simulated and observed sediment yield of 1967-1970.

CSAs delineation, no criteria about CSAs threshold load of HRUs can be found for CSAs identification. In this study, we used the approach proposed by White et al. (2009) to identify HRUs. The detail is introduced as follow: HRUs were first ranked in terms of average annual sediment yield. A cumulative sediment yield curve was generated illustrating the relationship of HRUs contribution area and its related sediment yield. Based on the sediment cumulative sediment yield curve, CSAs can be defined given the threshold of contribution area. In this study, CSAs was defined with threshold value of 10% contribution area.

RESULTS AND DISCUSSION

Steam flow and sediment yield

Daily simulated stream flow and sediment were plotted against the observed values as shown in Figures 6 and 7. Most of the points were distributed along with the 1:1 line.

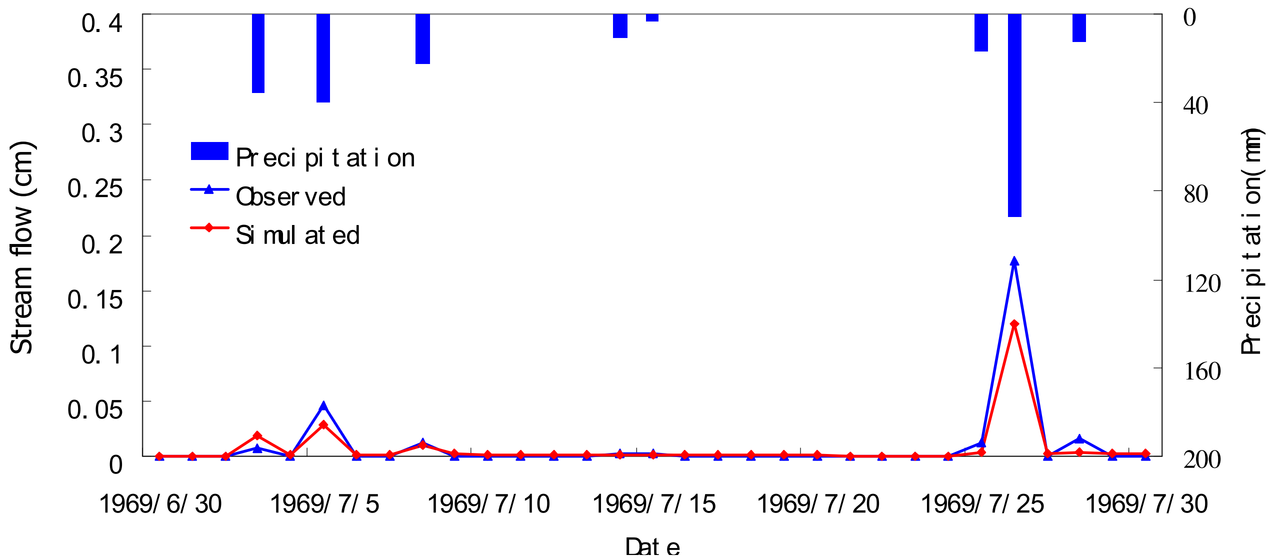

Figure 8. Simulated and observed stream flow in 1969 flood season.

