



# Effects of rainfall intensities on sediment loss and phosphorus enrichment ratio from typical land use type in Taihu Basin, China

Lixia Yang<sup>1</sup> · Guishan Yang<sup>2</sup> · Henpeng Li<sup>2</sup> · Shaofeng Yuan<sup>3</sup>

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## Abstract

Soil erosion induced by rainfall has become one of the major environmental disasters. It can lead to degradation of land productivity and water pollution, which limit human survival and development. Therefore, understanding the effects of rainfall intensities on soil nutrient and sediment transportation from farmland via surface runoff is important. This study simulated three types of rainfall intensities (low intensity  $0.83 \text{ mm min}^{-1}$ ; medium intensity  $1.17 \text{ mm min}^{-1}$  and  $1.67 \text{ mm min}^{-1}$ ; and high intensity  $2.50 \text{ mm min}^{-1}$ ). Field plots were established to evaluate the effects of rainfall intensities on sediment yield and phosphorus enrichment ratio ( $ER_P$ ) in runoff sediment. Each plot was 2 m long and 1 m wide. The rainfall lasted for 30 min after effective runoff generation. Runoff and sediment, as well as the phosphorus (P) concentration of sediment, were measured. Results showed that the low rainfall intensity had a longer time to begin runoff than high rainfall intensity. The runoff volume increased with the rainfall intensity; however, no obvious differences were observed in the runoff rate under three rainfall intensities, except for  $2.50 \text{ mm min}^{-1}$ . The curve value of sediment concentration increased after 5–10 min of effective runoff decreased slightly, and then relatively became stable after 20 min of effective runoff. Although no obvious differences were observed in the dynamic changes of sediment concentration and rainfall intensity, a power function existed between rainfall intensity and sediment loss. The similar curves of  $ER_P$  value showed that it was higher in the initial stage, decreased gradually, and reached a stable level after 25 min of effective runoff, which varied around 1. During the rainfall–runoff event, no significant correlation was noted between  $ER_P$  and sediment yield. Whether any relationship existed between them needs to be further studied by setting up different field plots under large-scale conditions. The findings of this study provide valuable aid to farmers on how to manage farmland effectively to prevent soil nutrient loss and reduce water eutrophication.

**Keywords** Soil erosion · Rainfall intensity · Sediment · Runoff · Nutrient · Enrichment ratio · Phosphorus · Taihu Basin

## Introduction

Soil erosion is one of the main environmental issues in ecosystems (Eswaran et al. 2001; Zheng et al. 2005; Terranova et al. 2009; Zhang et al. 2011; Abrol et al. 2013). It can cause some serious consequences, including soil degradation, cropland productivity reduction, and water environment eutrophication (Kumar and Saha 2011; Yang et al. 2014; Liu et al. 2015a, b). The United Nations Environmental Program (1991) reported that soil degradation rate is estimated to be occurring on approximately  $20 \times 10^6$  ha per year. The first census of water and soil conservation in the National Water Survey indicated that the soil erosion area in China is 295 million ha, which is up to 31.1% of the total census area (MEPPRC 2016). Soil degradation caused by water is the

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✉ Guishan Yang  
gsyang@niglas.ac.cn

✉ Shaofeng Yuan  
shaofengyuan1975@163.com

<sup>1</sup> School of Public Administration, Zhejiang University of Finance and Economics, Hangzhou 310018, China

<sup>2</sup> Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China

<sup>3</sup> Department of Land Resources Management, Zhejiang Gongshang University, Hangzhou 310018, China

main type in China. Topsoil is washed away by rainfall–runoff, snowmelt, and irrigation. The area by water erosion is up to 56.4% of the total land area (Zou et al. 2001). Rainfall is the most important driving force of water erosion and has become a research focus in fields related to soil erosion (Oztas et al. 2003; Jin et al. 2004; Liu et al. 2015a, b; Napoli et al. 2017). Erosion caused by rainfall includes a two-phase process, that is, soil particle detachment and sediment movement by flowing water (Defersha et al. 2011), which are controlled by the kinetic energy of raindrop splash. Therefore, rainfall can change the condition of soil aggregates and lead to soil nutrient loss (Berger et al. 2010; Zhu 2012).

