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Comparison of soil erosion models used to study the Chinese Loess Plateau

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Abstract

The Loess Plateau suffers from severe soil erosion that leads to a series of ecological and economic problems such as reduced land productivity, exacerbated rural poverty, decreased biodiversity and sedimentation of the riverbed in the lower reaches of the Yellow River. Soil erosion models are commonly used on the Loess Plateau to help target sustainable land management strategies to control soil erosion. In this study, we compared eleven soil erosion models that were previously used on the Loess Plateau. We studied their prediction accuracy, process representation, data and calibration requirements, and potential application in scenario studies. The selected models consisted of a broad range of model types, structures and scales. The comparison showed that process-based and empirical models did not necessarily yield more accurate results over one another for the Loess Plateau. Among the process-based models, Si' model, WEPP and MMF had the highest prediction accuracy. However, some of the selected models were tested with total sediment load while others were tested with suspended sediment load (i.e. bedload is not included), which is subject to several drawbacks. Research questions that each of the models can address on the Loess Plateau were suggested. Further improvement of soil erosion models for the Loess Plateau should concentrate on enhancing the quality of data for model implementation and testing, incorporating key processes into process-based models according to their aims and scales, comparing models that address the same research questions, and implementing internal and spatial model testing.

Key words: dryland; sediment; land use; modelling; prediction

1 Introduction

Soil systems are a key component of the delivery of many ecosystem services upon which societies depend, including those that are crucial to food security, climate mitigation, and water and nutrient cycling (de Vries et al., 2012). However, soil systems are facing erosion threats under climate change and intensified land management (Oldeman, 1994, Yang et al., 2003). Soil erosion leads to serious issues, including the reduction of soil depth, soil organic matter and nutrients (Pimentel, 2006), reduced crop yields (Wang et al., 2006), the loss of arable land and biodiversity (Pimentel et al., 1995), exacerbated rural poverty (Meng, 1997), water pollution (Rothwell et al., 2005) and enhancement of terrestrial carbon release (Pawson et al., 2012). Sediment transport and deposition may degrade streams, lakes, reservoirs, and estuaries (Uri, 2001). Globally, the total land area affected by water erosion was estimated to be 10.1 million km^2, of which 7.5 million km^2 was severely affected, and that by wind erosion was 5.5 million km^2, of which 3.0 million km^2 was severely affected (Oldeman, 1994). Among these areas, the Chinese Loess Plateau has been ranked as being most severely eroded (Shi and Shao, 2000). Although dramatically decreased in some areas during the last 20 years (Jiao et al., 2016, Tsunekawa et al., 2014), soil erosion rates on the plateau can reach 15,000 t km^{-2} yr^{-1}, with approximately 91,200 km^2 subject to a soil erosion rate of over 8,000 t km^{-2} yr^{-1} (NDRC et al., 2010, Shi and Shao, 2000). The plateau has therefore been an important area for soil erosion research.

Soil erosion research is generally carried out through field observation (Lal, 1994), tracer studies (Walling and Quine, 1990), experimental manipulation (Lal, 1994) and soil erosion modelling (Wainwright and Mulligan, 2013, Li et al., 2016b). Traditional experimental methods are easy to apply at small scales (e.g. patch scales and hillslope scales) and the outcomes are beneficial for investigations into the underlying mechanisms of soil erosion. However, these methods are difficult to apply over a large area (e.g. catchment scales and regional scales) given that such projects are labour intensive and costly. At the same time, there has been a number of investments supported by the Chinese central government aimed at reducing erosion on the Loess Plateau such as implementation of soil and water conservation measures (i.e. vegetation restoration, construction of check-dams and terraces etc.) and the ‘Grain-for-Green’ project (converting sloping croplands to forest/grasslands) (Tang, 2004, Mu et al., 2007, Wang et al., 2015, Feng et al., 2016). There is therefore a need to quantitatively assess the effects of different measures and their combinations on soil erosion reduction for the development of sustainable land-use strategies. However, it is difficult to fulfil this need solely using traditional experimental methods particularly if we are to include consideration of future climate change (Wainwright and Mulligan, 2013). Soil erosion models are able to operate over large regions with different possible inputs to include uncertainties in future change (Wainwright and Mulligan, 2013, Li et al., 2016a, Li et al., 2017a, 2017b).

Since the 1980s, there has been a remarkable advance in research on soil erosion models for the Loess Plateau. Many soil erosion models, originally developed for other areas, have been applied to the region, including Universal Soil Loss Equation (USLE) and its variants (e.g. Sun et al., 1990, Sun et al., 2014), Watershed Erosion Prediction Project (WEPP) (e.g. Zhang et al., 2005, Li et al., 2011), Limburg Soil Erosion Model (LISEM) (e.g. Hessel et al., 2003a, 2003b, Hessel and Jetten, 2007), Soil and Water Assessment Tool (SWAT) (e.g. Qiu et al., 2012, Zuo et al., 2016), Water and Tillage Erosion Model and Sediment Delivery Model (WATEM/SEDEM) (e.g. Zhao et al., 2015, Feng et al., 2010), and Morgan-Morgan-Finney model (MMF) (e.g. Li et al., 2010a). There have also been some soil erosion models developed specifically for the Loess Plateau including the Chinese Soil Loss Equation (CSLE) (Liu et al., 2002) and Digital Yellow River Model (DYRIM) (Wang et al., 2007), and those developed by Yang et al. (2012), Si et al. (2015), Tian et al. (2015), Tang et al. (1990), Jin et al. (2008), Jia et al. (2005), Cai et al. (1996), Fan et al. (1985) and Yin et al. (1989).

Although many models have been used on the Loess Plateau, it was unclear for model users how to choose an appropriate model for a specific research question. In order to address this issue, a thorough comparison of contemporary soil erosion models for the Loess Plateau was needed. Such a study should not only involve the key criteria for model comparisons such as those used in de Vente et al. (2013), but also take into account the nature of each model such as the research aims that the model was developed to address or the environment the model works well in. In doing so, the results of a model comparison should be beneficial for model users to help them choose an appropriate model, but also good for model developers to support understanding of future needs.

This paper aimed to compare contemporary soil erosion models for the Chinese Loess Plateau based on a survey of literature. We selected the soil erosion models that were well used on the Loess Plateau, and compared and discussed them in terms of performance, process representation, data requirements and calibration needs and potential for use in scenario studies. We suggested the research questions that each model can address on the Loess Plateau through combining model comparisons and the nature of each model. We also identified priorities for future development of soil erosion models for the Loess Plateau.

2 Basic concepts for soil erosion models

2.1 Model types

Two broad types of model are frequently used in soil erosion modelling: empirical and process-based. In empirical models, statistical techniques are employed to examine the relationships between different components of studied systems (Wainwright and Mulligan, 2013). Empirical models can achieve accurate results. However, they are limited to conditions for model development (Morgan and Quinton, 2001, Aksoy and Kavvas, 2005) and therefore often do not perform well when applied to other areas or other time periods (Sadeghi et al., 2013). In order to explain and predict the dynamic behaviour of the system as a whole, process-based models consist of algorithms derived from theoretical principles such as some forms of kinematic wave procedure for routing water and sediment (Wiltshire, 1983, Morgan and Quinton, 2001). Ideally the processes would be represented by process-based models, while all parameters could be measured in the field. In theory, process-based models are more transferable than empirical models (Wainwright and Mulligan, 2013). However, in practice, the lack of field data on drivers of the processes and the lack of understanding of the processes across scales present key limitations to model development and deployment.

2.2 Model structures

Soil erosion models are built in two structures: lumped and distributed (Jetten et al., 2003, de Vente et al., 2008). In lumped models, contributing factors of erosion are represented by a constant value over the study area (Aksoy and Kavvas, 2005). However, erosion-influencing factors, such as soil properties and topography, significantly vary over space even within areas as small as one field. This variability cannot be represented by a constant value. Recent advances in Geographic Information Systems (GIS) support better representations of the spatial variability (Jetten et al., 2003). In spatially-distributed models, a large area is divided into small sub-units, which have uniform characteristics such as climate, land use and topography (Aksoy and Kavvas, 2005). Models are then run within and between each of the sub-units to derive overall soil loss from the study area.

2.3 Model scales

A soil erosion model usually focuses on soil erosion and transport at specific spatial and temporal scales (de Vente and Poesen, 2005). Spatial or temporal scale refers to the spatial extent or time span that models operate at, while time step means the time interval used by a model during applications (e.g. predictions are made for every hour or every month). Spatial scales typically include hillslope (< 0.1 km^2), small catchment (0.1 km^2 ~1,000 km^2), medium catchment (1,000 km^2 ~ 10,000 km^2) and large catchment / regional (> 10,000 km^2), while temporal scales typically involve event, daily, monthly and annual. Process-based models usually fall within two groups: event and continuous models (Morgan and Quinton, 2001). Event models are developed to investigate the impact of single storm events or storms of different return periods with time steps of minutes to hours (Saavedra, 2005). Their algorithms are often developed for catchment-scale applications (Merritt et al., 2003). Continuous models operate on successive time increments, with time steps ranging from days to months, to estimate soil erosion and sediment yield at various spatial scales (Renschler and Flanagan, 2002, Merritt et al., 2003).

3 Soil erosion and transport on the Loess Plateau

3.1 Loess Plateau

The Loess Plateau (33°41’ N~41°16’ N, 100°52’ E~114°33’ E) lies in the middle reach of the Yellow River, China, extending horizontally over 640,000 km^2 and vertically between 1,000 and 1,600 m above the sea level (Chen et al., 2007; Zhao et al., 2013). The plateau is characterized by steep slopes formed by continuous loess deposits with an average depth of over 100 m, which has been delivered by wind from the northwestern Gobi desert since the beginning of the Quaternary (Cai, 2001). Typically containing up to 10% fine sand and up to 20% clay (Pye and Sherwin, 1999), the loess is loose, porous and easily detached by erosive forces, which, on the Loess Plateau, include raindrop impacts, running water (e.g. overland flow and pipe flow), gravity, freeze-thaw and wind (Wang et al., 2010, Fu, 1989, Shi et al., 2004, Wang et al., 2007, Zhu et al., 2002). The plateau is within the continental monsoon region with mean annual precipitation ranging from 150 mm in the northwest to 700 mm in the southeast (Zhao et al., 2013, Li et al., 2009). The precipitation is seasonally uneven and mainly takes place in summer months (July to September) in the form of intensive and short-duration rainfall events with one-minute-interval rainfall intensities often exceeding 100 mm h^{-1} (Hessel, 2002). Potential evapotranspiration is much higher than precipitation (Tsunekawa et al., 2014). This results in a low soil water content and desiccation, limiting the growth of vegetation (Jiao et al., 2016). Meanwhile, extensive historical human interventions, such as long-term cultivation (Zhu, 1989, Chen et al., 2007), development of energy industries (Shi and Shao, 2000) and grazing, have significantly reduced the vegetation cover. In places this vegetation cover has recently been partly restored by the ‘Grain-for-Green’ project (Jiao et al., 2016, Tsunekawa et al., 2014). However, large areas are still at severe risk of erosion. Overall, intensive rainfall, water flow and gravity are the key features that act on steep, sparsely vegetated and highly erodible loess slopes, accounting for the majority of the soil loss on the Loess Plateau (Zhang and Liu, 2005, Zhao et al., 2013, Shi and Shao, 2000). Therefore, here we focus on models of water-induced erosion and gravitational erosion.

3.2 Soil erosion and sediment transport processes

Water-induced erosion and gravitational erosion include the detachment of soil by rainsplash, water flow and gravity, the transport of detached soil particles via overland flow and pipeflow, and deposition of the entrained or transported soil particles (Han et al., 2012). This detachment-transport-deposition process redistributes loose soil, leading to a fractured and complicated terrain of well-connected hillslopes and stream channels on the Loess Plateau (Wang et al., 2007).