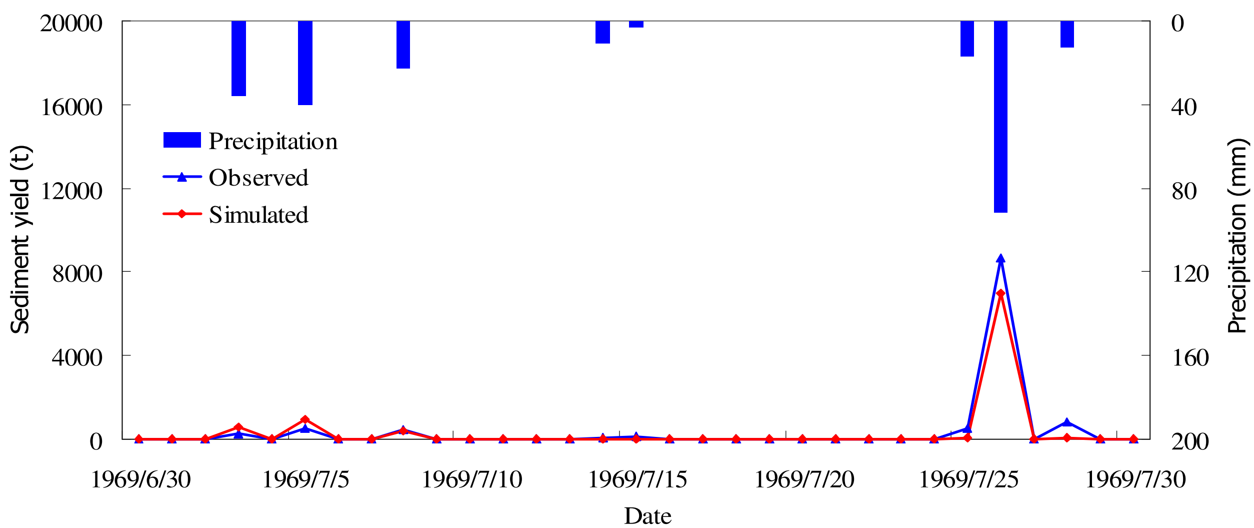

Figure 9. Simulated and observed sediment yield of 1969 flood season.

The Nash-Sutcliffe coefficient for the validation period is 0.88 for water yield and 0.89 for sediment yield. This indicated that there was a good agreement between the observed data and simulated results. Figures 8 and 9 show that the simulated results matched well with precipitation. However, the model slightly under-predict peak event in 1969 because the extreme storm which occurred in 1969 was of extremely low frequency.Figure 10 shows the spatial distribution of average 4-year sediment yield on HRUs scale. The distribution assumes moderate fine spatial detail with minimum HRUs of 3.5 m^2. By comparing with land use (Figure 3) and slope map (Figure 2), we can find that the spatial distribution of simulation result coincides with the distribution of land use and slope. The main sediment yield comes from sloppy farm land and bare land dominated by gully. As farmland in steep slopes and gully in barren land are the main source of soil erosion in Loess Plateau, the spatial distribution of simulation results captures the spatial variation of sediment yield and therefore is applicable to CSAs identification of the study's watershed (Figure 10).

Critical source areas of Yangdaogou watershed

CSAs are identified based on the ranking of HRUs. For the top 10% of sediment yield, 20 HRUs out of the 307 HRUs which exceed 44106 t km^{-2} per year were selected as CSAs. Figure 11 presents the spatial distribution of

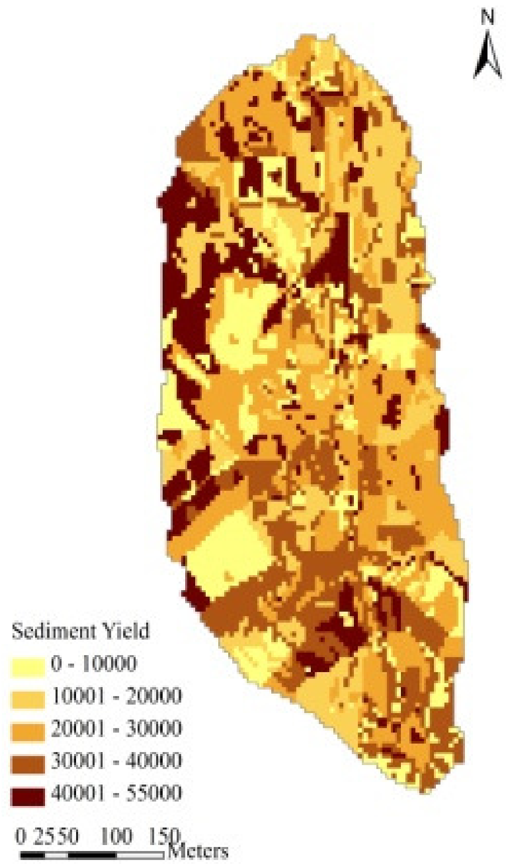

Figure 10. Simulated average 4-year sediment yield (t km^{-1} per year) distribution of study area.

