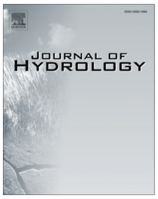
Journal of Hydrology 554 (2017) 600–612

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



Research papers

# Hydraulic-based empirical model for sediment and soil organic carbon loss on steep slopes for extreme rainstorms on the Chinese loess Plateau

L. Liu [a,e], Z.W. Li [a,b,*], X.D. Nie [a,b], J.J. He [c,*], B. Huang [d], X.F. Chang [a], C. Liu [a,b], H.B. Xiao [a], D.Y. Wang [b]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, CAS and MWR, Yangling, Shaanxi Province 712100, PR China
[b] College of Environmental Science and Engineering, Hunan University, Changsha 410082, PR China
[c] Base of the State Laboratory of Urban Environmental Processes and Digital Modeling, Key Laboratory of 3D Information Acquisition and Application, Ministry of Education, Capital Normal University, Beijing 100048, PR China
[d] Guangdong Key Laboratory of Agricultural Environmental Pollution Integrated Control, Guangdong Institute of Eco-environment Technology, Guangzhou 510650, PR China
[e] Graduate University of Chinese Academy of Sciences, Beijing 100049, PR China

## ARTICLE INFO

*Article history:*
Received 6 May 2017
Received in revised form 2 September 2017
Accepted 4 September 2017
Available online 22 September 2017
This manuscript was handled by G. Syme, Editor-in-Chief

*Keywords:*
SOC loss
Soil erosion
Simulated rainfall
Hydraulic factor
Model

## ABSTRACT

Building a hydraulic-based empirical model for sediment and soil organic carbon (SOC) loss is significant because of the complex erosion process that includes gravitational erosion, ephemeral gully, and gully erosion for loess soils. To address this issue, a simulation of rainfall experiments was conducted in a 1 m × 5 m box on slope gradients of 15°, 20°, and 25° for four typical loess soils with different textures, namely, Ansai, Changwu, Suide, and Yangling. The simulated rainfall of 120 mm $h^{-1}$ lasted for 45 min. Among the five hydraulic factors (i.e., flow velocity, runoff depth, shear stress, stream power, and unit stream power), flow velocity and stream power showed close relationships with SOC concentration, especially the average flow velocity at 2 m from the outlet where the runoff attained the maximum sediment load. Flow velocity controlled SOC enrichment by affecting the suspension–saltation transport associated with the clay and silt contents in sediments. In consideration of runoff rate, average flow velocity at 2 m location from the outlet, and slope steepness as input variables, a hydraulic-based sediment and SOC loss model was built on the basis of the relationships of hydraulic factors to sediment and SOC loss. Nonlinear regression models were built to calculate the parameters of the model. The difference between the effective and dispersed median diameter ($\delta D_{50}$) or the SOC content of the original soil served as the independent variable. The hydraulic-based sediment and SOC loss model exhibited good performance for the Suide and Changwu soils, that is, these soils contained lower amounts of aggregates than those of Ansai and Yangling soils. The hydraulic-based empirical model for sediment and SOC loss can serve as an important reference for physical-based sediment models and can bring new insights into SOC loss prediction when serious erosion occurs on steep slopes.

## 1. Introduction

Soil erosion can remove a significant portion of soil organic matter (SOM) (Lal, 2005; Schiettecatte et al., 2008a); such process is important to agricultural productivity (Prokop and Poręba, 2012; Yitbarek et al., 2012) and sustainable resource management (Li et al., 2017; Zhao et al., 2013). Meanwhile, soil organic carbon (SOC) mobilized by erosion can be lost to the atmosphere within a short period or transported off site (Polyakov and Lal, 2008). Breakup of initial soil aggregates by erosive forces increases $CO_2$ emission. Breakdown of aggregates causes exposure of encapsulated C to microbial processes, thereby increasing SOC mineralization rate (Lal, 2003). Thus, SOC loss accompanied with soil erosion is an important component of the net ecosystem carbon balance (Nadeu et al., 2014; Wang et al., 2014). However, in recent years, researchers have focused mainly on the SOC stability (Berhe and Kleber, 2013), SOC mineralization (Gregorich et al., 2015), SOC stocks (Li et al., 2017), or redistribution of SOC after erosion (Liu et al., 2017). SOC loss is mainly understood by sediment erosion (Palis et al., 1997). Although hydraulic process controlling sediment loss has been widely studied (Pan and Shangguan, 2006; Slattery and Bryan, 1992), the direct relationships between hydraulic factors and SOC concentration are yet to be studied for any soil in building a hydraulic-based SOC loss model.