On hillslopes of the Loess Plateau erosion processes usually follow a downslope sequence of splash-sheet-rill-shallow gully (Zhu, 1986, Zhang, 1993, Tsunekawa et al., 2014), since the initiation of rill and gully erosion requires sufficiently concentrated runoff that accumulates as the length of the slope increases (Loch and Silburn, 1996). On the flat lands of upper hillslopes, soil particles detached by rainfall splash form a thin layer of slurry, blocking soil pores and thus reducing the rate of infiltration (Gong, 1988). This accelerates the production of shallow infiltration-excess overland flow, resulting in sheet erosion. Along with the increase of slope gradient downward, the water flow from the upper hillslope moves over the soil surface through preferential pathways, and forms easily recognisable channels, which are termed rills. The areas between rills are termed interrills. Sediment from rill and interrill sources are transported by the flow in rills, which may also detach soil particles if the shear stress is sufficiently high (Aksoy and Kavvas, 2005, Yalin, 1963). Rills usually develop downslope into shallow gullies, which are then connected to permanent larger gullies in which flowing water is dominant in sediment detachment and transport (Bennett, 1974; Wang et al., 2007). However, there are not always shallow gullies above the headcuts of permanent gullies on the Loess Plateau. Rills can be obliterated by tillage. Shallow gullies, also termed ephemeral gullies, can be plowed out or may naturally infill in an episodic cut-and-fill process (Schumm, 1977), reforming at locations where flow concentrates (Poesen et al., 2011, Guo et al., 2015). Permanent gullies are too deep to be obliterated by tillage (Loch and Silburn,1996).

A tunnel or piping system typically comprises multiple pipe inlets that may be connected to a pipe outlet via underground conduits that are often many centimeters in diameter and several hundred meters in length (Holden et al., 2007, Zhu, 2006). The pipe system is an important way of transporting water, sediment and solutes from hillslopes (Holden et al., 2012, Holden et al., 2009, Holden et al., 2007). Piping systems on the Loess Plateau are among the largest and most complicated in the world (Zhu, 2006), sometimes accounting for a considerable proportion of soil loss and runoff production (Zhu, 1997, Zhu et al., 2002). Zhu (2012) found that gullies on the Loess Plateau were often formed through the collapse of large pipes.

Gravitational erosion, usually in the form of landslides, soil creep or bank collapse, occurs frequently in gullied regions of the Loess Plateau, as a result of steep slopes and the loose texture of loess soil (Gong, 1988). The nature of the soil and micro-landscape appear random but we have a poor understanding of the processes and their drivers on the Loess Plateau and therefore such processes tend to be modelled stochastically (Wang et al., 2007).

In-stream erosion consists of the direct removal of sediment from stream banks (lateral erosion) or stream beds (Merritt et al., 2003, Tsunekawa et al., 2014). Sediment also enters the stream due to slumping of the stream banks resulting from undercutting of the stream bank. There is deposition on stream beds when sediment concentrations are above the transport capacity (Aksoy and Kavvas, 2005, Tsunekawa et al., 2014). Given the high erosion rate of the Loess Plateau, there is a great amount of eroded soil entering stream channels. As a result, sediment concentrations in stream flow can become very high, with concentrations of up to 1000 g L^{-1} often occurring (van Maren et al., 2009, Hessel, 2006). Flow with such concentrations takes an intermediate position between normal streamflow and debris flow and is usually termed hyperconcentrated flow.

4 Selected models

4.1 Selection of modelling studies

From a survey of the literature, there were around thirty soil erosion and sediment transport models previously used on the Loess Plateau. Model calibrations and validations are often undertaken before the models are applied to a specific area (Jetten et al., 1999). However, some models were not well tested before they were applied to the Loess Plateau. This was the case for some of the models specifically developed for the Loess Plateau and particularly for the empirical ones established with catchment-outlet-based measurements. There were also some models that were thoroughly evaluated on the Loess Plateau but the results for sediment were described in a mainly qualitative manner. For example, LISEM was adapted to Loess Plateau conditions, calibrated and validated by Hessel et al., (2003a, 2011) as a part of modelling work on the central Loess Plateau (Hessel et al., 2003a, 2003b, Hessel and Van Asch, 2003, Hessel, 2006, Hessel and Jetten, 2007, Hessel et al., 2011). They reported the Nash-Sutcliffe coefficient (N_{sc}) (Nash and Sutcliffe, 1970) for runoff discharge, and for sediment they provided measured and simulated soil loss on an event basis, but the goodness-of-fit between measured and predicted sediment concentration was only described qualitatively (Hessel et al., 2003, 2011). The above two issues made a quantitative comparison of the corresponding models difficult, and thus those models were not included in our study. Eleven models (Table 1) were eventually chosen, representing a broad spectrum of model concepts, structures and scales. They were well calibrated and/or validated for the Loess Plateau and sufficient calibration and/or validation information was provided. The selected models are briefly introduced below as the detailed principles of them can be found in Morgan and Nearing (2011) and Morgan and Quinton (2001).

4.2 Specific models

4.2.1 RUSLE and MUSLE

The USLE model was developed by the US Department of Agriculture (USDA) to estimate average annual water erosion (i.e. sheet and rill erosion) based on rainfall erosivity, soil erodibility, slope length, slope gradient, crop management, and erosion control practice (Wischmeier and Smith, 1965, Wischmeier and Smith 1978). The revised USLE (RUSLE) is a systematic improvement of USLE through reviewing the

USLE and its database, data analysis, and fundamental theory (Renard et al., 1991). The modified USLE (MUSLE) has been an attempt to estimate stream sediment yield for individual storms by replacing the rainfall factor with a runoff factor (Williams, 1975, Sadeghi et al., 2013). The CLSE is a localization of USLE for China through incorporating steep slopes and soil conservation measures (Liu et al., 2002).

4.2.2 Zheng's model

Zheng et al. (2008) developed a proportional function for event sediment yield prediction through analyzing the field observations at 12 small catchments over the Loess Plateau. Sediment yield is estimated as a function of runoff depth and a regression coefficient, which represents the mean sediment yield per unit runoff, or mean sediment concentration for all the events considered. Zheng et al. (2011) examined data on 717 flow events observed at 17 gauging stations and two runoff experimental plots in the Dalihe watershed. The event mean sediment concentration was found to increase following a power function with drainage basin area up to about 700 km^2. The proportional model proposed by Zheng et al. (2008) was then updated through deriving the regression coefficient from the power function.

4.2.3 WEPP

The WEPP is a process-based, spatially-distributed model used for runoff and erosion modelling at a field or small catchment scale (< 260 ha) (Laflen et al., 1991, Ascough, 1997), and has a number of updates for different conditions and expansion of capabilities (Flanagan and Livingston, 1995, Flanagan et al., 2007, 2012). Runoff is assumed to occur only if the rainfall excess derived based on the Green & Ampt equation overcomes depression storage. This process also provides the amount of soil infiltration to determine the water balance and crop growth, and influences runoff routing and erosion parameters. The steady-state sediment continuity equation is used to predict rill and interrill processes (Nearing et al., 1989). Rill erosion occurs if the shear stress exerted by flow exceeds the critical shear stress. Interrill erosion is conceptualized as a process of sediment delivery to rills (Tiwari et al., 2000). Detachment, transport and deposition within channels are modelled by the sediment continuity equation.

4.2.4 SWAT

The SWAT is a process-based, spatially-distributed, continuous time soil erosion model originally developed by Arnold et al (1998), and was regularly updated by the USDA (Neitsch et al., 2011) to predict the long-term impact of land management practices on catchment water and sediment yield. The soil water balance equation is the basis for hydrological modelling in SWAT. Surface runoff is estimated by a modified Soil Conservation Service (SCS) curve number equation (USDA, 1972) or the Green & Ampt infiltration method (Green and Ampt, 1911). Runoff flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method. Erosion and sediment yield are estimated with MUSLE (Williams, 1975). Sediment transport is a function of deposition and degradation, which are determined through comparing the sediment concentration and maximum sediment concentration (Neitsch et al., 2011).

4.2.5 MMF

The MMF is a process-based, spatially-distributed model, developed by Morgan et al. (1984) to predict annual soil loss from field-sized areas on hillslopes. The model is composed of a water phase and sediment phase. In the water phase, runoff volume is estimated as an exponential function of rainfall, with a consideration of vegetation interception, topography, soil water storage and routing. In the sediment phase, the MMF estimates rainfall splash via rainfall energy and interception and transport capacity of runoff based on runoff volume, slope gradient and crop management. Annual sediment yield is determined as the lesser of the amount of soil-particle detachment and transport capacity. The MMF model underwent three revisions including integration with GIS (de Jong, 1994) incorporation of flow detachment as well as plant height and leaf drainage for rainfall splash estimation (Morgan, 2001), and incorporation of particle-size selectivity and vegetation cover impacts (Morgan and Duzant, 2008).

4.2.6 DYRIM

The DYRIM is a process-based, spatially-distributed and continuous model developed by Wang et al. (2007) to predict soil erosion and sediment transport for Loess Plateau catchments. Continuous hillslope overland flow (mainly Horton flow) and infiltration are simulated based on soil hydrodynamics theory (Li et al., 2009). Hillslope erosion, including rainsplash erosion, sheet erosion and shallow gully erosion, increases with the reinforced surface flow along the hillslope (Wang et al., 2005b). Gravitational erosion is simulated through considering the balance between the sliding forces and sliding resistance of the soil body (Wang et al., 2005a, Wang et al., 2007, Li et al., 2008). To account for the perceived randomness, fuzzy analysis is applied to assess the probability in which gravitational erosion occurs (Wang et al., 2005a). The sediment routing model is based on the diffusive wave method, assuming a V-shaped channel cross-section (Wang et al., 2007).

4.2.7 WATEM/SEDEM

The WATEM/SEDEM model is a spatially-distributed model originally developed by Van Rompaey et al. (2001) for the prediction of sediment delivery to river channels. The model has three main components: (i) the assessment of the mean annual soil erosion rate based on a two-dimensional RUSLE; (ii) the assessment of a mean annual transport capacity as a function of the potential rill erosion (Desmet and Govers, 1995, Van Oost et al., 2000); (iii) an algorithm that routes the sediment along a continuous flowpath towards the river system, taking into account the topography and transport capacity. The WATEM/SEDEM model has undergone some modifications, including derivation of the transport capacity based on upslope areas and slope gradients to consider gully erosion (Verstraeten et al., 2007), and incorporation of the slope gradient factor proposed by Liu et al., (1994) for steep slope erosion (Zhao et al., 2015).

4.2.8 Tian's model

Tian et al. (2015) developed a process-based, spatially-distributed soil erosion and sediment transport model for the hilly loess region of the Loess Plateau. The model calculates the soil erosion rate and transport capacity for hillslopes, and the final sediment yield entering stream channels equals the lesser of the soil erosion rate and transport capacity. Soil erosion rates on hillslopes are derived from a modified version of RUSLE taking into account the shallow gullies proposed by Jiang et al. (2005). The transport capacity is estimated with the algorithm that Verstraeten et al. (2007) proposed to modify the WATEM/SEDEM model for gully erosion modelling. A trapping efficiency is employed to simulate the impact of check-dams on sediment transport over landscapes.

4.2.9 Si's model

A semi-physical catchment sediment yield model was developed by Si et al. (2015) with modules of hillslope erosion, gully erosion and in-stream transport. The sediment yield from hillslopes is estimated through a balance between hydraulic erosion capacity driven by transport capacity, runoff depth and slope surface area, and soil erosion resistance capacity approximately described with an exponential curve. The sediment concentration resulting from gully erosion is estimated from flow velocity based on the Bagnold's stream power function (Bagnold, 1960). A mass balance is adopted to simulate the sediment transport through a stream section, and its erosion and deposition state. The proposed model is coupled with the Xinanjiang hydrological model developed by Zhao (1984). The model includes an evapotranspiration calculation based on a three-layer soil moisture structure, vertically-mixed runoff production, and slope flow concentration using the Muskingum method (Zhao et al., 1995).

4.2.10 Yang's model

A DEM-based, process-based, spatially-distributed runoff and erosion simulation model was developed by Yang et al. (2012) in order to improve current understanding of soil erosion processes in the Loess Plateau. In the model, overland flow is generated when rainfall intensity is higher than infiltration rate estimated by the Horton infiltration model (Horton, 1939). The generated runoff is then routed with a kinematic wave equation (Tang and Chen, 1997). The soil erosion and transport processes are modelled based on algorithms that use the particular characteristics of loess slopes, gully slopes and stream channels to characterize the unique features of the hilly-gully Loess Plateau (Tang et al., 1990, Tang and Chen, 1997).

