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Effects of collection time intervals of surface runoff and sediment on soil erosion analysis during rainfall

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ABSTRACT

In simulation studies of soil erosion, analyzing runoff and sediment curves is important for accurately characterizing soil erosion on hillslopes. The objectives of this study were to measure the effects of surface runoff and sediment collection time intervals (CTIs) on runoff and sediment curves and to determine how CTIs affect soil erosion analyses. Experiments were conducted in runoff plots that were 4 m long and 1 m wide. The slope gradient was 15°, and the soil surface was smooth. Rainfall was applied at intensities of 60, 90 and 120 mm/h, and one short CTI (i.e., 2 min) and four longer CTIs (i.e., 4, 6, 8 and 10 min) were used. The results showed that longer surface runoff and sediment CTIs obviously influenced the runoff and sediment curves and the soil erosion analysis results, especially during the early period of runoff. The amount of accumulated runoff decreased at longer CTIs, and the amount of accumulated sediment increased at longer CTIs. Therefore, it is important to choose an appropriate CTI in simulated rainfall experiments to improve the reliability of soil erosion analyses. The use of an inappropriate CTI will adversely affect the results of such analyses. Based on these results, we suggest using a short CTI to collect surface runoff and sediment measurements during the rising period of the runoff rate; longer CTIs should be used only after the runoff rate has reached a steady state because the temporal variations in runoff and sediment yield are lower during this period.

1. Introduction

In soil erosion research, rainfall simulation is one of the most commonly used experimental methods for studying soil erosion. Consequently, researchers have generally focused on the performances of rainfall simulators, especially in terms of the raindrop distribution and kinetic energy (Sharpley and Kleinman, 2003). Many researchers at institutions around the world have attempted to develop rainfall simulators that mimic natural rainfall (Fister et al., 2012; Imeson, 1977; Kamphorst, 1987; Zheng and Zhao, 2004). Because of their quick, reproducible and controllable characteristics for varied rainfall conditions, rainfall simulators have been used worldwide by different research institutes/groups for simulating the process of soil erosion in the laboratory and in the field (Cerdà et al., 1997; Zhao et al., 2014).

In simulated rainfall experiments, surface runoff and sediment curves are important because they are used to analyze the dynamic characteristics of soil erosion. By analyzing surface runoff and sediment curves, researchers can observe hydrologic processes and better understand the mechanisms of soil erosion on hillslopes (Helming et al., 1998; Römkens et al., 2002). In general, runoff and sediment curves show changes in runoff and sediment rates with time. In particular, runoff curves show increasing surface runoff at the beginning of runoff, followed by a steady period. During this process, the sediment curve initially decreases and then remains stable. The dynamic characteristics of both the runoff and sediment curves are affected by a variety of natural and human factors, such as the soil surface conditions, rainfall characteristics, and surface vegetation cover (Huang and Lee, 2009; Pappas et al., 2008; Rai et al., 2010).

Because runoff and sediment curves are sequentially and separately connected to the runoff and sediment rates, the amount of runoff and the rate of sediment transport control the dynamic characteristics of the resulting runoff and sediment curves. Runoff and sediment rates are determined by dividing the weights of the runoff and the sediment collected from the outlet of the study area by the collection time. During simulated rainfall experiments, the runoff and sediment are not measured instantaneously due to technological and cost limitations. In fact, runoff and sediment samples are collected by hand at collection time intervals (CTIs) and treated to separate the water and the sand (Darboux and Huang, 2005; Zhao et al., 2016). Under these conditions, the runoff and sediment curves are based on discrete data points such that each point represents one CTI (Helming et al., 1998). Therefore, shorter CTIs correspond to more precise runoff and sediment curves. In

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fact, to save energy or enhance consistency, most researchers use 1 min as their minimum CTI (e.g., (Darboux and Huang, 2005; Helming et al., 1998; Zhao et al., 2016)). Runoff and sediment curves are determined from the ratios of the collected runoff and sediment to the CTI. Although simulated rainfall has commonly been used for studying soil erosion for > 30 years, few studies have determined the relationships between the CTIs of runoff and sediment samples and the final experimental results. However, even more serious is the fact that there is no standard CTI and that the CTI is unclear in many published studies. For example, Huang et al. (Huang et al., 1999) used a CTI of 3 min, whereas Gómez and Nearing (Gómez and Nearing, 2005) and Pappas et al. (Pappas et al., 2008) used CTIs of 2 and 4 min, respectively.

The objectives of this study were to determine the effects of surface runoff and sediment CTIs on runoff and sediment curves and to analyze how CTIs affect soil erosion analyses. To accomplish these goals, we used an experimental setup to model a natural smooth slope and applied artificial rainfall to study changes in runoff and sediment with various CTIs in a laboratory. The results of this study will be helpful for designing rainfall experiments and for reducing systematic errors in soil erosion analyses.

2. Materials and methods

2.1. Soil

Topsoil (depth of 0–20 cm) was collected from farmland at Yangling (34°17′56″N, 108°04′07″E), Shaanxi Province, China. The farmland had been cultivated continuously for > 10 years. The site has a temperate, semi-humid climate with a mean annual temperature of 13 °C, an annual precipitation of 620 mm, and a potential evaporation of 1400 mm per year. The soil is classified as an Eum-Orthic Anthrosol and is a sandy clay loam consisting of 57% sand, 18% silt and 25% clay. The soil organic matter content is 16.66 g/kg; the concentrations of total nitrogen and phosphorus are 0.91 and 0.50 g/kg, respectively; and the cation exchange capacity of the soil is 18.47 cmol/kg.