Among rainfall characteristics, rainfall intensity affects surface runoff generation and nutrient concentrations in runoff (Ran et al. 2012; Zhao et al. 2015; Zhou et al. 2016). Therefore, the effects of rainfall intensities on soil erosion have been discussed by many researchers (Bradford et al. 1987; Römkens et al. 2001; Parsons and Stone 2006). Mermut et al. (1997) observed that the load of rainfall splash under a rainfall intensity of  $100 \text{ mm h}^{-1}$  was 2.5–4 times that of  $40 \text{ mm h}^{-1}$ . Marques et al. (2008) found that sediment yield in highly intensive events was obviously greater than that in medium intensive events. Ran et al. (2012) indicated that high rainfall intensity produces a high runoff peak. Raindrop splash of high rainfall intensity increases soil particle detachment and can transfer increased suspended sediment load because a high rainfall intensity results in a high runoff volume (Rose 1993). Mohamadi and Kavian (2015) found that a linear relationship exists between soil loss and rainfall intensity in low rainfall intensities. Many studies have explored the effects of rainfall intensities on sediments and nutrient discharging into water environment in farmlands, paddy fields, and pastures. However, the dynamic process of sediment and phosphorus (P) loss transported by runoff from vegetable lands in relation to rainfall intensity is not well known. Vegetable lands with high fertilizer application are distributed along tributaries, canals, and ditches of Taihu. Soil nutrients from vegetable lands easily enter the surrounding water bodies through surface runoff; this phenomenon is a considerable threat to water environment. As the third largest freshwater lake in China, Lake Taihu is a primary drinking water source. However, in recent years, frequent cyanobacteria outbreaks caused by agricultural non-point sources have resulted in serious water eutrophication in Lake Taihu. Therefore, this study aims to estimate the dynamic characteristics of sediment concentration and investigate the effects of rainfall intensities on sediment P concentration and enrichment ratio (ER) in vegetable lands. This study can provide valuable guide for farmers in farmland cultivation and management. The findings can also provide experimental parameters of non-point source pollution models for estimating sediment nutrient losses.

