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Effects of four storm patterns on soil loss from five soils under natural rainfall

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ABSTRACT

The effects of rainfall intensity on erosion processes for intra-storm variations are extensively investigated based on rainfall simulation experiments. However, there is a distinction between natural and simulated rainfall. Soil loss data from a total of 84 erosive storms from 2006 through 2013 with hyetograph rainfall data were collected from five plots located in Beijing, each with soils from different Chinese zones, to investigate the effects of erosive storm patterns on soil loss under natural rainfall conditions and to detect if this influence was consistent among the five soil types. The storms were divided into four patterns according to the period of the most concentrated rainfall, including advanced, intermediate, delayed, and uniform patterns. The results indicate that 1) the prevalent storm pattern in Beijing is advanced, which accounts for 43% of storms and contributes the most to total soil loss (approximately 55 to 68%). 2) Storm pattern significantly affected soil loss, with the delayed pattern yielding more soil loss than the other three patterns after taking into account EI_{30}. 3) The effect of storm patterns on soil loss was consistent between the five soil types. 4) Coefficients for quantifying the effects of storm pattern on soil loss were not significantly different among these five soils, but exhibited significant differences among the storm patterns, e.g., the coefficient for the delayed pattern was 2.07, for the uniform pattern was 0.42, and for the advanced and the intermediate patterns were approximately 1. Rainfall erosivity generated by an erosive storm with a known pattern could be estimated by multiplying the corresponding adjustment coefficient, which would further improve the accuracy of soil erosion prediction, especially for storm level prediction.

1. Introduction

The Universal Soil Loss Equation (USLE) and its successors (RUSLE, RUSLE2) are widely used to predict long-term average annual soil erosion by water (Wischmeier and Smith, 1965, 1978; Renard et al., 1997; Foster, 2004). Rainfall erosivity (R) is one of the basic factors in the USLE and it is usually represented by the EI_{30} index, the product of the total storm energy and the maximum 30-min intensity during the storm, which reflects a storm's rainfall amount, intensity, and peak intensity. However, the factor does not account for storm pattern effect, which refers to the timing of peak intensity occurring within a storm (Flanagan et al., 1988), also defined as the rainfall event profile (Dunkerley, 2012). Wischmeier (1959) noted that the storm pattern was not taken into consideration when deriving the R factor for two reasons: (1) no significant effect of storm pattern on soil loss was found based on the statistical analysis of the unit plot data and (2) if the storm pattern does effect the relationship of EI_{30} to soil loss, the long-term average erosion impact could be ignored because different types of storms are randomly distributed in time, and thus serious bias is not likely to occur.

However, many researchers have demonstrated the influence of storm pattern on erosion processes, especially on runoff, soil loss, and particle distribution, under the conditions of rainfall simulation experiments (Flanagan et al., 1988; Zhang et al., 1997; Frauenfeld and Truman, 2004; Parsons and Stone, 2006; de Lima et al., 2012; Dunkerley, 2012; An et al., 2014). Flanagan et al. (1988) designed a programmable rainfall simulation to a 3 m wide by 9.9 m long plot, with six patterns delivering the same average intensity (64 mm h^{-1}) and duration (1 h). Four patterns reached a peak of 250 mm h^{-1}, respectively, at 0, 20, 40, and 60 min after the rain began. One pattern reached a peak of 125 mm h^{-1} at 20 min and one pattern had a uniform intensity of 64 mm h^{-1}. The results showed that the storm pattern had significant effects on runoff and soil loss under dry soil conditions. Storms peaking at 60 min yielded 4 to 8 times higher runoff rates and 1.5 to 8.5 times higher soil loss rates than storms peaking at earlier stages. Compared to uniform intensity storm patterns, the runoff rate (soil loss) was 6 times (3 times) higher. Parsons and Stone (2006) argued that storms with the same average intensity as those in Flanagan et al. (1988) cannot ensure different patterns generating equal kinetic energy. Therefore, five simulated storm patterns delivering the same total kinetic energy

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were designed with a constant intensity of 93.9 mm h^{-1}. These patterns were increasing, decreasing, rising then falling, falling then rising, and remaining constant. The study showed that runoff and soil loss were affected by storm patterns. Soil loss by uniform-intensity storms was 75% of that by variable-intensity storms.