2.2. Experimental procedures

Experiments were performed in runoff plots that were 4 m long by 1 m wide. At the downslope end of each plot, a V-shaped drainage outlet was placed for collecting surface runoff and sediment. The gradient of the test slope was 15°, and rainfall intensities of 60, 90 and 120 mm/h were used. The rainfall durations were 60 min for the 60 mm/h rainfall events, 50 min for the 90 mm/h rainfall events and 40 min for the 120 mm/h rainfall events. Using these rainfall durations, steady rates of both surface runoff and sediment production were obtained with all the rainfall intensities. One short CTI (i.e., 2 min) and four long CTIs (i.e., 4, 6, 8 and 10 min) were used to measure the amounts of surface runoff and transported sediment, which were used for soil erosion analysis.

The rainfall simulator was equipped with a side-spray nozzle that produced raindrops with a kinetic energy impact rate that was 80% of that of natural rainfall with a corresponding intensity. The simulator nozzles were installed at a height of 6 m above the ground. Changes in rainfall intensity were controlled by adjusting the water pressure in the supply pipe. Two rainfall nozzles were placed 1 m in front and behind the runoff plots, and the nozzles were positioned to face the soil surface and were located in the center of each the runoff plots. Before the rainfall application, eight gauges were evenly placed throughout the rainfall area to calibrate the rainfall intensity. The results showed that the rainfall uniformity was > 90%, which is higher than that of the local natural rainfall reported by Wu et al. (Wu et al., 2011). The effective rainfall area was 7 m by 5 m.

To remove the effect of surface microtopography on runoff-erosion processes, a smooth soil surface was prepared for the rainfall testing. First, the surface soil in the runoff plots was plowed using a shovel. Then, the larger clods were crushed using a wooden hammer. Third, the soil surface was smoothed using a smoothing harrow. Before the rainfall experiments, a pre-rainfall event with a rainfall intensity of 30 mm/h was applied to each surface until runoff was initiated at the outlet of the runoff plots. The soil surface conditions were the same for each rainfall experiment, and thus the runoff initiation times for the 30 mm/h pre-rainfall events were all approximately 11 min. Then, the experimental soil was left undisturbed for 12 h. Using the above method, the effects of human disturbance on the soil were removed, and a thin soil crust formed, which decreased soil infiltration and reduced its effect on surface runoff and sediment production.

During the rainfall experiments, the surface runoff and sediment produced by the runoff plots were collected in 5 L plastic buckets. An empty bucket was switched in at the collection point every 2 min, and the runoff and sediment samples were labeled in order as R_1, R_2, …, and R_n. After the rainfall, the contents of each bucket (ZR_i) were weighed. The weight of the sediment in each bucket (ZS_i) was measured after drying the sediment at 110 °C for 12 h. The accuracy of the electronic scale used for the weighing was 0.01 g.

2.3. Data analysis

The surface runoff and sediment rates were calculated based on the weights of the contents in the buckets at the 2 min CTI as follows:

Runoff rate

$$RR_i = \frac{ZR_i}{2 \times 60} \qquad (i = 1, 2, \cdots, n) \tag{1}$$

Sediment rate

$$SR_i = \frac{ZS_i}{2 \times 60} \qquad (i = 1, 2, \cdots, n) \tag{2}$$

where RR_i and SR_i are the runoff and sediment rates at time i during the rainfall (units of g/s).

The runoff and sediment rates at 4, 6, 8 and 10 min were calculated based on the runoff and sediment collected during each 2 min CTI. The calculation methods are shown in Table 1.

Using the above data, a group of runoff and sediment curves was drawn. Then, these curves were used to analyze the effects of various CTIs on the dynamic characteristics of surface runoff and sediment production.

Scatterplots of the runoff rate vs. time and the sediment rate vs. time were drawn. Then, regression models between the runoff rate and runoff time and between the sediment rate and runoff time were created using the least squares method. The selected models had determination coefficients (i.e., R^2) greater than 0.90; least squares theory is commonly used for obtaining soil erosion models. The total amounts of runoff and sediment obtained within 30 min were determined by

Table 1
Methods for calculating runoff and sediment rates for the longer collection time intervals.

Collection intervals	Formulas	Descriptions
4 min	$RR_i = \frac{\sum(ZR_i + ZR_{i+1})}{4 \times 60}$ $SR_i = \frac{\sum(ZS_i + ZS_{i+1})}{4 \times 60}$	RR_i is runoff rate, SR_i is sediment rate (units of g/s); ZR_i and ZS_i are the weight of runoff and sediment, respectively (units of g); i is rainfall time, (unit of min).
6 min	$RR_i = \frac{\sum(ZR_i + ZR_{i+1} + ZR_{i+2})}{6 \times 60}$ $SR_i = \frac{\sum(ZS_i + ZS_{i+1} + ZS_{i+2})}{6 \times 60}$	
8 min	$RR_i = \frac{\sum(ZR_i + ZR_{i+1} + ZR_{i+2} + ZR_{i+3})}{8 \times 60}$ $SR_i = \frac{\sum(ZS_i + ZS_{i+1} + ZS_{i+2} + ZS_{i+3})}{8 \times 60}$	
10 min	$RR_i = \frac{\sum(ZR_i + ZR_{i+1} + ZR_{i+2} + ZR_{i+3} + ZR_{i+4})}{10 \times 60}$ $SR_i = \frac{\sum(ZS_i + ZS_{i+1} + ZS_{i+2} + ZS_{i+3} + ZS_{i+4})}{10 \times 60}$	

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