5 Comparison of the selected models

5.1 Comparison criteria

Four criteria were employed to evaluate the selected models, with reference to those used in de Vente et al. (2013) and the specific conditions of the Loess Plateau.

(1) Accuracy of the predicted erosion rates/sediment yield evaluated with the coefficient of determination (R^2) and N_{sc} reported in the literature. The R^2 and N_{sc} are given by,

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2} \sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2}} \right)^2$$

$$N_{sc} = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2}$$

where, $\overline{O}$ and $\overline{P}$ are the average of observed (O_i) and predicted (P_i) value respectively. The R^2 lies between zero and one, and N_{sc} ranges from -∞ to one. A value of R^2 and N_{sc} closer to one denotes a higher model accuracy.

(2) Ability to consider the unique characteristics or sediment generation and transport processes on the Loess Plateau

(3) Requirements of input data and calibration efforts to implement the model

(4) Capability of the model used for scenario studies of climate change and land management shifts (including soil and water conservation measures).

Prediction accuracy is widely employed as an indicator of model performance (Morgan and Quinton, 2001, Morgan and Nearing, 2011). R^2 and N_{sc} are commonly-used to assess the prediction accuracy of soil erosion models used on the Loess Plateau. However, models with accurate predictions do not necessarily mean they are suitable for the study areas. As noted by Morgan and Quinton (2001), an analysis on the rationality of soil models is needed to determine whether they are able to (explicitly or implicitly) consider the dominant soil erosion and sediment transport mechanisms of the region. Model users, including policy-makers, are sometimes not aware of the principles behind the models they choose for their study area, and may not have sufficient expertise (Jetten et al., 1999). Therefore convenience for application is important for a model, which can usually be assessed based on the complexity of input data preparation and calibration. The land-use pattern on the Loess Plateau has been undergoing rapid changes driven by large scale vegetation restoration and soil conservation measures (Jiao et al., 2016, Tang, 2004, Feng et al., 2016) and climate change (Sun et al., 2015). Therefore, soil erosion models are needed to estimate soil erosion and sediment yield under contemporary land-use situations, and help determine suitable future land management strategies (including design of conservation strategies) through examining different possible land-use patterns under climate change scenarios (Morgan and Quinton, 2001, Morgan and Nearing, 2011).

5.2 Prediction accuracy

Overall, empirical models produced sound soil erosion rates or sediment yield predictions. MUSLE and Zheng's model were found to produce less satisfactory predictions for low-magnitude events (Wang et al., 2010, Zheng et al., 2008, 2011) (Table 2). Nevertheless, on the Loess Plateau soil loss is dominated by large storms and small storms are less important for the soil loss. Process-based models can be grouped in three categories according to prediction accuracies: (i) Si's model, WEPP and MMF, which satisfactorily predicted sediment yield in previous tests over various temporal and spatial scales (Si's model, event/continuous and hillslopes to large catchments (Si et al., 2015); WEPP, event/annual/continuous and plots/catchments of < 12 km^2 (Wang et al., 2007, 2008, Yu et al., 2009); MMF, annual and medium to large catchments (Li et al., 2010)); (ii) Yang's model and Tian's model, which provided good sediment yield predictions for small and medium-sized catchments at event and annual scales (i.e. Tian's model, annual and medium catchment (Tian et al., 2015); Yang's model, event and small catchments (Yang et al., 2012)) in limited previous tests (i.e. no more than two sites); (iii) WATEM/SEDEM, SWAT and DYRIM, which produced unsatisfactory/unstable predictions. WATEM/SEDEM achieved a negative N_{sc} at a pixel level (Feng et al., 2010), although the modified version soundly estimated annual sediment yield for a small catchment (Zhao et al., 2015). SWAT produced considerably lower sediment yield predictions during validation than those during calibration (Li et al., 2010b, Qiu et al., 2012, Zuo et al., 2016), while DYRIM produced unstable results (Li et al., 2008, Li et al., 2009).

Some of the selected models have been applied to the same catchments including Lvergou, Chabagou and Huangfuchuan (Table 2). For the Lvergou catchment, MUSLE appeared to provide a higher validation R^2 than WEPP. For the Chabagou catchment, Yang's model produced more stable validation N_{sc} than DYRIM, and the calibration R^2 produced by Zheng's model was always higher than 0.9. However, it should be noted Yang's model was validated at the outlet of the Chabagou, while DYRIM was validated for subcatchments of the Chabagou. For the Huangfuchuan catchment, the validation N_{sc} of Si's model was much higher than that of SWAT and Tian's model. The SWAT model gave higher calibration R^2 and N_{sc} but lower validation results than Tian's model.

Process-based models theoretically have a greater transferability than empirical models, and are thus more likely to achieve sound predictions when applied to other places (Wainwright and Mulligan, 2013). However, for the Loess Plateau empirical models such as RUSLE and MUSLE could produce sound predictions, and process-based models such as SWAT and DYRIM sometimes produced unsatisfactory results (Table 2). This demonstrates that more complex models do not necessarily yield better predictions than simpler models (Beven and Binley, 1992).

It should be noted that the above comparison results are not absolute because of the following reasons: (i) modelling studies listed in Table 2 cover a wide range of spatial and temporal scales, varying from plots to the whole of the Loess Plateau and from storm events to multi-year scales; (ii) the spatial resolution and time-step used by the models are different; (iii) most models were evaluated with field records from different sites. For those tested for the same catchments, field data were usually collected at different time periods. Hence, the environmental conditions for testing are different among the models. (iv) some models were tested with total sediment yield (e.g. RUSLE, WATEM/SEDEM), while others were tested with suspended sediment measurements. Suspended sediment measurements are subject to several shortcomings. First, bedload is not included which contributes a considerable proportion of total sediment yield from steep slopes and river channels (Shi et al., 2012). Second, their accuracy is impacted by the time interval of sampling. Third, given that data is usually collected for a limited period such models tested with suspended sediment measurements may not be able to capture extreme events (de Vente et al., 2013), which are common on the Loess Plateau in summer months (i.e. July-September).

The soil erosion models studied were usually tested through comparing sediment yield predictions and measurements (Table 2). Measurements of the internal processes driving the production and routing of sediment tended to not be well assessed against field data for those processes. It may be that the model predicts reasonable runoff discharge and sediment yield based on incorrect mechanisms, and many different parameter sets might result in equal model performance (Qiu et al., 2012, Yang et al., 2012). An internal validation of the models is thus desirable. However, we also need to improve our understanding of the underlying mechanisms of erosion processes and the relative importance of them on the Loess Plateau. Sediment budget studies may help fulfil this need (Evans et al., 2006, Evans and Warburton, 2005). The majority of the model tests and sensitivity analyses were outlet based, where either sedigraphs were compared with measured data, or the models were used to predict future events. There were few studies that compared simulated soil erosion patterns with observed soil erosion patterns on the Loess Plateau (e.g. Li et al., 2008, 2009, Feng et al., 2010).

5.3 Process representation

Among the selected empirical models, Zheng's model is capable of implicitly representing all the erosion processes for its study catchments. RUSLE and its modifications are often incorporated into process-based models to account for sediment generation from hillslopes or small sub-catchments (e.g., SWAT, WATEM/SEDEM and Tian's model). All of the process-based models selected only look at a selection of soil erosion processes, no models involve all the erosion processes. All of them involve hillslope erosion and transport, while only some of them estimate deposition (i.e. WEPP, MMF, WATEM/SEDEM and Tian's model). WEPP, SWAT, DYRIM, Si's model and Yang's model include channel routing, but only WEPP, SWAT and Si's model simulate channel sediment deposition. Combined, WEPP involves the detachment-transport-deposition processes of hillslopes and stream channels. So it has more potential application for studies that investigate the source and sink of the sediment within a catchment. However, the WEPP model does not take account of gully erosion. Although pipeflow could be partly represented by simulations as a form of rapid flow that might be similar in some ways to overland flow (Li et al., 2016b), several aspects of pipeflow that affect the runoff and final sediment yield cannot be dealt with by current Loess Plateau models. These include different Manning's n, different slope and distance to catchment outlets caused by tortuous pipeflow and additional soil loss due to the erosion of pipe walls and the collapse of pipe roofs. Therefore, pipe erosion is not explicitly accounted for by any of the models selected in our paper. Compared to WEPP, other process-based models (i.e. SWAT, MMF, DYRIM, WATEM/SEDEM, Tian's model, Si's model and Yang's model) may only be appropriate for the identification of sediment sources because they do not simulate hillslope deposition or channel deposition (Table 1). Si's model is spatially lumped, limiting its use for sediment source detection (Table 1). Most of the selected models focus on the event and catchment scale such as WEPP, SWAT, DYRIM, Si' model and Yang's model, and they involve processes on land surfaces and stream channels. Models that were developed for the long-term and/or regional scale use such as MMF, WATEM/SEDEM and Tian's model concentrate on eroded materials generated on hillslopes and their delivery to stream channels and channel routing is not accounted for.

A high density of deep and wide gullies, steep slopes and hyperconcentrated flow are three key features of the Loess Plateau, which need to be addressed by soil erosion models (Stolte et al., 2003, Wang et al., 2007, Hessel and Jetten, 2007, Hessel, 2006, Poesen et al., 2011). In the selected models, Si's model, Yang's model and the modified WATEM/SEDEM take account of gully erosion (Yang et al., 2012, Si et al., 2015). DYRIM is capable of simulating gravitational erosion on gully slopes in a stochastic way, providing estimates of the probability of the occurrence of gravitational erosion (Wang et al., 2005a, Wang et al., 2007, Li et al., 2008). Slope stability models may also be useful to predict the collapse of gully heads on the Loess Plateau (Hessel and van Asch, 2003). Unfortunately, the selected models do not either distinguish the ephemeral gullies from permanent gullies or consider the initiation and evolution of gullies (or rills). A landform evolution model (e.g. Coulthard, 2001), which simulates changing terrain induced by catastrophic soil erosion, sediment transport and deposition, may be useful to include the development of gullies through time. None of the models simulate interactions between gullies and other hydrological or erosion processes such as pipe erosion (Poesen et al., 2011).

Among the selected models, WEPP is the only one that explicitly incorporates rill and interrill erosion processes (Laflen et al., 1991). WEPP is capable of simulating sediment yield from steep slopes (> 20°) (Wang et al., 2008). SWAT, WATEM/SEDEM and Tian’s model predict sediment generation with RUSLE or MUSLE, which was originally developed for gently-sloping (< 20°) land areas. A method for calculation of a steep slope factor proposed in CSLE (Liu et al., 2002) has often been incorporated into these models to implicitly account for sediment production from steep slopes (e.g. gully walls). Zheng’s model, Yang’s model, Si’s model and DYRIM are specifically developed for the Loess Plateau, meaning that they ought to include factors associated with steep sloping conditions from the outset (Wang et al., 2007, Zheng et al., 2008, Yang et al., 2012, Si et al., 2015). However, only Yang’s model and Si’s model explicitly simulate sediment erosion on steep slopes (e.g. gully walls).

It has been demonstrated that, for a highly erodible region like the Loess Plateau, a transport capacity term is particularly necessary for soil erosion models (Guo et al., 2014, Hessel and Jetten, 2007). For example, DYRIM lumps hillslope erosion (rainsplash, rills and shallow gullies) together, and the sediment transport capacity is not involved, leading to an ever-increasing rate of soil erosion per unit area as a function of the slope length (Guo et al., 2014). An improved hillslope erosion module has been developed to include the transport capacity term, and will be incorporated into DYRIM (Guo et al., 2014). Meanwhile, the behaviour of hyperconcentrated flow is quite different from that of clear water because of increased fluid density, viscosity and velocity resulting from increased sediment concentration, while steep slopes often lead to a sudden sediment deposition when slope angles decrease abruptly (Hessel et al., 2003a). As a result, sediment transport algorithms that are commonly used in soil erosion models may be challenged when applied to the Loess Plateau (Hessel and Jetten, 2007). Hessel and Jetten (2007) demonstrated that the Govers equation (Govers, 1990) that is employed by LISEM performed better for the Loess Plateau than other widely-used equations including the one that underpins the sediment transport in WEPP (i.e. Yalin equation, Yalin, 1963). Further testing of sediment transport equations incorporated in soil erosion models is desirable.