---

* Corresponding authors at: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, CAS and MWR, Yangling, Shaanxi Province 712100, PR China (Z.W. Li).

*E-mail addresses:* lizw@hnu.edu.cn (Z.W. Li), Hejiun_200018@163.com (J.J. He).

https://doi.org/10.1016/j.jhydrol.2017.09.010
0022-1694/

SOC loss is usually estimated by sediment loss (Häring et al., 2014; Li et al., 2016c). A few physical-process sediment models, such as Water Erosion Prediction Project (WEPP), have been built (Foster et al., 1995; Nearing et al., 1989). However, WEPP, which is a widely used physical-based model, is a steady state model and cannot obtain high-sediment prediction accuracy when complex erosion processes occur, such as gravitational erosion, ephemeral gully, and gully erosion (Zheng, 2006). In China, serious erosion usually occurs on farmlands with steep slopes (Fu, 1989); this serious erosion is usually accompanied with gravitational erosion, ephemeral gully, and gully erosion on the hill slopes on the Loess Plateau (Zheng, 2006). Therefore, building a hydraulic-based sediment and SOC loss model can provide a reference for the SOC loss prediction and help improve WEPP applicability in China. Sediment transport capacity is usually calculated by runoff rate, slope, and flow velocity (Govers, 1990; Quinton et al., 2006; Schiettecatte et al., 2008b), and flow velocity is a good predictor of sediment concentration (Arjmand and Mahmoodabadi, 2015). A hydraulic-based sediment and SOC loss model can be built by clarifying the relationship between hydraulic factors and SOC concentration.

In recent decades, SOM dynamic models, such as Century (Smith et al., 1997) or erosion productivity impact calculator models (Sharpely and Williams, 1990) mainly focusing on the SOC change of the ecosystem, have been proposed. SOC loss is an important component of SOC dynamic models and is calculated mainly by two methods (Häring et al., 2014; Li et al., 2016c). In the first traditional method, cumulative SOC loss is simply calculated as the product of SOC concentration, SOC enrichment ratio, and cumulative sediment loss. According to our previous study (Li et al., 2016c), the predicted precision of traditional method is low under high rainfall intensity for loess soils. The second method is the recently developed carbon, input, decomposition, and erosion (CIDE) approach. CIDE calculates SOC loss on the basis of the comparison between un-eroded and eroded cultivated sites; this method requires large amounts of costly input variables (e.g., carbon isotope) (Häring et al., 2013). Therefore, building a hydraulic-based SOC loss model, which is rational and scientific, may be significant for SOC prediction when severe erosion occurs.

On average within 100 years, 50% of SOM transported off site can be attributed to erosion on steep slopes (Polyakov and Lal, 2004). Soil texture demonstrates a major control over organic matter dynamics, and clay percentage determines the SOC concentration of sediments (Avnimelech and McHenry, 1984; Parton et al., 1987). Therefore, steep slope and soil texture were the two main factors considered in our study. The present study aimed to (i) investigate the effect of hydraulic factors on sediment SOC concentration for four loess soils with different soil textures on steep slopes and (ii) build a hydraulic-based sediment and SOC loss model for providing options and references for soil loss and SOC dynamic models.