Dunkerley (2008a) reported that rainfall records selected from 26 studies indicated a mean intensity of 3.47 mm h^{-1} and records from another 17 studies of extreme storms showed a mean maximum intensity of 86.3 mm h^{-1}, which was notably lower than the intensity generally used in simulations. For example, Flanagan et al. (1988) selected 64 mm h^{-1} as the mean intensity and 250 mm h^{-1} as the peak intensity; Zhang et al. (1997) had 50 mm h^{-1} as the mean intensity and 125 mm h^{-1} as the peak intensity; Parsons and Stone (2006) designed the mean intensity larger than 90 mm h^{-1} and the peak intensity of 150 mm h^{-1}, etc. According to rainfall intensity classification by Tokay and Short (1996), the rainfall intensity exceeding 20 mm h^{-1} can be defined as extreme intensity. Considering that the high rainfall intensity used in previous studies may not be realistic, Dunkerley (2012) conducted simulated storms with a mean intensity of 10 mm h^{-1} and a peak intensity of 30 mm h^{-1}. He reported runoff ratios and peak runoff rates for the experiments with varying intensity measuring of 85 to 570% greater than those with uniform intensity.

Previous studies based on simulated rainfall are difficult to extrapolate to natural rainfall conditions. Analysis of natural storms is necessary to explore the relationship between storm patterns and soil loss. Aquino et al. (2013) divided 139 natural storms in Brazil into three patterns—advanced, intermediate and delayed—and conducted comparisons on total erosion and per event erosion among these three patterns of typic dystrophic Tb Haplic Cambisol (CXbd) and typic dystrophic Red Latosol (LVdf) two soils (classified according to Brazilian System of Soil Classification). The results demonstrated that the advanced pattern dominated and yielded the largest soil loss (1998–2002) among these three patterns. However, in examining per event erosion, the delayed pattern yielded the most erosion for CXbd soils, whereas, the advanced pattern yielded the most erosion for LVdf soils.

The effect of storm patterns on soil loss was not consistent with different soils. Zhang et al. (1997) applied different storm patterns on Cecil and Miami soils. The results indicated that Miami soils yielded the highest soil loss under the delayed pattern; whereas, Cecil soils yielded the highest soil loss under the advanced pattern. In Parsons and Stone (2006), three soil types including clay loam, sandy loam and sandy soils yielded the highest soil loss under the delayed, advanced and intermediate patterns, respectively. Frauenfeld and Truman (2004) demonstrated that the uniform-intensity pattern yielded more soil loss than the variable-intensity pattern for Tifton loamy sand; however, this was not the case for Greenville sandy clay loam.

Wischmeier (1959) also argued that storm patterns were randomly distributed in time; therefore, ignoring storm patterns does not influence long-term prediction of EI_{30}. In fact, for some areas, there could be one or two prevalent storm patterns. For example, in South Africa, approximately 84% of the storms with peak intensity occur during the first half of duration (Werner, 2007); in the Rio de Janeiro State of Brazil, advanced and delayed conditions are the prevailing patterns in moist and dry periods, respectively (Machado et al., 2008); in the Minas Gerais State of Brazil, the advanced pattern accounts for 60% of total storms (Aquino et al., 2013); and in China, 47.1% of storms have rainfall concentrated during the first third of duration for the entire year, and 52.2% for the summer season (Yin et al., 2014). If the storm pattern impacts the EI_{30} index, then the seasonal variation of rainfall erosivity on soil loss must be taken into consideration. Furthermore, soil loss caused by a single storm sometimes must be estimated, such as for non-point source pollution (Kinnell, 2000; Zhang and Zheng, 2004; Sun et al., 2009) and hazard assessment, in which case, the impact of storm patterns on soil loss should not be ignored.