5.4 Input data and calibration requirements

Unlike empirical models, process-based models usually require extensive input data and calibration effort (Table 3). This inevitably limits their applications to large areas or areas without sufficient data support. Low input data requirements and calibration needs allow empirical models to run over a large region such as the Loess Plateau. On the other hand, process-based models rather than empirical models are capable of reproducing different components of soil erosion and transport processes, and can therefore provide model users with detailed information on the evolvement of soil erosion processes.

Among the process-based models, input data requirements for the ones simulating a water balance (i.e. WEPP, SWAT, MMF, DYRIM, Si's model and Yang's model) are generally higher than those deriving soil erosion directly based on rainfall (WATEM/SEDEM and Tian's model). However, the number of calibration parameters for the former ones is not always higher than that for the latter ones. Calibration strategies may be different when applying a process-based model to different sites. For example, the number of calibration parameters in SWAT and WATEM/SEDEM varied in the selected studies (Table 3). Moreover, continuous simulation models may have a larger input data requirement, particularly information about meteorological conditions, than event models. This is because continuous models continuously recalculate the water and sediment balance over a long-term period to determine the starting conditions of each storm, while event models only simulate short-term responses based on assumptions about the starting conditions of each event, particularly soil moisture (Morgan and Quinton, 2001).

Climate (e.g. precipitation and temperature), topographic information, land use and vegetation cover and soil properties are widely recognized as basic inputs for soil erosion and transport models (Chen et al., 2001, Chen et al., 2006). Errors in these input parameters are often considered as the main source of uncertainties surrounding model predictions, particularly for those of process-based models (Quinton, 1997). However, the resolution and representativeness of the input data are also important sources of the uncertainty.

Topographic characteristics such as slope gradient and slope aspect determine not only the energy driving the flow of runoff and sediment but also the direction of runoff and sediment flow. This is particularly important for the case of the soil erosion modelling for the Loess Plateau, which is topographically complex (Liu et al., 1994, Liu et al., 2000, Wang et al., 2007). Digital elevation models (DEM) are now a widely-applied means for the derivation of topographical characteristics. The highest resolution of DEM for the selected modelling studies is 5 m (Table 2), which also represents the finest resolution in soil erosion modelling for the Loess Plateau. This resolution is sufficiently fine to capture the majority of topographical changes (e.g. slope length, slope gradient), gullies and drainage networks. However, the width of rills and shallow gullies is often less than 5 m over the Loess Plateau, which means most of the current modelling practices are subject to inaccuracy resulting from the resolution of the DEM.

Changes in vegetation coverage of the Loess Plateau can be quantitatively assessed via remote sensing-derived Normalized Difference Vegetation Index (NDVI) (Sun et al., 2015, Sun et al., 2014, Jiao et al., 2016) or the vegetation growth module incorporated into the soil erosion models (e.g. SWAT, WEPP). However, the temporal dynamics of land-use patterns on the plateau are difficult to represent during soil erosion modelling. Moreover, the spatial resolution of land use and vegetation coverage data is often not sufficiently fine to capture small-scale changes in ground cover conditions. For example, the spatial resolution of the NDVI data for the Loess Plateau is usually greater than 1 km (Jiao et al., 2016, Wang et al., in press). Therefore, it is possible to improve the accuracy of model predictions through increasing the resolution of input data. For example, fine-resolution DEMs, such as those derived from light detection and ranging technologies (LIDAR) (Harpold et al., 2015), can be useful for the modelling of detailed geomorphological processes (e.g. rills). However, finer-resolution input data requires more computational resources, limiting the applications of the models over regions. Therefore, it is advisable to seek a balance between the accuracy of input data and the convenience for model implementation.

In Loess Plateau soil erosion modelling (e.g. Zhao et al., 2015, Tian et al., 2015), soil properties determined through field sampling at certain sites were usually used over the whole study area. Although these data are accurate for the specific sampling sites, it is not clear how representative they are for other sites or for the study area as a whole. The climate condition (e.g. rainfall and temperature) over the study region is often represented by measurements at single stations (e.g. Zhao et al., 2015, Si et al., 2015) or interpolated results based on measurement from several stations (e.g. Li et al., 2010a, Sun et al., 2014). The former approach ignores spatial differences in climate conditions. The accuracy of the latter is limited by the distribution and density of gauging stations as well as the interpolation method which often does not consider the impact of topography on climate conditions.

5.5 Potential for application in scenario studies

WEPP, SWAT, MMF, DYRIM, Si’s model and Yang’s model may be suitable for assessing the impacts of climate change, land-use shifts and land management practices, given that these models simulate a water balance (Bathurst, 2011). However, Si’s model is spatially-lumped, and is not capable of simulating the spatial pattern of erosional response to climate shifts and land-use/management change over a large area. The impacts of terraces and check-dams are often not explicitly accounted for by contemporary erosion models mainly because the feedback of conservation measures to hydrological processes (Mu et al., 2007) largely increases the complexity of erosion-transport-deposition processes (de Vente et al., 2013). As noted above, although finer-resolution DEMs (e.g. LIDAR DEMs) may provide a way of modelling these processes, the dramatic increase in computational demand may largely offset their practicability. Hence models capable of simulating these processes in alternative ways are still desirable. SWAT and WEPP take reservoirs into account (Neitsch et al., 2011, Zhang et al., 2004), and Tian's model (although not simulating a water balance) considers the sediment trapped by check-dams via a trapping efficiency (Tian et al., 2015). They are therefore potentially useful for examining the impact of check-dams. A process-based terrace algorithm has been developed and incorporated into SWAT to make the model capable of modelling terraces (Shao et al., 2013).

6 Model selection

While the above comparisons provide a useful reference for soil erosion model selection for the Loess Plateau, a good understanding of research objectives in using a model is always fundamental to model selection. This is because each model is developed to address specific research questions. As Morgan (2011) pointed out, the first step of model development is to set a clear objective, including research aims (or questions) that the model addresses, temporal and spatial scales that the model works on, the output (e.g. rates/location of erosion/deposition) produced by the model, and the level of prediction accuracy required. In order to choose a suitable model, model users need to make sure that their research objectives can be met by the candidate model. The priority of the above four criteria may change during model selection for different research objectives. For example, the prediction accuracy of models may not be the top priority when a model application focuses on determining the source and sink of sediment over a region rather than predicting soil erosion rates/sediment yields.

Soil erosion models are usually developed for particular environments, which means they only involve (explicitly or implicitly) erosion processes that are important in those environments based on various assumptions and simplifications (Favis-Mortlock et al., 2001). For example, among the models taking account of sediment movement over landscapes, those specifically developed for the Loess Plateau condition generally include gully erosion such as Si's, Yang's and Tian's model, while those initially developed for other regions do not such as WEPP and SWAT. Process descriptions in contemporary erosion models are often subject to empiricism making them more locally relevant, but not necessarily globally appropriate (Merritt et al., 2003, Morgan and Quinton, 2001). For example, among the selected models, those developed outside the Loess Plateau are usually not capable of simulating the unique characteristics and processes on the Loess Plateau (e.g. steep slopes). Adaptations are therefore needed to loosen the boundary conditions and make the model applicable to the Loess Plateau. For example, USLE-based models (e.g. RUSLE, MUSLE, SWAT, WATEM/SEDEM and Tian's model) were not developed for steep-sloping conditions, but the incorporation of the steep slope factors of CLSE (Liu, 2002) ensured their applicability to the Loess Plateau. WATEM/SEDEM was also modified to include gully erosion (Verstraeten et al., 2007, Zhao et al., 2015).

If an inappropriate model is used and does not work, it is the fault of the user not the model. Table 4 synthesises which models are considered most effective and efficient to answer specific research questions at specific spatial and temporal scales for the Loess Plateau, and the environments which the models are considered to be suitable for based on a combination of the comparisons in section 5 and the nature of the models. Although not all possible research needs are covered, this table represents an attempt to help model users select a suitable model.

7 Future improvements to Loess Plateau soil erosion models

In terms of the model comparison and discussion in section 5, further improvement of the Loess Plateau soil erosion models should concentrate on the following three aspects:

(i) More work should be done to improve the quality of sediment yield data (e.g. including bedload), the spatial resolution of DEMs and vegetation coverage data, the spatial-temporal resolution of land-use data, and the representativeness of soil and climate data. Meanwhile, modellers should bear in mind that the finer resolution of input data means increased computational needs and decreased practicability. It is therefore advisable to balance the resolution of the input data against the convenience for model implementation.

(ii) Future development of soil erosion models should concentrate on the improvement of process-based models in the following aspects: (a) separate simulation of rill and interrill erosion, (b) incorporation of gully and rill initiation and evolvement, (c) incorporation of gravitational erosion via stochastic modelling or slope stability models, (d) explicit simulation of soil erosion on steep slopes, (e) further evaluation of contemporary sediment transport equations, (f) incorporation of pipe erosion, (g) explicit incorporation of soil and water conservation measures (e.g. check-dams, terraces). The suggested priorities for future development of process-based models are not universal since dominant processes are not always the same for models with different research aims and scales (Morgan and Quinton, 2001, Morgan, 2011). For example, a detailed representation of rill initiation and evolvement is important for short-term, hillslope or catchment scale models but it may not be necessary or even problematic for a long-term, large spatial scale model.

So a scheme is needed to help determine the representation of different processes in a model to avoid over-detailed or over-simplified representation of processes. The framework introduced in Favis-Mortlock et al. (2001) may be valuable for this need. It classifies processes of a system into three time scales, which are fast, dynamic and slow processes, and prescribes a suitable modelling approach for each process. Fast processes occur much faster than the time resolution of observations or model time-step, dynamic processes occur on a similar time scale to observations or model time-step, and slow processes occur much slower than the duration of observations or simulation. In the models, fast processes are represented using constant values or statistically-derived values, dynamic processes are represented directly, and slow processes are parameterized as a constant value.

(iii) For model evaluation, models capable of addressing the same research questions in terms of Table 4 should be compared against each other for the same datasets. An internal and spatial validation of the models is also needed.

8 Conclusions

This study compared eleven soil erosion models for the Loess Plateau based on their prediction accuracy, process representation, data requirements and calibration needs, and potential for use in scenario studies. The comparison showed that the prediction accuracy did not increase with the complexity of the model. Empirical models are useful for a quick assessment of soil erosion rates and sediment yields over an area, while process-based models can be used for detailed soil erosion and sediment yield assessments including determination of sediment sources and sinks and scenario analysis. The process-based models we compared can be grouped into three categories: (1) Si’s model, WEPP and MMF produced satisfactory predictions. (2) Yang’s model and Tian’s model produced fairly good predictions but may need further evaluation for wider use. (3) WATEM/SEDEM, SWAT and DYRIM produced less satisfactory/unstable predictions for the Loess Plateau. Si's model was able to accurately predict event/continuous sediment yield at spatial scales ranging from hillslope to large catchments. WEPP is a powerful tool for simulating event/annual soil erosion rates at the hillslope scale and continuous sediment yield at the small catchment scale. MMF is most promising for accurate annual sediment yield predictions for medium to large catchments. However, it should be noted that some of the selected models were tested with total sediment load while others were tested with suspended sediment load (i.e. bedload is not included), which is subject to several drawbacks. The preferred research questions that each of the selected models can address were identified through a combined consideration of model comparisons based on the four criteria and the nature of the models. Further improvement of soil erosion models for the Loess Plateau should concentrate on enhancing the quality of data for model implementation and testing improving process representations in the contemporary process-based models in terms of their aims and scales, and comparing models capable of addressing the same research questions, and implementing internal and spatial testing.

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References

Aksoy, H., Kavvas, M.L., 2005. A review of hillslope and watershed scale erosion and sediment transport models. Catena. 64, 247-271.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development. Journal of the American Water Resources Association. 34, 73-89.

