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Effects of urban grass coverage on rainfall-induced runoff in Xi'an loess region in China

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Abstract

In this study, laboratory rainfall simulation experiments were conducted to investigate the regulatory effects of grass coverage on rainfall-runoff processes. A total of 80 grass blocks planted with well-grown manilagrass, together with their root systems, were sampled from an eastern suburban area of Xi'an City in the northwest arid area of China and sent to a laboratory for rainfall simulation experiments. The runoff and infiltration processes of a slope with different grass coverage ratios and vegetation patterns were analyzed. The results show that the runoff coefficient decreases with the increase of the grass coverage ratio, and the influence of grass coverage on the reduction of runoff shows a high degree of spatial variation. At a constant grass coverage ratio, as the area of grass coverage moves downward, the runoff coefficient, total runoff, and flood peak discharge gradually decrease, and the flood peak occurs later. With the increase of the grass coverage ratio, the flood peak discharge gradually decreases, and the flood peak occurs later as well. In conclusion, a high grass coverage ratio with the area of grass coverage located at the lower part of the slope will lead to satisfactory regulatory effects on rainfall-induced runoff.

Keywords: Rainfall simulation; Urban vegetation in arid area; Rainfall-runoff process; Regulatory effect; Xi'an loess region

1. Introduction

In the process of urbanization, natural vegetation and agricultural land are being replaced by urban impervious land (Dobbs et al., 2014; Morse et al., 2003; Robinson and Lundholm, 2012; Savva et al., 2010; Wang et al., 2001). The increase in urban impervious land surface results in drastic changes in urban hydrology, such as an increase in total rainfall-induced runoff, a sharp increase in peak flow, and an earlier occurrence of the flood peak (Fletcher et al., 2013; Han and Burian, 2009; Jacobson, 2011; Miller et al., 2014). These phenomena have intensified the threat of urban storm floods, and the world has become more concerned with the resulting urban waterlogging issues.

In view of these problems, many scholars suggest that priority be given to the development of eco-friendly *sponge cities* (Argent et al., 2008; Juncosa et al., 2007; Liu et al., 2016). The improvement of urban ecology is closely related to the full play of various types of urban vegetation (Mason et al., 2010; Mitchell et al., 2016; Scholz and Yazdi, 2009; Sheets and Manzer, 1991). As a kind of natural osmosis mechanism, urban vegetation not only collects and stores rain water and increases soil infiltration, but also reduces flood peak discharge, delays flood peak occurrence, and mitigates urban waterlogging (Cerdà, 2001; Dwivedi and Sreenivas, 2002; Li, 2012; Piekarczyk et al., 2012; Zhao et al., 2004). Studying the regulatory effects of urban vegetation on rainfall-induced runoff is highly significant to preventing urban waterlogging and utilizing flood water.

Many studies have been conducted on the relationship between urban vegetation and rainfall-runoff processes, and

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numerous achievements have been made. For example, hydrological models have been used to study factors in urban rainfall-runoff processes (Cuo et al., 2010; Jacobson, 2011; Yang and Wang, 2014; Yu and Lane, 2006; Zoppou, 2001), the effects of urban land use on rainfall-runoff processes, the effects of the type and coverage of vegetation on rainfall-runoff processes (Blanco et al., 2004; Dunne et al., 1991; Marques et al., 2007; Pan and Shangguan, 2006), the relationship between vegetation surface runoff and rainfall intensity, and the control of urban storm floods (Cerdà et al., 2016; Ellis et al., 2012; Melville and Morgan, 2006; Pitt et al., 2008; Susca et al., 2011). However, most of these studies have focused on rainy and wet regions and few on arid regions where water resources are relatively deficient.

In this study, a total of 80 grass blocks, each sized 0.5 m × 0.5 m × 0.5 m, were taken from a well-grown grass slope in the eastern suburban area of Xi'an City in Shannxi Province of China and sent to a laboratory for rainfall simulation experiments in order to investigate the effects of urban grass coverage on rainfall-runoff processes. The main purposes of the study were (1) to analyze the runoff and infiltration processes of urban land covered with vegetation at different coverage ratios, (2) to investigate the regulatory effects of grass coverage on rainfall-runoff processes, and (3) to analyze the effects of grass coverage on the flood peak discharge and occurrence time of the flood peak. This study was carried out to provide a scientific basis for storm flood control in cities in arid regions.