The purpose of this study was to (1) investigate whether storm patterns influence soil loss under natural rainfall conditions, (2) detect if this influence is consistent among five soil types, and (3) design an adjustment coefficient to improve the EI_{30} index in soil loss estimation under different rainfall patterns. This finding could be meaningful for improving prediction accuracy for soil loss by rainfall erosivity, especially at the event scale.

2. Materials and methods

2.1. Database of rainfall and soil loss

Five plots were constructed in 2005 at the Experimental Field Station of the State Key Laboratory of Earth Surface Processes and Resource Ecology in the Fangshan District (39.75°E, 116.13°N), Southwest of Beijing, where the climate is a typical warm temperate, semi-humid, continental monsoon climate with an annual average temperature of 12.9 °C and mean annual precipitation of 539.6 mm (Fig. 1). The precipitation mainly concentrates during the flood season from June through September. Pluviograph rainfall records from 2006 through 2013 were collected to determine storm patterns and EI_{30} index. Pluviograph data were interpreted from pluviograph paper chart recorded by a siphon self-recording rain gauge. Records for 2006 were incomplete because the self-recording rain gauge had not been installed until July 9. Records for 2013 were partially discarded because of a malfunction of the self-recording rain gauge. Data after May 9, 2013, were credible and therefore utilized.

The plots are with a slope of 5 degrees, width of 2.1 m (equivalent to the width of 3 rows of corn), and horizontal length of 20 m, which are only slightly different in length from the unit plot of 22.1 m defined by Wischmeier and Smith (1965). In the five plots, 0 to 20 cm depth was filled with Black soils, Cinnamon soils, Loessial soils, Purplish soils, and Red soils, according to the Genetic Soil Classification of China (Shi et al., 2010), and Mollisols, Alfisols, Entisols, Inceptisols, and Oxisol, according to the U.S.A. taxonomy respectively (Soil Survey Staff, 1999). The soils were sampled from Heilongjiang province in Northeast China (49.17°N, 125.22°W), Beijing municipal in North China (40.37°N, 116.85°W), Shaanxi province in Northwest China (38.29°N, 109.75°W), Sichuan province in Southwest China (30.79°N, 106.08°W), and Fujian province in Southeast China (25.07°N, 118.18°W), respectively. The particle distribution and organic matter content of the investigated soils are shown in Table 1. Each plot was filled with Cinnamon soil (a type of local soil in Beijing) at a depth of 20 to 50 cm. The plots were annually tilled along the slopes around April to keep a continuous, fallow condition (Bajracharya and Lal, 1992). Light chiseling eliminated the visible crust when necessary. On a semi-monthly basis, the plots were weeded by hand (no herbicide) to maintain vegetation coverage under 5%.

The collection system for each plot was designed with the intention that all of the runoff could be collected in the tanks without spillover (Fig. 1). A trough was built on the lower end of the plot to collect runoff. The trough has dimensions of width of 0.10 m, depths of 0.05 m on both sides of the plot, and 0.11 m at the center. The trough bottom is inclined at 5.7% slope from both sides to the center where the runoff outlet is located. The pipe connecting the plot trough to the diversion barrel is 0.075 m in diameter and 0.170 m in height difference (water head). According to the pipe flow equation (Eq. (1)), the maximum flow rate through the pipe is 0.004997 $m^3\ s^{-1}$, which corresponds to runoff depth per unit time of 428.4 mm h^{-1}, given the plot size of $2.1\ m * 20\ m = 42\ m^2$. The Beijing area (the plot location) has never had such a heavy rain. The largest peak intensity among all the observed data in this study was 176.4 mm h^{-1}, and the maximum 30-min intensity I_{30} was 87 mm h^{-1}.

$$Q = 0.62 \cdot A \cdot \sqrt{2gH} \qquad (1)$$