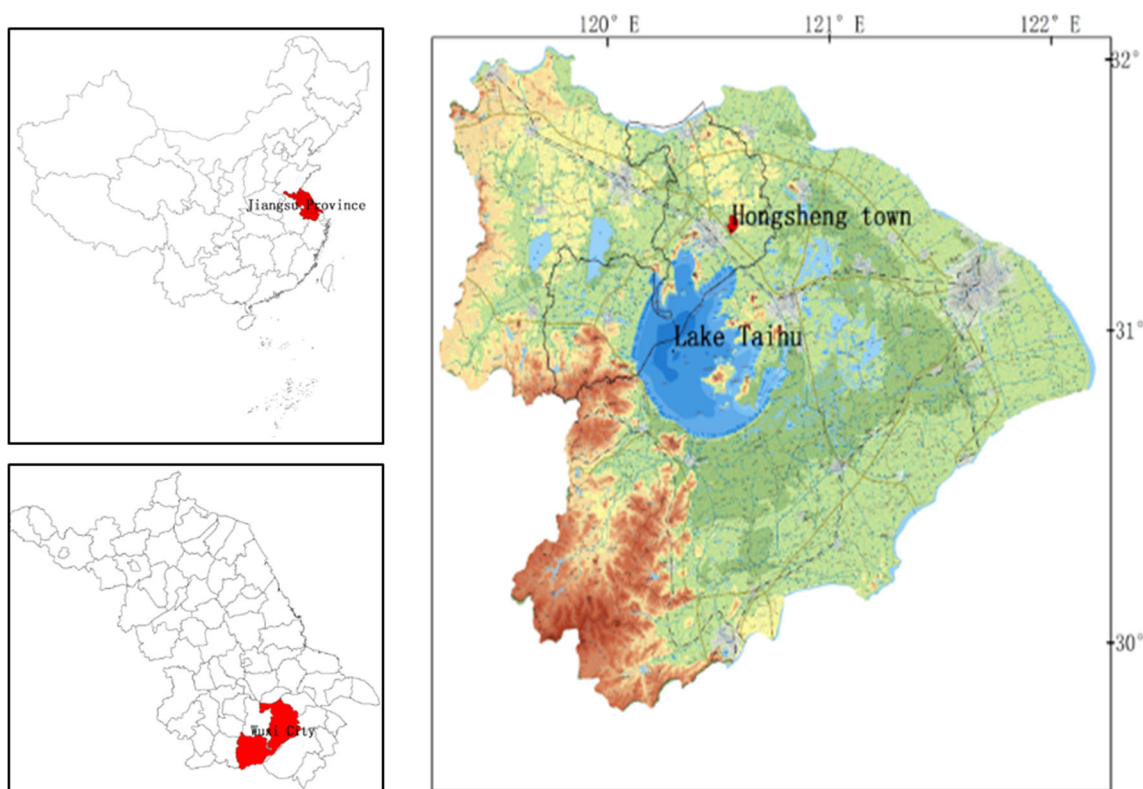
## Materials and methods

### Study area

The experiment was set up in a typical land use type of Hongsheng Town, Wuxi City, Jiangsu Province, in the upper river basin of Lake Taihu (Fig. 1). Given preponderant geographical location, many vegetables have been planted in the town to supply for Wuxi City. Vegetable land is considered a typical land use type in the Taihu Basin, which has high P content in soils because a large amount of fertilizers are amended into the soil with extensive plantation time. The study area has more than 10 years for experiment plots. The climate has an average annual temperature of  $15.5 \text{ }^{\circ}\text{C}$  and an average annual rainfall of 1000 mm, with most of the rain falling in May to September. The agricultural land has a high multiple-crop index due to good natural conditions, which results in high fertilizer input. In view of the fertilization practice used by local farmers, rates of inorganic nitrogen fertilizer (carbamide), P fertilizer (superphosphate phosphate), and potassium fertilizer (potassium chloride) are 200, 75, and  $100 \text{ kg ha}^{-1}$  by surface broadcast, respectively. The surface soil (0–15-cm depth) in vegetable field was collected. On the basis of the United States Department of Agriculture classification system, the soil texture in the plots is a silt loam type. The bulk gravity is  $1.23 \text{ g cm}^{-3}$ . The soil has  $29.75 \text{ g kg}^{-1}$ ,  $1.23 \text{ g kg}^{-1}$ , and  $174.47 \text{ mg kg}^{-1}$  of organic matter, total P, and Olsen P. The pH and water content of the soil are 5.85 and 13.30%, respectively.

### Simulated rainfall experiments

Rainfall was generated by a portable artificial rainfall simulator of BX-1 type (Institute of Soil and Water Conservation, Chinese Academy of Science). The equipment consisted of a nozzle, a driver, and dynamic water supply systems. By adjusting the nozzle sizes and changing water pressure, this equipment could splash different raindrops in the range of  $10\text{--}332 \text{ mm h}^{-1}$ . The height for this simulation equipment was 6 m. This instrument had a uniformity coefficient of  $>80\%$  within  $3 \times 5 \text{ m}^2$ . On the basis of the local historical rainfall records and average recurrence periods, the simulated rainfall intensities were set to low intensity ( $0.83 \text{ mm min}^{-1}$ ), medium intensity ( $1.17 \text{ mm min}^{-1}$  and  $1.67 \text{ mm min}^{-1}$ ), and high intensity ( $2.50 \text{ mm min}^{-1}$ ). Experimental plots were rectangular with a size of  $1 \times 2 \text{ m}^2$  with a random block design and uniform vegetable coverage density. The runoff frame borders for the sides of the test plots were constructed from PVC boards, whereas the bottoms were constructed from steel equipment. The top and side of each plot were surrounded by PVC borders. These PVC borders were inserted into the soil depth at approximately 15 cm, which



**Fig. 1** Experimental site at Hongsheng Town, Wuxi City, Jiangsu Province

was 10 cm higher than the soil surface. Each experiment was conducted in three replicates, and a total of 10 simulated rainfalls were conducted. For different rainfall intensities, the rainfall lasted 30 min after effective runoff generation for each treatment. All the data used in the figure are the average values of the experimental data.