2. Materials and methods

2.1. Experimental materials

Experimental loess was taken from the eastern suburban area of Xi'an City. Soil samples were dried, screened, and purified, with the moisture content and dry bulk density limited to around 11% and 1.30 g/cm^3, respectively. The well-grown manilagrass with root systems was sampled from the field, and sent to the laboratory for one-week curing before use. Grass blocks sized 0.5 m × 0.5 m × 0.5 m were used in the experiment.

2.2. Experiment design

In rainfall simulation experiments, the rainfall intensity and slope gradient were determined to be 2.0 mm/min and 21°, respectively. Four grass coverage ratios were used in the experiment: 0% (bare slope), 25%, 50%, and 75%. Several vegetation patterns were selected, depending on the position of vegetation and grass coverage ratio, with the 25% coverage ratio scenario including four patterns (L1, IL1, IU1, and U1), the 50% coverage ratio scenario including five patterns (L2, M2, U2, IL2, and IU2), and the 75% coverage ratio scenario including two patterns (L3 and U3), as shown in Fig. 1.

The experimental soil bin was 4 m long, 1 m wide, and 0.8 m high. Each soil bin was divided into four grids, each having a plane size of 1 m × 1 m. Before the experiment, a 20 cm-thick natural sand layer was laid at the bottom of the soil bin to ensure that the soil permeability was uniform and close to the natural state. Subsequently, experimental soil and grass blocks with a thickness of 50 cm were laid on the sand layer to form different vegetation patterns, as shown in Fig. 1. Gaps between soil and grass blocks were filled with soil that was compacted to prevent the grass blocks from sliding during rainfall.

Twelve rainfall simulation experiments were conducted for the twelve vegetation patterns (L0, L1, IL1, IU1, U1, L2, M2, U2, IL2, IU2, L3, and U3). In the experiment, rainfall was produced using tap water from lateral jets, 4 m above the ground. Rainfall drops (with a median diameter of 2.2 mm) followed a parabolic trajectory and fell vertically to the soil surface nearly at the terminal velocity with a controllable intensity and a uniformity of over 85%. The rainfall lasted for more than 60 min in each run. Plastic containers with a volume of 20 L were used to collect the runoff output from the soil bins at a 1-min interval.

3. Results and discussion

3.1. Runoff process

As shown in Fig. 2, runoff gradually increases as rainfall continues, and the runoff generation from the slope in scenarios with grass coverage is lower than that in the bare slope scenario.

At a 25% coverage ratio, the initial runoffs of the vegetation patterns L1, IL1, IU1, and U1 were 2.44 L, 1.05 L, 1.99 L, and 2.14 L, respectively, showing small differences between one another. However, the influence of the vegetation pattern on the reduction of runoff varies greatly. During each run of the rainfall simulation experiments, the total runoff from the slope for different vegetation patterns decreases in the order of U1, IU1, IL1, and L1, indicating that the vegetation pattern with the area of grass coverage located at the lower part of the slope reduces runoff generation more than other patterns (Fig. 2 (a)).

At a 50% coverage ratio, the total runoff from the slope decreases in the order of U2, IU2, M, IL2, and L2, also indicating that the vegetation pattern with the area of grass coverage located at the lower part of the slope controls runoff generation more than other patterns. In general, the controlling effect at a 50% coverage ratio is better than that at a 25% coverage ratio. Nevertheless, the runoff process at a 50% coverage ratio seems chaotic and lacks regularity (Fig. 2(b)).

At a 75% coverage ratio, the total runoffs from the slope were 171.13 L and 193.55 L for vegetation patterns L3 and U3, respectively, during each run of the rainfall simulation experiments, indicating the better effect of pattern L3 on the reduction of runoff than that of pattern U3 (Fig. 2(c)). Compared with 25% and 50% coverage ratios, there is a significant reduction of slope runoff at a 75% coverage ratio.

At 0% coverage ratio (bare slope), the total runoff from the slope was 352.55 L. The average values were 250.58 L, 221.59 L, and 182.34 L at 25%, 50%, and 75% coverage

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