Ascough, J.C. II, Baffaut, C., Nearing, M.A., Liu, B.Y., 1997. The WEPP watershed model: I. Hydrology and erosion. Transactions of American Society of Agricultural Engineers. 40, 921-934.

Bagnold, R.A., 1960. Sediment discharge and stream power--A preliminary announcement. US Geological Survey, Virginia.

Bathurst, J.C, 2011. Predicting impacts of land use and climate change on erosion and sediment yield in river basins using SHETRAN, in: Morgan, R.P.C., Nearing, M.A. (eds), Handbook of Erosion Modelling. Wiley-Blackwell Publishing Ltd., New Jersey, pp. 263-288.

Bennett, J.P., 1974. Concepts of mathematical modeling of sediment yield. Water Resources Research. 10, 485-492.

Beven, K., Binley, A., 1992. The future of distributed models: model calibration and uncertainty prediction. Hydrological Processes. 6, 279-298.

Beven, K.J., Wood, E.F., Sivapalan, M., 1988. On hydrological heterogeneity – catchment morphology and catchment response. Journal of Hydrology. 100, 353-375.

Cai, Q., 2001. Soil erosion and management on the Loess Plateau. Journal of Geographical Sciences. 11, 53-70.

Cai, Q., Lu, Z., Wang, G., 1996. Process-based soil erosion and sediment yield model in a small basin in the hilly loess region. Acta Geographica Sinica. 51, 108-117. (in Chinese with English abstract)

Chen, C., Tsai, C., Tsai, C., 2006. Simulation of sediment yield from watershed by physiographic soil erosion-deposition model. Journal of Hydrology. 327, 293-303.

Chen, L., Wang, J., Fu, B., Qiu, Y., 2001. Land-use change in a small catchment of northern Loess Plateau, China. Agriculture, Ecosystems & Environment. 86, 163-172.

Chen, L., Wei, W., Fu, B., Lv, Y., 2007. Soil and water conservation on the Loess Plateau in China: review and perspective. Progress in Physical Geography. 31, 389-403.

Chu, S.T., 1978. Infiltration during an unsteady rain. Water Resources Research. 14, 461-466.

Coulthard, T., 2001. Landscape evolution models: a software review. Hydrol. Process. 15, 165-173.

de Jong, S.M., 1994. Applications of reflective remote sensing for land degradation studies in a Mediterranean environment. Netherlands Geographical Studies, 177.

de Roo, A., 1996. Validation problems of hydrologic and soil-erosion catchment models: examples from a Dutch erosion project, In: Anderson, M.G., Brooks, S.M. (eds.), Wiley, Chichester, pp. 669-683.

de Roo, A., Jetten, V., 1999. Calibrating and validating the LISEM model for two data sets from the Netherlands and South Africa. Catena. 37, 477-493.

de Vente, J., Poesen, J., 2005. Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models. Earth-Science Reviews. 71, 95-125.

de Vente, J., Poesen, J., Verstraeten, G., Govers, G., Vanmaercke, M., Van Rompaey, A., Arabkhedri, M., Boix-Fayos, C., 2013. Predicting soil erosion and sediment yield at regional scales: Where do we stand? Earth-Science Reviews. 127, 16-29.

de Vente, J., Poesen, J., Verstraeten, G., Van Rompaey, A., Govers, G., 2008. Spatially distributed modelling of soil erosion and sediment yield at regional scales in Spain. Global and Planetary Change. 60, 393-415.

de Vries, F.T., Liiri, M.E., Bjornlund, L., Bowker, M.A., Christensen, S., Setala, H.M., Bardgett, R.D., 2012. Land use alters the resistance and resilience of soil food webs to drought. Nature Climate Change. 2, 276-280.

Desmet, P.J.J., Govers, G., 1995. GIS-based simulation of erosion and deposition patterns in an agricultural landscape: a comparison of model results with soil map information. Catena 25, 389–401.

Dun, S., Wu, J.Q., Elliot, W.J., Robichaud, P.R., Flanagan, D.C., Frankenberger, J.R., Brown, R.E., Xu, A.D., 2009. Adapting the Water Erosion Prediction Project (WEPP) Model for forest applications. Journal of Hydrology, 366, 45–54.

Evans, M., Warburton, J., 2005. Sediment budget for an eroding peat-moorland catchment in northern England. Earth Surface Processes and Landforms. 30, 557-577.

Evans, M., Warburton, J., Yang, J., 2006. Eroding blanket peat catchments: Global and local implications of upland organic sediment budgets. Geomorphology. 79, 45-57.

Fan, R., 1985. Study on formula for computation of soil loss from small watershed on the middle reaches of the Huanghe River. Soil and Water Conservation in China. 35, 12-18. (in Chinese with English abstract)

Favis-Mortlock, D., Boardman, J., MacMillan, V., 2001. The limits of erosion modeling-why we should proceed with care, In: Harmon, R.S., Doe III, W.W. (eds), Landscape erosion and evolution modeling. Kluwer Academic/Plenum Publisher, New York, pp. 477-516.

Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lv, Y., Zeng, Y., Li, Y, Jiang, X., 2016. Revegetation in China’s Loess Plateau is approaching sustainable water resource limits. Nature Climate Change. doi:10.1038/nclimate3092.

Feng, X., Wang, Y., Chen, L., Fu, B., Bai, G., 2010. Modeling soil erosion and its response to land-use change in hilly catchments of the Chinese Loess Plateau. Geomorphology. 118, 239-248.

Flanagan, D., Frankenberger, J., Ascough, J., 2012. WEPP: Model use, calibration, and validation. Transactions of the the American Society of Agricultural and Biological Engineers. 55, 1463-1477.

Flanagan, D., Gilley, J.E., Franti, T.G., 2007. Water Erosion Prediction Project (WEPP): Development history, model capabilities, and future enhancements. Transactions of the American Society of Agricultural and Biological Engineers. 50, 1603-1612.

Flanagan, D., Livingston, S.J., 1995. Water Erosion Prediction Project: User Summary. US Department of Agriculture, Washington.

Fu, B., 1989. Soil erosion and its control in the Loess Plateau of China. Soil Use and Management. 5, 76-82.

Gong, S., 1988. Particular features of soil erosion on the Loess Plateau of the Yellow River valley. Soil and Water Conservation in China. 78, 4-11+64. (in Chinese with English abstract)

Govers, G., 1990. Empirical relationships for the transport capacity of overland flow. IAHS Publication. 189, 45-63.

Graham, D.N., Butts, M.B., 2005. Flexible, integrated watershed modelling with MIKE-SHE, in: Singh, V.P., Frevert, D.K. (eds), Watershed models. CRC Press Inc., Florida, pp. 245-272.

Green, W.H., Ampt, G., 1911. Studies on soil physics part1: The flow of air and water through soils. Journal of Agricultural Science. 4, 1-24.

Guo, D., Yu, B., Fu, X., Li, T., 2014. Improved hillslope erosion module for the Digital Yellow-River Model. Journal of Hydrologic Engineering. 20, C4014011.

Guo, M., Wang, W., Li, J., Zhu, B., Shi, Q., 2015. Effect of tillage on runoff and sediment yields and morphology development characteristic of ephemeral gully in loessial region. Transactions of the Chinese Society of Agricultural Engineering. 31, 114-123. (in Chinese with English abstract)

Harpold, A.A., Marshall, J.A., Lyon, S.W., Barnhart, T.B., Fisher, B.A., Donovan, M., Burbaker, K.M., Crosby, C.J., Glenn, N.F., Glennie, C.L., Kirchner, P.B., Lam, N., Mankoff, K.D., McCreight, J.L., Molotch, N.P., Musselman, K.N., Pelletier, J., Russo, T., Sangireddy, H., Sjoberg, Y., Swetnam, T., West, N., 2015. Laser vision: lidar as a transformative tool to advance critical zone science. Hydrology and Earth System Sciences. 19, 2881-2897.

Han, X., Qian, J., Wang, L., Liu, F., Mao, Z., 2012. Progress in studying multi-scale process of soil erosion (water erosion) and soil conservation in the Loess Plateau. Journal of Glaciology and Geocryology. 34, 1487-1498. (in Chinese with English abstract)

Hesse, R., 2002. Modelling soil erosion in a small catchment on the Chinese Loess Pleateau. PhD thesis, Utrecht University.

Hessel, R., 2006. Consequences of hyperconcentrated flow for process-based soil erosion modelling on the Chinese Loess Plateau. Earth Surface Processes and Landforms. 31, 1100-1114.

Hessel, R., Jetten, V., 2007. Suitability of transport equations in modelling soil erosion for a small Loess Plateau catchment. Engineering Geology. 91, 56-71.

Hessel, R., Jetten, V., Liu, B., Zhang, Y., Stolte, J., 2003a. Calibration of the LISEM model for a small Loess Plateau catchment. Catena. 54, 235-254.

Hessel, R., Messing, I., Liding, C., Ritsema, C., Stolte, J., 2003b. Soil erosion simulations of land use scenarios for a small Loess Plateau catchment. Catena. 54, 289-302.

Hessel, R., Van Asch, T., 2003. Modelling gully erosion for a small catchment on the Chinese Loess Plateau. Catena. 54, 131-146.

Holden, J., Shotbolt, L., Bonn, A., Burt, T., Chapman, P., Dougill, A., Fraser, E., Hubacek, K., Irvine, B, Kirkby, M., 2007. Environmental change in moorland landscapes. Earth-Science Reviews. 82, 75-100.

Holden, J., Smart, R., Chapman, P., Baird, A., Billett, M., 2009. The role of natural soil pipes in water and carbon transfer in and from peatlands, In*:* BAIRD, A.J., LISA, R., BELYEA,X., REEVE, A., SALTER, L. (eds.), Carbon Cycling in Northern Peatlands. American Geographical Union, Washington D.C., pp. 251-264.

Holden, J., Smart, R.P., Dinsmore, K., Baird, A., Bollett, M., Chapman, P., 2012. Natural pipes in blanket peatlands: major point sources for the release of carbon to the aquatic system. Global Change Biology. 18, 3568-3580.

Horton, R.E., 1939. Analysis of runoff-plot experiments with varying infiltration capacity. Eos, Transactions American Geophysical Union. 20, 693-711.

Jetten, V., de Roo, A., Favis-Mortlock, D., 1999. Evaluation of field-scale and catchment-scale soil erosion models. Catena. 37, 521-541.

Jetten, V., Govers, G., Hessel, R., 2003. Erosion models: quality of spatial predictions. Hydrological Processes. 17, 887-900.

Jia, Y., Zheng, F., Yang, Q., 2005. Distributed water erosion prediction model for small watershed in Loess Plateau. Shuili Xuebao. 36, 328-332. (in Chinese with English abstract)

Jiang, Z., Zheng, F., Wu, M., 2005. Prediction model of water erosion on hilslopes. Journal of Sediment Research. 1-6. (in Chinese with English abstract)

Jiao, Q., Li, R., Wang, F., Mu, X., Li, P., An, C., 2016. Impacts of re-vegetation on surface soil moisture over the Chinese Loess Plateau based on remote sensing datasets. Remote Sensing. 8, 156.

Jin, X., Hao, Z., Zhang, J., Wang, J., 2008. Distributed soil erosion model with the effect of gravitational erosion. Advances in Water Science. 19, 257-263. (in Chinese with English abstract)

Laflen, J., Lane, L., Foster, G., 1991. WEPP: A new generation of erosion prediction technology. Journal of Soil and Water Conservation. 46, 34-38.

Lal, R., 1994. Soil erosion research methods. CRC Press Inc., Columbus.

Li, C., Qi, J., Feng, Z., Yin, R., Guo, B., Zhang, F., Zou, S., 2010a. Quantifying the effect of ecological restoration on soil erosion in China's Loess Plateau region: an application of the MMF approach. Environmental Management. 45, 476-87.

Li, C., Qi, J., Feng, Z., Yin, R., Zou, S., Zhang, F., 2010b. Parameters optimization based on the combination of localization and auto-calibration of SWAT model in a small watershed in Chinese Loess Plateau. Frontiers of Earth Science in China. 4, 296-310.