## 2. Methods and materials

### 2.1. Experimental devices

Simulated rainfall experiments were conducted at the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau. A down sprinkler rainfall simulator device with a rainfall intensity ranging from 30 mm $h^{-1}$ to 350 mm $h^{-1}$ was used to simulate rainfall; rainfall intensity was also adjusted by the change in nozzle size and water pressure (Shen et al., 2016). Prior to performing the experiments, rainfall intensity calibration was conducted to reach the target of rainfall intensity with a uniformity of > 0.90. The structure of the soil pan constructed with metal sheets was 5 m (length) × 1 m (width) × 0.5 m (depth); a metal runoff collector was set at the end of the soil pan (Shi et al., 2012). The slope of the pan could be electronically adjusted to a desired slope between 0° and 30°. Tap water (electrical conductivity = 0.7 dS $m^{-1}$) was used for all experiments. The soils used in the experiments were four loess soils with clay contents of 26%, 21%, 16%, and 12%. The sample sites were Suide (37°29′N, 110°14′E), Changwu (35°22′N, 107°80′E), Yangling (34°16′N, 108°4′E), and Ansai (36°58′N, 109°20′E); these sites are distributed from south to north across the Loess Plateau of China (Fig. S1). The four sampled fields have been cultivated with crops for many years. Thus, the sampling depth was 20 cm. Sampling time was before the crop cultivation. The properties of the loess soils are shown in Table 1. The basic properties of soil were determined using standard analytical methods (Finkner and Gilley, 1988).

### 2.2. Rainfall simulation experiments

All soil samples were air dried to ~10% moisture content (gravimetric) and were passed through a 10 mm sieve. The soil pan was packed with the bulk density, as presented in Table 1. Before packing the plow layer, a 10 cm-thick layer of coarse sand was added to the bottom of the experiment plot to maintain permeable conditions. Subsequently, fine gauze was placed on top of the layer of coarse sand. Finally, a 30 cm-thick soil layer was laid on the coarse sand layer at 5 cm increments. Each layer of the plot was raked lightly to ensure uniformity and continuity in soil structure. The packed soil samples were ensured to be coherent with the wall by gluing the soil into the tray wall to avoid ponding water. Considering the similarity of soil properties at different slope locations (e.g., slope positions or slope angles) for each soil, three typical slope gradients of 15°, 20°, and 25° were applied. The slope gradient of 25° corresponded with the maximum slope for cultivated land according to the classification of farmland slopes in the Loess Plateau (Comprehensive Scientific Expedition, 1990). Prior to simulating rainfall, the plot slope was adjusted to a desired slope. The soil samples were wetted from the top with water applied as mist. After the soils reached full saturation, the plots were exposed to a simulated rainfall of 120 mm $h^{-1}$, a peak intensity of strong storms in the subhumid climatic regions of China (Cai et al., 1998; Chen, 1987). A total of 12 treatments were conducted (4 × soils with 3 × slope angles each). Each treatment was repeated by repacking the plot and repeating the simulated rainfall process and was tested in two replicates. The experimental results of the repeated treatments did not show a significant difference and were consistent with that in the experiment conducted by Wang and Shi (2015), who focused on the size selective erosion of the same two loess soils.

### 2.3. Measurements

#### 2.3.1. Sediment and SOC measurements

For each rainfall event, runoff was volumetrically measured and sampled at 1 min intervals for sediment concentration after initiation. Each sample was dried and weighed in forced-air ovens at 60 °C for 24 h. During the rainfall, the runoff-yield time, rill initiation times, rill location, and rill shape were also recorded. The rill width, length, and location were frequently measured with a millimeter-scale ruler at numerous locations. Sediment transport and soil surface conditions were visually observed and recorded during and after simulating storms. Sediment concentration was determined by the ratio of each dry sediment mass to sampled runoff volume. Meanwhile, total sediment loss was defined as the total sediment load present in runoff water. The SOC concentration of each sample was determined using the dichromate oxidation method (Walkley and Black, 1934) and was defined as the