When the simulated rainfall began, the time for simulating rainfall and the initiation time for producing runoff were recorded. All runoff and sediment samples were collected in a marked plastic container on a 5-min interval for 30 min. Runoff volumes were measured. By stirring the samples, 500 ml of each sample was taken to measure the sediment concentration and sediment P loss. These samples were stored in a refrigerator at 4 °C for analyzing different items. During the simulated rainfall, rainwater was collected as a blank contrast.

The following properties of soil samples were measured: pH (water-to-soil ratio of 2.5:1, glass electrode), total P ( $\text{HClO}_4\text{--H}_2\text{SO}_4$  digestion, molybdenum blue colorimetry), Olsen P ( $\text{NaHCO}_3$ , molybdenum blue colorimetry), organic matter ( $\text{K}_2\text{CrO}_7\text{--H}_2\text{SO}_4$  oxidation), bulk specific gravity (loop reamer), and soil containing water content (drying method). The methods are detailed in the “Analytical Handbook of Soil Agricultural Chemistry” (Lao 1988). Sediment concentration was determined by dry weight method. The total P in sediment was measured by  $\text{HClO}_4\text{--H}_2\text{SO}_4$  digestion and molybdenum blue colorimetry.

The total P contents in parent soils and sediments were measured. The P enrichment ratio ( $ER_p$ ) in sediments is calculated as follows (Li et al. 2016):

$$ER_p = P_{\text{sediment}}/P_{\text{plot-soil}}, \quad (1)$$

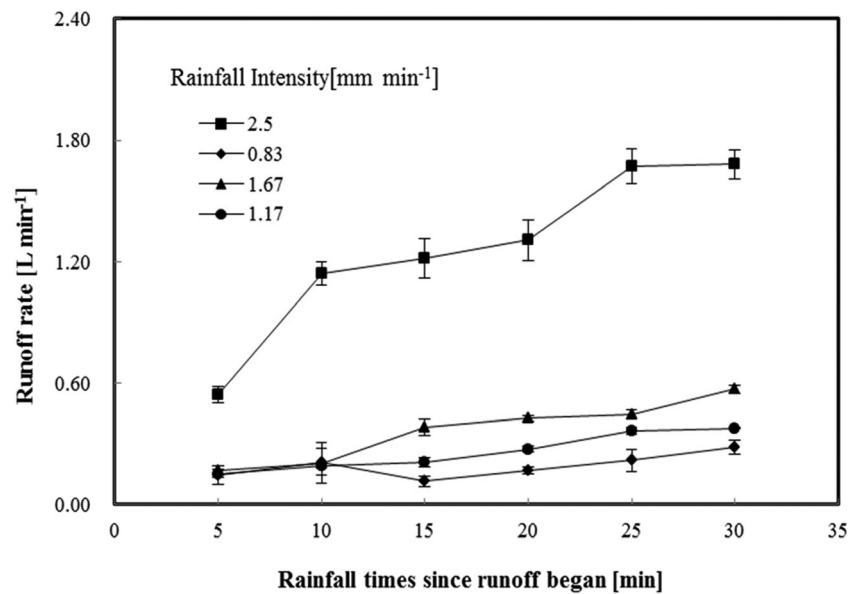
where  $P_{\text{sediment}}$  is the P content in sediments, and  $P_{\text{plot soil}}$  is the P content in plot soils.

## Results

### Effects of rainfall intensities on runoff rate and runoff yield

With the increase in rainfall intensity, the time to begin runoff had the following values: 31.20, 15.80, 10.40, and 4.27 min. The low rainfall intensity had a longer time to begin runoff than high rainfall intensity. The dynamic process of runoff rate showed no significant differences between the other three rainfall intensities, except for high intensity ( $2.50 \text{ mm min}^{-1}$ ; Fig. 2). In high intensity ( $2.50 \text{ mm min}^{-1}$ ), the runoff rate increased rapidly, the soil infiltration capacity decreased, the time when runoff began was relatively shortened, and the runoff increased considerably. During a 30-min rainfall after the runoff began, the high rainfall intensity ( $2.50 \text{ mm min}^{-1}$ ) produced  $18.91 \text{ L m}^{-2}$  runoff yield, which was 3, 5, and 7

**Fig. 2** Runoff rate with rainfall times since runoff began for different rainfall intensities



times that of the other three rainfall intensities. The effects of rainfall intensities on runoff yield were evident.