Li, P., Holden, J., Irvine, B., 2016a. Prediction of blanket peat erosion across Great Britain under environmental change. Climatic Change. 134, 177-191.

Li, P., Holden, J., Irvine, B., Grayson, R., 2016b. PESERA-PEAT: a fluvial erosion model for blanket peatlands. Earth Surface Processes and Landforms. 41, 2058-2077.

Li, P., Holden, J., Irvine, B., Mu, X., 2017a. Spatial variability of fluvial blanket peat erosion rates for the 21st Century modelled using PESERA-PEAT. Catena. 150, 302-316.

Li, P., Holden, J., Irvine, B., Mu, X., 2017b. Erosion of Northern Hemisphere blanket peatlands under 21st-century climate change. Geophysical Research Letters. 44. doi: 10.1002/2017GL072590

Li, T., Wang, G., Huang, Y., Fu, X., 2009. Modeling the process of hillslope soil erosion in the Loess Plateau. Journal of Environmental Informatics. 14, 1-10.

Li, T., Wang, G., Zhang, C., Xue, H., 2008. Simulation of gravitational erosion in river basins on Loess Plateau. Journal of Tianjin University. 41, 1136-1140. (in Chinese with English abstract)

Li, Z., Liu, W.Z., Zhang, X.C., Zheng, F.L., 2011. Assessing the site-specific impacts of climate change on hydrology, soil erosion and crop yields in the Loess Plateau of China. Climatic Change. 105, 223-242.

Liu, B., Nearing, M., Risse, L., 1994. Slope gradient effects on soil loss for steep slopes. Transactions of the American Society of Agricultural Engineers. 37, 1835-1840.

Liu, B., Nearing, M., Shi, P., Jia, Z., 2000. Slope length effects on soil loss for steep slopes. Soil Science Society of America Journal. 64, 1759-1763.

Liu, B., Zhang, K., Xie, Y., 2002. An empirical soil loss equation, in: Proceedings of 12th International Soil Conservation Organization Conference, volume III. Tsinghua University Press, Beijing, pp. 21-25.

Loch, R., Silburn, D., 1996. Constraints to sustainability-soil erosion, in: Clarke, L., Wylie, P.B. (eds), Sustainable crop production in the sub-tropics: an Australian perspective. QDPI.

Meng, Q., 1997. Soil and water conservation of Loess Plateau. Yellow River Water Conservancy Press, Zhengzhou. (in Chinese)

Merritt, W.S., Letcher, R.A., Jakeman, A.J., 2003. A review of erosion and sediment transport models. Environmental Modelling & Software. 18, 761-799.

Morgan, R.P.C., 2001. A simple approach to soil loss prediction: a revised Morgan–Morgan–Finney model. Catena. 44, 305-322.

Morgan, R.P.C., 2001. Model development: a user’s perspective, In: Morgan, R.P.C., Nearing, M.A. (eds), Handbook of erosion modeling. Wiley-Blackwell, Chichester, pp. 9-32.

Morgan, R.P.C., Duzant, J, 2008. Modified MMF (Morgan–Morgan–Finney) model for evaluating effects of crops and vegetation cover on soil erosion. Earth Surface Processes and Landforms. 33, 90-106.

Morgan, R.P.C., Morgan, D., Finney, H., 1984. A predictive model for the assessment of soil erosion risk. Journal of Agricultural Engineering Research. 30, 245-253.

Morgan, R.P.C., Nearing, M.A. (Eds.), 2011. Handbook of erosion modelling. Wiley-Backwell, Chichester.

Morgan, R.P.C., Quinton, J., 2001. Erosion modeling, In: Harmon, R.S., Doe III, W.W. (eds.), Landscape erosion and evolution modeling. Kluwer Academic/Plenum Publishers, New York, pp. 117-143.

Morgan, R.P.C., Quinton, J., Smith, R., Govers, G., Poesen, J., Auerswald, K., Chisci, G., Torri, D., Styczen, M., 1998. The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. Earth Surface Processes and Landforms. 23, 527-544.

Mu, X., Zhang, L., McVicar, T.R., Chille, B., Gao, P., 2007. Analysis of the impact of conservation measures on stream flow regime in catchments of the Loess Plateau, China. Hydrological Processes. 21, 2124-2134.

Nash, J., Sutcliffee, J., 1970. River flow forecasting through conceptual models part I--A discussion of principles. Journal of Hydrology. 10, 282-290.

NDRC, MWR, MA, SFA. National Development and Reform Commission, Ministry of Water Resources, Ministry of Agriculture, State Forestry Administration, People’s Republic of China, 2010. Programming for comprehensive management of the Loess Plateau (2010-2030). 69, 8-10.

Nearing, M., Foster, G., Lane, L., Finkner, S., 1989. A process-based soil erosion model for USDA-Water Erosion Prediction Project technology. Trans. ASAE. 32, 1587-1593.

Neitsch, S., Arnold, J., Kiniry, J., Williams, J., King, K., 2011. SWAT2009 theoretical documentation. Texas Water Ressources Institute, Texas.

Oldeman, L., 1994. The global extent of soil degradation, In: ISRIC Bi-Annual Report 1991-1992. ISRIC, Netherlands, pp. 19-36.

Pawson, R., Evans, M., Allott, T., 2012. Fluvial carbon flux from headwater peatland streams: significance of particulate carbon flux. Earth Surface Processes and Landforms. 37, 1203-1212.

Pimentel, D., 2006. Soil erosion: a food and environmental threat. Environment, development and sustainability. 8, 119-137.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., Mcnair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., 1995. Environmental and economic costs of soil erosion and conservation benefits. Science-AAAS-Weekly Paper Edition. 267, 1117-1122.

Poesen, J.W.A., Torri, D.B., Vanwalleghem, T., 2001. Gully erosion: Procedures to adopt when modelling soil erosion in landscapes affected by gullying, In: Morgan, R.P.C., Nearing, M.A. (eds), Handbook of erosion modeling. Wiley-Blackwell, Chichester, pp. 360-386.

Pye, K., Sherwin, D., 1999. Loess, in: Goudie, A.S., Livingstone, I., Stokes, S. (eds), Aeolian environments, sediments and landforms. Wiley, Chichester, pp. 213-238.Qiu, L.J., Zheng, F.L., Yin, R.S., 2012. SWAT-based runoff and sediment simulation in a small watershed, the loessial hilly-gullied region of China: capabilities and challenges. International Journal of Sediment Research. 27, 226-234.

Quinton, J.N., 1997. Reducing predictive uncertainty in model simulations: a comparison of two methods using the European Soil Erosion Models (EUROSEM). Catena. 30, 101-117.

Renard, K., Foster, G., Weesies, G., Porter, J., 1991. RUSLE: Revised universal soil loss equation. Journal of Soil and Water Conservation. 46, 30-33.

Renschler, C.S., Flanagan, D.C., 2002. Implementing a process-based decision-support tool for natural resource management the GeoWEPP example, in: Rizzoli, A.E., Jakeman, A.J. (eds), Integrated assessment and decision support. Lugano University Press, Switzerland, pp. 187-192.

Rothwell, J.J., Robinson, S.G., Evans, M.G., Yang, J., Allott, T.E.H., 2005. Heavy metal release by peat erosion in the Peak District, southern Pennines, UK. Hydrological Processes. 19, 2973-2989.

Saavedra, C., 2005. Estimating spatial patterns of soil erosion and deposition in the Andean region using geo-information techniques. PhD thesis, Wageningen University.

Sadeghi, S., Gholami, L., Khaledi Darvishan, A., Saeidi, P., 2013. A review of the application of the MUSLE model worldwide. Hydrological sciences journal. 59, 365-375.

Schumm, S.A., 1977. The fluvial system. Wiley, Chichester.

Shao, H., Baffaut, C., Gao, J., Nelson, N., Janssen, K., Pierzynski, G., Barnes, P., 2013. Development and applications of algorithms for simulating terraces within SWAT. Transactions of the ASABE. 56, 1715-1730.

Shi, H., Shao, M., 2000. Soil and water loss from the Loess Plateau in China. Journal of Arid Environments. 45, 9-20.

Shi, P., Yan, P., Yuan, Y., Nearing, M.A., 2004. Wind erosion research in China: past, present and future. Progress in Physical Geography. 28, 366-386.

Shi, Z., Fang, N., Wu, F., Wang, L., Yue, B., Wu, G. 2012. Soil erosion processes and sediment sorting associated with transport mechanisms on steep slopes. Journal of Hydrology. 454, 123-130.

Si, W., Bao, W., Jiang, P., Zhao, L., Qu, S., 2015. A semi-physical sediment yield model for estimation of suspended sediment in loess region. International Journal of Sediment Research. 32, 12-19.

Stolte, J., Liu, B., Ritsema, C.J., Van Denelsen, H.G.M., Hessel, R., 2003. Modelling water flow and sediment processes in a small gully system on the Loess Plateau in China. Catena. 54, 117-130.

Sun, B., Zhao, T., Qi, S., 1990. Application of USLE in loessial gully hilly area. Memoir of NISWC, Academia Sinica & Ministry of Water Conservancy. 12, 50-58. (in Chinese with English abstract)

Sun, W., Shao, Q., Liu, J., Zhai, J., 2014. Assessing the effects of land use and topography on soil erosion on the Loess Plateau in China. Catena. 121, 151-163.

Sun, W., Song, X., Mu, X., Gao, P., Wang, F., Zhao, G., 2015. Spatiotemporal vegetation cover variations associated with climate change and ecological restoration in the Loess Plateau. Agricultural and Forest Meteorology. 209, 87-99.

Tang, K., 2004. Soil and water conservation in China. Science Press, Beijing. (in Chinese)

Tang, L., Chen, G., 1997. A dynamic model of runoff and sediment yield from small watershed. Journal of Hydrodynamics. 12, 164-174. (in Chinese with English abstract)

Tang, L., Chen, G., Cai, M., 1990. A mathematical model of sediment yield on small watershed in the gullied-hilly Loess Plateau. Journal of Hohai University. 18, 10-16. (in Chinese with English abstract)

Tian, P., Zhao, G., Mu, X., Wen, Z., Wang, F., 2015. A modified RUSLE model to estimate sediment yield in the Huangfuchuan watershed. Resources Science. 37, 832-840. (in Chinese with English abstract)

Tiwari, A., Risse, L., Nearing, M., 2000. Evaluation of WEPP and its comparison with USLE and RUSLE. Transactions of the ASAE. 43, 1129-1135.

Tsunekawa, A., Liu, G., Yamanaka, N., Du, S., 2014. Restoration and development of the degraded Loess Plateau, China. Springer, Tokyo.

URI, N.D., 2001. The environmental implications of soil erosion in the United States. Environmental monitoring and assessment. 66, 293-312.

USDA, 1972. National Engineering Handbook, Section 4: Hydrology. US Department of Agriculture, Washington, D.C.

Van Maren, D.S., Winterwerp, J.C., Wu, B.S., Zhou, J.J., 2009. Modelling hyperconcentrated flow in the Yellow River. Earth Surface Processes and Landforms. 34, 596-612.

Van Oost, K., Govers, G., Desmet. P.J.J., 2000. Evaluating the effects of landscape structure on soil erosion by water and tillage. Landscape Ecology. 15, 579–591.

Van Rompaey, A.J., Verstraeten, G., Van Oost, K., Govers, G., Poesen, J., 2001. Modelling mean annual sediment yield using a distributed approach. Earth Surface Processes and Landforms. 26, 1221-1236.

Verstraeten, G., Prosser, I.P., Fograty, P., 2007. Predicting the spatial patterns of hillslope sediment delivery to river channels in the Murrumbidgee catchment. Journal of Hydrology. 334, 440-454.

Wainwright, J., Mulligan, M., 2013. Environmental modelling: finding simplicity in complexity. Wiley-Blackwell Publishing Ltd., Chichester.

Walling, D., Quine, T., 1990. Calibration of caesium-137 measurements to provide quantitative erosion rate data. Land Degradation & Development. 2, 161-175.

Wang, G., Wu, B., Li, T., 2007. Digital Yellow River Model. Journal of Hydro-environment Research. 1, 1-11.