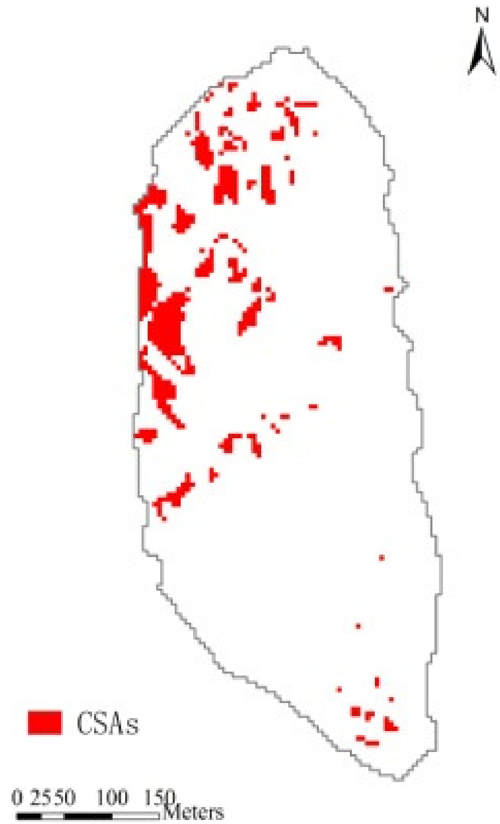

Figure 11. Critical source areas of study area.

CSAs using the HRU scale.

CSAs shown in Figure 11 are spatially dispersed with mostly small patch which indicates that CSAs identified on HRUs level could capture more spatial detail compared with that of sub-basin level. By comparing with land use (Figure 3) and slope map (Figure 2), we can find that the CSAs were mainly located in the steep farmland areas and gully dominated areas. The HRUs in the valley plain with flat terrain are seldom defined as CSAs as soil erosion is less severe in these areas. The result indicates that the CSAs are formed by the combined action of land use and slope. The slope farmland (with intensive agricultural activity and steep slope) and the gully area (with little vegetation cover) are more likely to be CSAs. This is reasonable, as in this study area, the slope farmland with intensive agricultural activity and the gully area with little vegetation cover are prone to soil erosion and are the main resource of sediment.

The CSAs identified in this study which occupied 10% of the watershed, contributed 30% sediment yield to the watershed. Such a trend is more obvious under larger storms. For example, in the flood season of 1969, the 10% occupied CSAs yielded 36% of sediment to the watershed outlet. As critical source areas have high sediment yield contribution, CSAs have a distinct potential for soil erosion control and should be considered as the priority for placement management practices in this study area.

For conservation practices, it might be impractical to make decisions directly on HRUs as some of them are very small. However, the identified CSAs could be reprocessed to facilitate decision making. For example, the HRUs which are adjacent to each other can be treated with one conservation practice and the HRUs which are separated and very small can be ignored when designing conservation practice.

Conclusions

This research aims to identify critical source areas of soil erosion on a moderate spatial detail level in a small watershed of Loess Plateau in China. SWAT model was used to simulate hydrological and sediment yield processes and then to delineate CSAs in a small watershed of Loess Plateau in China. The model was firstly calibrated and validated for stream flow and sediment yield simulation, and the verified model then predicted sediment yield distribution of HRUs. The HRUs were then ranked in terms of 4-year average annual sediment yield and the top 10% (in area) of HRUs were defined as CSAs in this study area.

The result shows that CSAs are spatially dispersed, which indicate that CSAs of HRUs level could capture more spatial detail than that of sub-basin level. The CSAs were mainly located in steep slope farmland areas and gully dominated area. The 10% occupied CSAs areas contributed to 30% sediment yield of watershed. Such a trend is more obvious under larger storms. For example, in the flood season of 1969, these CSAs contributed to 36% of the sediment yield to the watershed outlet. This leads to a conclusion that CSAs identification on moderate fine spatial detail scale (HRUs level) is suitable for site-specific management plan design of watershed. This study also confirms that CSAs identification could be a potential approach in assisting water quality control in loess plateau in China.

The limitation of SWAT model for CSAs identification

SWAT model is a useful tool for CSAs identification and effectiveness assessment. However, from this study, we found that SWAT does have some limitations to model the soil erosion process and then identify CSAs. Firstly, the model is semi-distributed with hydrological response unit (HRU), which is homogeneous in terms of land use and soil, as basic modeling unit. Runoff and sediment is calculated for each HRU, and then added to channel and routed to the outlet. The independence of each HRU and lack of spatial connection restricted the models' ability of capturing spatial details of target processes. For example, SWAT could not adequately account for the deposition of sediment between upland areas and the stream, which may not depict a realistic sediment distribution. Such a limitation may influence which areas should be defined as CSAs and their relative contribution in sediment yield.

Meanwhile, although SWAT is a physical-processes-based model which considered all critical processes related to watershed processes, the specific equations used to calculate essential components are basically empirical ones. For example, overland stream flow is calculated by SCS curve number method, while soil erosion is simulated by MUSLE equation. With such a limitation, the model may be insufficient for soil erosion processes simulation in a desired detailed level.

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