**Effects of rainfall intensities on sediment loss**

As shown in Fig. 3, no obvious differences were found in the dynamic change of sediment concentration. Except for 2.50 mm min<sup>-1</sup>, sediment concentration was higher after 5–10 min of effective runoff, and sediment concentration decreased slightly with the rainfall duration. The relatively stable stage of sediment concentration occurred after 20 min of effective runoff. During the rainfall duration, the average sediment concentration for 2.50 mm min<sup>-1</sup> was 2.85 g L<sup>-1</sup>, which was highest in all rainfall intensities. Average sediment concentration for the other three rainfall intensities varied from

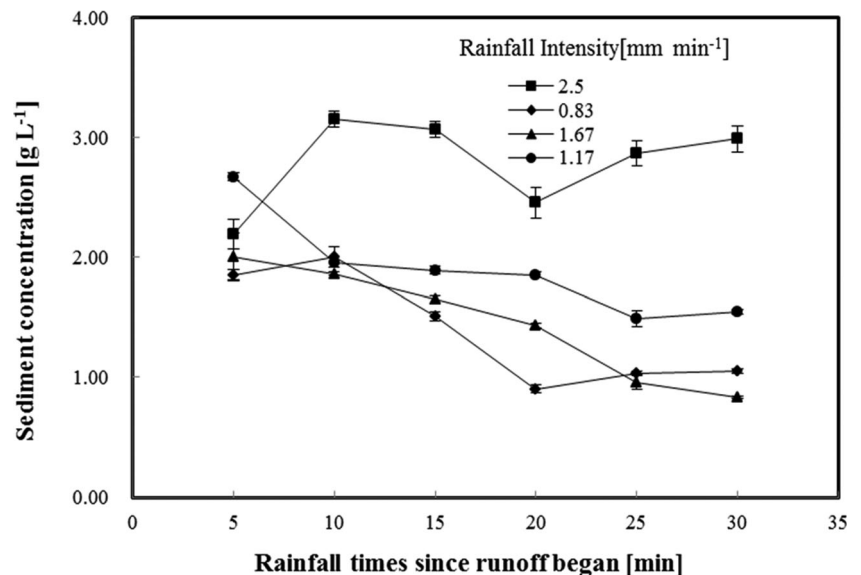
1.30 to 1.79 g L<sup>-1</sup>. Therefore, sediment losses were more sensitive to the runoff caused by high intensity than for runoff caused by low and medium rainfall intensities.

When the rainfall intensity increased from 0.83 to 1.67 mm min<sup>-1</sup>, the sediment loss increased by 2 times; however, sediment loss increased rapidly by 7.51 times when rainfall intensity increased from 1.67 to 2.50 mm min<sup>-1</sup>. Hence, a critical point for sediment loss was observed between 1.67 and 2.50 mm min<sup>-1</sup>. Therefore, rainfall intensity had an obvious effect on sediment loss.

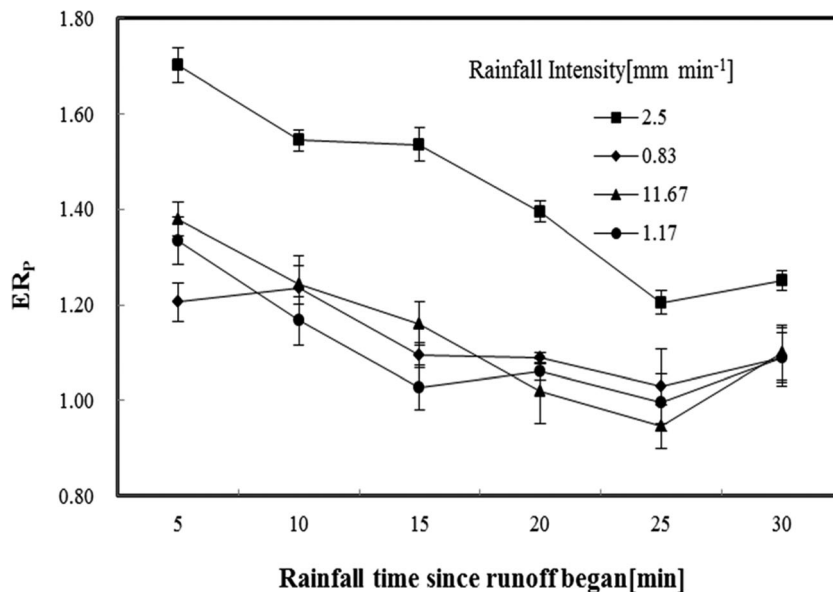
**Effects of rainfall intensities on ER<sub>p</sub> in sediment**