Wang, G., Xue, H., Li, T., 2005a. Mathematical model for gravitational erosion in gully area. Journal of Basic Science and Engineering. 13, 335-344. (In Chinese with English abstract)

Wang, G., Xue, H., Liu, J., 2005b. Sediment yield model on slopes. Journal of Basic Science and Engineering. Supplement 1, 1-7. (in Chinese with English abstract)

Wang, J., Zheng, F., Jiang, Z., Zhang, X., 2007. Assessment of WEPP model applicability (Hillslope version) on hill-gully region of the Loess Plateau-A case study in slope length factor. Bulletin of Soil and Water Conservation. 27, 50-55. (in Chinese with English abstract)

Wang, J., Zheng, F., Jiang, Z., Zhang, X., 2008. Assessment of WEPP model applicability (Hillslope version) to hill-gully region of the Loess Plateau-A case study in slope gradient factor. Journal of Sediment Research. 52-60. (in Chinese with English abstract)

Wang, L., Shao, M.A., Wang, Q., Gale, W.J., 2006. Historical changes in the environment of the Chinese Loess Plateau. Environmental Science & Policy. 9, 675-684.

Wang, S., Fu, B., Piao, S., Lv, Y., Ciais, P., Feng, X., Wang, Y., 2015. Reduced sediment transport in the Yellow River due to anthropogenic changes. Nature Geoscience. 9, 38-41.

Wang, S., Zhang, Z., Tang, Y., Guo, J., 2010. Evaluation of spatial distribution of soil erosion and sediment yield for a small watershed of the Loess Plateau by coupling MIKE-SHE with MUSLE. Transactions of the CSAE. 26, 92-98. (in Chinese with English abstract)

Wang, T., Wu, J., Kou, X., Oliver, C., Mou, P., Ge, J., 2010. Ecologically asynchronous agricultural practice erodes sustainability of the Loess Plateau of China. Ecological Applications. 20, 1126-1135.

Wang, L., Wang, F., Li, P., in press. Relationships Between Vegetation Restoration and Soil Moisture on the Chinese Loess Plateau. Research of Soil and Water Conservation. (in Chinese with English abstract).

Williams, J.R., 1969. Flood routing with variable travel time or variable storage coefficients. Transactions of the ASAE, 12, 100-0103.

Williams, J.R., 1975. Sediment-yield prediction with universal equation using runoff energy factor, in: Present and prospective technology for predicting sediment yields and sources. Vol. ARS-S-40, 244-252.

Wiltshire, R., 1983. Periodic heat conduction in a non-uniform soil. Earth Surface Processes and Landforms. 8, 547-555.

Wischmeier, W., Smith, D.D., 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains: Guide for selection of practices for soil and water conservation. US Department of Agriculture, Washington D.C.

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses: A guide to conservation planning. US Department of Agriculture, Washington D.C.

Yalin, M., 1963. An expression for bed-load transportation. Journal of the Hydraulics Division, 89, 221-250.

Yang, D., Kanae, S., Oki, T., Koike, T. & Musiake, K., 2003. Global potential soil erosion with reference to land use and climate changes. Hydrological Processes. 17, 2913-2928.

Yang, T., Xu, C.Y., Zhang, Q., Yu, Z., Baron, A., Wang, X., Singh, V.P., 2012. DEM-based numerical modelling of runoff and soil erosion processes in the hilly–gully loess regions. Stochastic environmental research and risk assessment. 26, 581-597.

Yin, G., Chen, Q., 1989. Characteristic index and statistical model of sediment yield in small drainage basins of Loess Plateau in China. Acta Geographica Sinica. 44, 32-46. (in Chinese with English abstract)

Yu, X., Zhang, X., Niu, L., 2009. Simulated multi-scale watershed runoff and sediment production based on GeoWEPP model. International Journal of Sediment Research. 24, 465-478.

Zhang, X.C., Li, Z.B., Ding, W.F., 2005. Validation of WEPP sediment feedback relationships using spatially distributed rill erosion data. Soil Science Society of America Journal. 69, 1440-1447.

Zhang, X.C., Liu, W.Z., 2005. Simulating potential response of hydrology, soil erosion, and crop productivity to climate change in Changwu tableland region on the Loess Plateau of China. Agricultural and Forest Meteorology. 131, 127-142.

Zhang, Y., Zheng, F., Jia, Y., 2004. WEPP model and its application. Research of Soil and Water Conservation. 11, 146-149. (in Chinese with English abstract)

Zhang, Z., 1993. The basic features of soil erosion in Loess Plateau. Quaternary Sciences. 34-40. (in Chinese with English abstract)

Zhao, G., Klik, A., Mu, X., Wang, F., Gao, P., Sun, W., 2015. Sediment yield estimation in a small watershed on the northern Loess Plateau, China. Geomorphology. 241, 343-352.

Zhao, G., Mu, X., Wen, Z., Wang, F. Gao, P., 2013. Soil erosion, conservation, and eco- environment changes in the loess plateau of China. Land Degradation & Development, 24, 499-510.

Zhao, R., 1984. Catchment hydrological modelling-the Xinanjiang model and Shanbei model. Water Resources and Elecctric Power Press, Beijing. (in Chinese)

Zhao, R., Liu, X., Singh, V., 1995. The Xinanjiang model, in: Singh, V.P. (eds), Computer models of watershed hydrology. Water Resources Publications, Colorado, pp. 215-232.

Zheng, M., Cai, Q., Cheng, Q., 2008. Modelling the runoff-sediment yield relationship using a proportional function in hilly areas of the Loess Plateau, North China. Geomorphology, 93, 288-301.

Zheng, M., Qin, F., Sun, L., Qi, D., Cai, Q., 2011. Spatial scale effects on sediment concentration in runoff during flood events for hilly areas of the Loess Plateau, China. Earth Surface Processes and Landforms. 36, 1499-1509.

Zhu, T., 1997. Deep-seated., complex tunnel systems-a hydrological study in a semi-arid catchment, Loess Plateau, China. Geomorphology. 20, 255-267.

Zhu, T., 2006. Initiation and development processes of tunnel systems in the hilly loess region of northern China. International Journal of Sediment Research. 21, 171-179.

Zhu, T., 2012. Gully and tunnel erosion in the hilly Loess Plateau region, China. Geomorphology. 153, 144-155.

Zhu, T., Luk, S., Cai, Q., 2002. Tunnel erosion and sediment production in the hilly loess region, North China. Journal of Hydrology. 257, 78-90.

Zhu, X., 1986. Land resources in the Loess Plateau of China. Shaanxi Science and Technique Press, Xian. (in Chinese)

Zhu, X., 1989. Soil and agiculture on the Loess Plateau. Agricultural Press, Beijing. (in Chinese)

Zuo, D., Xu, Z., Yao, W., Jin, S., Xiao, P., Ran, D., 2016. Assessing the effects of changes in land use and climate on runoff and sediment yields from a watershed in the Loess Plateau of China. Science of the Total Environment. 544, 238-250.

Model	Type	Scale		Structure	Time step	Channel routing	Transport capacity		Deposition		RUSLE based	Loess Plateau processes	Unique features	Reference
		Spatial	Temporal				Land	Stream	Land	Stream				
RUSLE	Empirical	Hillslope	Annual	Lumped	Annual	No	No	No	No	No	Yes	No	Often incorporated into other models	Renard et al. (1991)
MUSLE	Empirical	Small catchment	Event	Lumped	Event	No	No	No	No	No	Yes	No		Williams, (1975), Sadeghi et al. (2013)
Zheng's model	Empirical	Small catchment	Event	Lumped	Event	No	No	No	No	No	No	No	Applicable for high and medium-magnitude events	Zheng et al. (2008; 2011)
WEPP	Process-based	Hillslope/small catchment	Event/ continuous	Distributed	Daily	Yes	Yes	Yes	Yes	Yes	No	No	Rill and interrill erosion modelled separately. Reservoir processes included.	Laflen et al. (1991), Flanagan and Livingston (1995), Flanagan et al. (2007, 2012)
SWAT	Process-based	Catchment	Event/continuous	Distributed	Daily	Yes	No	Yes	No	Yes	Yes	No	Reservoir processes included	Arnold et al. (1998), Neitsch et al.,(2011)
MMF	Process-based	Hillslope/regional	Annual	Distributed	Annual	No	Yes	No	Yes	No	No	No	Runoff and sediment are modelled separately on a coarse temporal scale	Morgan et al. (1984), Morgan (2001), Morgan and Duzant (2008)
DYRIM	Process-based	Catchment	Event/ continuous	Distributed	Min-daily	Yes	No	Yes	No	No	No	Yes	Gravitational erosion included	Wang et al. (2007), Guo et al. (2014)
WATEM/SEDEM	Process-based	Catchment	Annual	Distributed	Annual	No	Yes	No	Yes	No	Yes	Yes	Gully erosion included in the modified version	Van Rompaey et al. (2001), Verstraeten et al. (2007), Zhao et al. (2015)
Tian's model	Process-based	Catchment	Annual	Distributed	Monthly	No	Yes	No	Yes	No	Yes	Yes	Check-dam impacts included	Tian et al. (2015)
Si's model	Process-based	Hillslope/catchment	Event/ continuous	Lumped	Min-daily	Yes	No	Yes	No	Yes	No	Yes	Gully erosion included	Si et al. (2015)

Yang's model	Process-based	Catchment	Event	Distributed	Half-hour	Yes	No	No	No	No	No	Yes	Gully erosion included	Yang et al. (2012), Tang et al. (1990), Tang and Chen (1997)

Table 1 Basic characteristics of the eleven selected models

Table 2 A summary of information reported in literature on the evaluation of the eleven selected models, including study site, region of the Loess Plateau (LP) that the study site is located (region), the number of sites used for model tests (N), spatial and temporal scales of the tests, coefficient of determination (R^2) and Nash-Sutcliffe coefficient (N_{sc}), types of sediment load used for model testing, and testing strategies.

Model	Study site	Region	N	Area (km^2)	resolution (m)	period	Time-interval	Calibration		Validation		Sediment load for model testing	Testing strategy	Reference
								R^2	N_{sc}	R^2	N_{sc}			
RUSLE	Loess Plateau (LP)	LP	1	620,000	1,000	2000-2010	annual	N/A	N/A	0.887	0.77	total	Tested with sediment yield at six ecological stations over the Loess Plateau	Sun et al. (2014) n/a
MUSLE	Lvergou^{e}	Southern LP	1	12.01	50	1983-1984	event	N/A	N/A	0.977	N/A	suspended	Out-based testing	Wang et al. (2010) n/a
Zheng's model	Chabagou^{f}	Central LP	9	0.107	N/A	1959-1967	event	0.986	N/A	N/A	N/A	suspended	Tested with sediment yield measurement at nine gauging stations in the Chabagou catchment and three sations in the Wangjiagou catchment	Zheng et al. (2008) n/a
				0.133	N/A	1959-1967	event	0.984	N/A	N/A	N/A			
				0.18	N/A	1961-1969	event	0.976	N/A	N/A	N/A			
				4.26	N/A	1960-1969	event	0.975	N/A	N/A	N/A			
				5.74	N/A	1960-1967	event	0.961	N/A	N/A	N/A			
				21	N/A	1959-1969	event	0.929	N/A	N/A	N/A			
				49	N/A	1959-1967	event	0.989	N/A	N/A	N/A			
				96.1	N/A	1959-1967	event	0.984	N/A	N/A	N/A			
				187	N/A	1959-1969	event	0.979	N/A	N/A	N/A			
	Wangjiagou	Central LP	3	9.1	N/A	1955-1981	event	0.984	N/A	N/A	N/A			
				0.206	N/A	1956-1970	event	0.959	N/A	N/A	N/A			
				0.193	N/A	1956-1970	event	0.956	N/A	N/A	N/A			
	Dalihe	Central LP	13	3.32-662	N/A	1959-1969	event	N/A	-0.19^{a}	N/A	-0.59^{a}	suspended	Tested with sediment yield measurement at 17 gauging stations in the Dalihe catchment	Zheng et al. (2011) n/a
					N/A	1959-1969	event	N/A	0.49^{b}	N/A	0.76^{b}			
					N/A	1959-1969	event	N/A	0.96^{c}	N/A	0.91^{c}			
WEPP	Ansai station	Central LP	4	0.00005-0.0002	N/A	1985-1992	annual	N/A	0.744	N/A	0.764	total	Calibrated and validated with hillslope sediment yield, no internal or spatial pattern testing	Wang et al. (2007)
					N/A	1985-1992	event	N/A	0.744	0.867	0.853			
					N/A	1985-1992	annual	N/A	0.744	0.779	0.758			
					N/A	1985-1992	mean-annual	N/A	0.744	0.995	0.456			
	Ansai station	Central LP	6	0.0001	N/A	1985-1992	annual	0.811	0.786	0.805	0.757	total	Calibrated and validated with hillslope sediment yield, no internal or spatial pattern testing	Wang et al. (2008)
					N/A	1985-1992	event	0.811	0.786	0.875	0.858			
					N/A	1985-1992	annual	0.811	0.786	0.806	0.772			
					N/A	1985-1992	mean annual	0.811	0.786	0.995	0.827			
	Qiaozidonggou	Southern LP	3	1.36	N/A	1985-2004	daily	N/A	0.89	N/A	0.87	suspended	Outlet-based testing, no internal or spatial pattern	Yu et al. (2009)

	Qiaozixigou	Southern LP		1.09	N/A	1985-2004	daily	N/A	0.81	N/A	0.82		testing.	
	Lvergou[e]	Southern LP		12.01	N/A	1982-2004	daily	N/A	0.9	N/A	0.88			
SWAT	Zhifanggou	Central LP	1	8.27	5	1998-2003	event	0.82	0.61	0.79	0.56	suspended	Outlet-based testing, no internal or spatial pattern testing	Qiu et al. (2012)
	Anjiagou	Southwestern LP	1	8.29	10	1984-1987	daily	0.74	0.67	0.51	0.32	suspended	Outlet-based testing, no internal or spatial pattern testing	Li et al. (2010b)
	Huangfuchuan[g]	Northeastern LP	1	3246	30	1979-1984	monthly	0.99	0.99	0.47	0.43	suspended	Outlet-based testing, no internal or spatial pattern testing	Zuo et al. (2016)
MMF[d]	Zuli river basin	Southwestern LP	4	10,653	100	1970-1998	annual	N/A	0.74	N/A	0.74	suspended	Tested with sediment yield measurements at four gauging stations within the study catchment, no internal testing	Li et al. (2010a)
				5,462	100	1970-1998	annual	N/A	0.64	N/A	0.64			
				1,007	100	1970-1998	annual	N/A	0.59	N/A	0.59			
				1,645	100	1970-1998	annual	N/A	0.7	N/A	0.7			
DYRIM	Wudinghe	Central LP	3	N/A	100	1977	N/A	N/A	0.58	N/A	N/A	suspended	Tested with sediment yield measurements at three hydrological stations within the study catchment, no internal testing	Li et al. (2008)
				N/A	100	1977	N/A	N/A	0.53	N/A	N/A			
				N/A	100	1977	N/A	N/A	0	N/A	N/A			
	Chabagou[f]	Central LP	6	4.26	50	1967	N/A	N/A	N/A	N/A	0.69	suspended	Tested with sediment yield measurements at six gauging stations within the study catchment, no internal testing	Li et al. (2009)
				5.74	50	1967	N/A	N/A	N/A	N/A	0.35			
				21	50	1967	N/A	N/A	N/A	N/A	0.43			
				49	50	1967	N/A	N/A	N/A	N/A	0.63			
				96.1	50	1967	N/A	N/A	N/A	N/A	0.76			
				187	50	1967	N/A	N/A	N/A	N/A	0.6			
WATEM/ SEDEM	Yangjuangou	Central LP	1	2	20	N/A	mean annual	N/A	-0.32	N/A	N/A	total	Spatial pattern tested, no internal testing	Feng et al. (2010)
	Xiaoshilata	Northeastern LP	1	0.64	5	1958-1972	annual	N/A	can be >0.9	N/A	N/A	total	Outlet-based testing, no internal or spatial pattern testing	Zhao et al. (2015)
Tian's model	Huangfuchuan[g]	Northeastern LP	1	3,246	50	1991-2009	monthly	0.79	0.7	0.64	0.51	suspended	Outlet-based testing, no internal or spatial pattern testing	Tian et al. (2015)
Si's model	TSG #3	Central LP	16	0.0009	N/A	N/A	1 min	N/A	N/A	N/A	0.815	suspended	Internal processes tested, no spatial pattern testing,	Si et al (2015)
	TSG 7#	Central LP		0.00574	N/A	N/A	1 min	N/A	N/A	N/A	0.803			
	TSG 9#	Central LP		0.0172	N/A	N/A	1 min	N/A	N/A	N/A	0.877			
	TSG	Central LP		0.18	N/A	N/A	2 min	N/A	N/A	N/A	0.855			
	SWG	Central LP		0.107	N/A	N/A	2 min	N/A	N/A	N/A	0.942			
	TYG	Central LP		0.491	N/A	N/A	4 min	N/A	N/A	N/A	0.918			
	NYG	Central LP		0.732	N/A	N/A	2 min	N/A	N/A	N/A	0.917			
	SPZG	Central LP		0.823	N/A	N/A	4 min	N/A	N/A	N/A	0.947			
	YWG	Southwestern LP		0.9	N/A	N/A	2 min	N/A	N/A	N/A	0.8			
	WJG	Central LP		1.67	N/A	N/A	4 min	N/A	N/A	N/A	0.95			

	SJG	Central LP		4.26	N/A	N/A	5 min	N/A	N/A	N/A	0.931			
	PJM	Central LP		41.2	N/A	N/A	5 min	N/A	N/A	N/A	0.881			
	JYG	Central LP		63.9	N/A	N/A	10 min	N/A	N/A	N/A	0.773			
	HJP	Southwestern LP		100	N/A	N/A	hourly	N/A	N/A	N/A	0.849			
	HFC[g]	Northeastern LP		3,199	N/A	1954-1963	daily	N/A	N/A	N/A	0.87			
	HKZ-LMZ	Central LP		132,830	N/A	1953-1962	daily	N/A	N/A	N/A	0.844			
Yang's model	Chabagou[f]	Central LP	2	205	20	1970-2001	30-min	N/A	0.58-0.79	N/A	0.51-0.65	suspended	Outlet-based testing, no internal or spatial pattern testing	Yang et al. (2012)
	Xingzihe	Central LP		1,486	20	1982	30-min	N/A	0.58-0.79	N/A	0.50-0.62			

a, prediction accuracy for low-magnitude events
b, prediction accuracy for medium-magnitude events
c, prediction accuracy for high-magnitude events
d, R^2 and N_{sc} were derived through combining the calibration and validation periods
e, Both MUSLE and WEPP have been applied to Lvergou catchment
f, Zheng's model, DYRIM and Yang's model have been used in the Chabagou catchment
g, SWAT, Tian's model and Si's model have been used in the Huangfuchuan catchment

Table 3 Inputs and calibrations needed for the eleven selected models. For the models simulating a water balance (i.e. LISEM, WEPP, SWAT, MMF, DYRIM, Si’s model and Yang’s model), data requirements and the number of calibration parameters for runoff and sediment simulation are listed.

Model	Input data	No. of calibration parameters	Calibration parameters	References
RUSLE	Low	0	0	Sun et al. (2014)
MUSLE	Low	0	0	Wang et al. (2010)
Zheng's model	Low	1	Regression coefficient	Zheng et al. (2008)
		1		Zheng et al. (2011)
WEPP	High	3	Effective hydraulic conductivity, critical soil shear strength, soil erodibility for rills	Wang et al. (2007)
		3	Effective hydraulic conductivity, critical soil shear strength, soil erodibility for rills	Wang et al. (2008)
		N/A	N/A	Yu et al. (2009)
SWAT	High	16	Initial SCS CN II value, soil available water capacity, saturated hydraulic conductivity, depth from the soil surface to the bottom of the layer, soil evaporation compensation factor, base flow alpha factor, threshold depth of water in a shallow aquifer for return flow, average slope length, plant evaporation compensation factor, channel effective hydraulic conductivity, groundwater re-evaporation coefficient, linear parameters for sediment re-entrainment, channel erodibility factor, exponent parameter for sediment re-entrainment, channel cover factor, USLE C factor for land cover	Qiu et al. (2012)
		7	Maximum canopy index, channel cover factor, soil evaporation compensation factor, snow melt base temperature, linear parameters for sediment re-entrainment, exponent parameter for sediment re-entrainment, snow pack temperature lag factor	Li et al. (2010b)
		N/A	N/A	Zuo et al. (2016)
MMF	Moderate	N/A	N/A	Li et al. (2010a)
DYRIM	High	N/A	N/A	Li et al. (2008)
		N/A	N/A	Li et al. (2009)
WATEM/SEDEM	Low	6	Low transport capacity coefficient, high transport capacity, transport contribution for grass, transport contribution coefficient for shrub and woodland, patch connectivity for farmland and orchard parcel	Feng et al. (2010)
		2	High transport capacity coefficient, low transport capacity coefficient	Zhao et al. (2015)
Tian's model	Moderate	3	Vegetation cover factor, soil erodibility, transport capacity coefficients	Tian et al. (2015)
Si's model	High	N/A	N/A	Si et al. (2015)
Yang's model	High	4	Maximum (or initial) infiltration rate, minimum (or equilibrium) in filtration rate, infiltration constant, overland flow routing coefficient	Yang et al. (2012)

Table 4 The

environment that each model works well in and the specific research questions that each model can address on the Loess Plateau.

Model	Environment	Research questions and the corresponding spatial and temporal scales		
		Spatial scale	Temporal scale	Specific research questions
RUSLE	Gentle/steep sloping	Hillslope/regional	Annual	On-site soil erosion rates
MUSLE	Gentle/steep sloping	Small catchment	Event	Off-site sediment yields
Zheng's model	Hilly-gully areas	Small catchment	Event	Off-site sediment yields
WEPP	Gentle/steep sloping, ungullied	Hillslope/small catchment	Event/annual/continuous	On-site soil erosion rates, off-site sediment yields, climate and land use scenarios, sediment sources and sinks
SWAT	Gentle/steep sloping, ungullied	Catchment	Event/continuous	Climate and land use scenarios, sediment sources
MMF	Gentle-sloping, ungullied	Medium to large catchment/regional	Annual	Off-site sediment yields, climate and land use scenarios, sediment sources
DYRIM	Gentle/steep sloping, gullied	Catchment	Event/continuous	Climate and land use scenarios, sediment sources
WATEM/SEDEM	Gentle/steep-sloping, gullied	Catchment	Annual	Sediment sources
Tian's model	Hilly-gully areas	Catchment	Annual	Land-use scenarios (i.e. check-dams), sediment sources
Si's model	Loess Plateau	Hillslope to large catchment/regional	Event/ continuous	On-site soil erosion rates, off-site sediment yields
Yang's model	Hilly-gully areas	Catchment	Event	Climate and land use scenarios, sediment sources

Abstract

The Loess Plateau suffers from severe soil erosion that leads to a series of ecological and economic problems such as reduced land productivity, exacerbated rural poverty, decreased biodiversity and sedimentation of the riverbed in the lower reaches of the Yellow River. Soil erosion models are commonly used on the Loess Plateau to help target sustainable land management strategies to control soil erosion. In this study, we compared eleven soil erosion models that were previously used on the Loess Plateau. We studied their prediction accuracy, process representation, data and calibration requirements, and potential application in scenario studies. The selected models consisted of a broad range of model types, structures and scales. The comparison showed that process-based and empirical models did not necessarily yield more accurate results over one another for the Loess Plateau. Among the process-based models, Si' model, WEPP and MMF had the highest prediction accuracy. However, some of the selected models were tested with total sediment load while others were tested with suspended sediment load (i.e. bedload is not included), which is subject to several drawbacks. Research questions that each of the models can address on the Loess Plateau were suggested. Further improvement of soil erosion models for the Loess Plateau should concentrate on enhancing the quality of data for model implementation and testing, incorporating key processes into process-based models according to their aims and scales, comparing models that address the same research questions, and implementing internal and spatial model testing.