The curves of ER<sub>p</sub> values in sediment under different rainfall intensities are shown in Fig. 4. The ER<sub>p</sub> values from high to

**Fig. 3** Characteristics of sediment concentration in runoff for different rainfall intensities



**Fig. 4**  $ER_p$  in sediment for different rainfall intensities



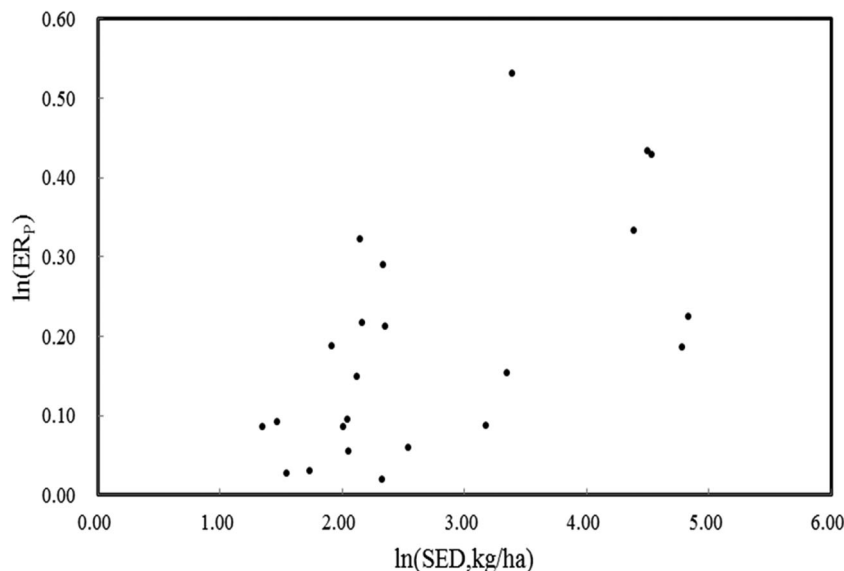
low rainfall intensity varied in the ranges of 1.20–1.70, 0.95–1.38, 1.00–1.30, and 1.03–1.21; all of these values varied around 1. The  $ER_p$  curves had similar shapes.  $ER_p$  was higher in the initial stage, decreased gradually, and reached a stable level after 25 min of effective runoff because the fine clay content, which was detached and transported by rainfall–runoff, absorbed a high P nutrient in the initial stage. During the rainfall–runoff, the total P concentration in sediment for the four types of rainfall intensity decreased by 26%, 20%, 18%, and 12%. This result was mainly caused by the coarse soil particles, which were detached and transported by rainfall–runoff; these particles absorbed low P nutrient, and the runoff volume increased gradually, which had a dilution effect on the sediment P erosion. Although the total changing trend was similar for all rainfall intensities, the  $ER_p$  for 2.50 mm min<sup>-1</sup>

was the highest in the 30 min of effective runoff, which showed a critical value between 1.67 and 2.50 mm min<sup>-1</sup>. This critical value must be further studied. The average  $ER_p$  for different rainfall intensities increased with the rainfall intensity. In the entire rainfall event, no significant connection was found between  $ER_p$  and sediment yield (Fig. 5).

**Discussion**

The present study clearly demonstrates that rainfall intensity is an important factor that influences runoff, which affects not only the speed of runoff formation but also the runoff volume. Many researchers have analyzed the effect of rainfall on runoff. Some researchers have demonstrated that infiltration rate

**Fig. 5** Changes in  $\ln(ER_p)$  with  $\ln(SED)$  under different rainfall intensities



increases with rainfall intensity, and runoff volume might decrease due to the spatial heterogeneity of soil infiltration (Römken et al. 1990; Parsons and Stone 2006; Mu et al. 2015). Other researchers have indicated that runoff volume increases with rainfall intensity (Zhang and Liang 1995), which is similar to findings of the present study. At the beginning of rainfall, soil infiltration capacity is greater than that of rainfall volume. With the increase of rainfall, the soil surface water content increases gradually and the infiltration capability of soil gradually decreases due to soil crust formation. When the infiltration rate is equal to or less than the rainfall intensity during soil surface sealing, the soil surface begins to accumulate water and produces surface runoff (Römken et al. 2001; Dijk et al. 2002). The surface runoff increases gradually with the rainfall duration and the decrease in infiltration rate. The results of this study show that rainfall intensity has an obvious effect on initial runoff time and runoff yield.

Sediment loss induced by rainfall–runoff events includes two physical processes, namely detachment and transportation of soil particles (Defersha et al. 2011; Sirjani and Mahmoodabadi 2012). Raindrop splash detaches soil particles from the soil surface and produces detached materials that can be transported by runoff (Sadeghi et al. 2017). Transportation rate resulting from transferring the splashed particles away from the soil surface depends on the force of water flowing by rainfall (Ali et al. 2012). The on-site consequences of detaching and transporting soil particles are mainly soil degradation, and the off-site consequences can result in sediment and nutrients being transferred by runoff away into natural water bodies (Blanco and Lal 2010; Noor et al. 2013). Therefore, nutrient attached in sediment is easily transported by runoff (Schoellhamer et al. 2007; Fazli and Noor 2013). Different rainfall intensities have varied effects on sediment loss due to the various dynamic energy of raindrop splash and detaching parent soil particles. The volume of loose soil particles detached by runoff greatly increases with rainfall intensity. Therefore, detached particles splashed by raindrop are rich in high rainfall intensity. The raindrop splash energy of high rainfall is greater than that of low rainfall intensity, which can lead to a relatively greater sediment transport capacity. In this study, a power function relationship is observed between rainfall intensity and sediment loss. Bouraima and He (2016) observed that the relationship between sediment and rainfall intensity is an exponential function. Wang et al. (2013) observed a positive correlation between rainfall intensity and runoff loss of soil organic carbon via an experiment. The growth of water algae is enhanced when P concentration exceeds  $0.02 \text{ mg L}^{-1}$  (Moore et al. 1992). However, in the entire rainfall–runoff process in this experiment, sediment-associated P concentration is higher than the limited concentration. At concentrations exceeding the threshold levels, nutrient transportation in surface runoff associated with sediment from vegetable fields can enhance the growth of aquatic plants and become a potential threat to the surrounding water environment.

The process of soil particle being transported by rainfall is essentially a selective process of particle size. Abundant nutrient content is stored in fine particles. These fine-textured particles are easily moved due to their features, which result in nutrient enrichment in sediments in comparison with that of the parent soil (Sharpley 1985; Quinton et al. 2001). ER has been defined as the ratio of nutrient content between the eroded sediment and the parent soil (Massey and Jackson 1952). On the basis of several experiments and models, the general conclusion is that  $ER_{\text{nutrient}}$  is greater than 1 (Panuska and Karthikeyan 2010). Young et al. (1986) found that the value of ER approaches 1 for different rainfall intensities, which correspond with the result of the experiment in the present study. Some researchers have shown specific linear equation relationships between ER and sediment loss (Menzel 1980; Young et al. 1989). However, no significant correlation between  $ER_p$  and sediment yield is observed in the present work. The effect of  $ER_p$  on sediment loss is unclear and should be further explored by setting up different experiments at a larger scale.

## Conclusions

Low rainfall intensity had a longer time to begin runoff compared with high rainfall intensity. The runoff volume increased with rainfall intensity. No obvious differences in runoff rate were obtained among the other three rainfall intensities, except for high rainfall intensity ( $2.50 \text{ mm min}^{-1}$ ). No distinct difference was observed in the dynamic change of sediment concentration and rainfall intensity. The  $ER_p$  curves had similar shapes, and all  $ER_p$  values varied around 1.  $ER_p$  was higher in the initial stage, decreased gradually, and reached a stable level after 25 min of effective runoff. The average  $ER_p$  for different rainfall intensities increased with rainfall intensity. In the entire rainfall–runoff event, no distinct correlation was found between  $ER_p$  and sediment yield.

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