Journal of Hydrology 513 (2014) 115–126

Contents lists available at ScienceDirect

Journal of Hydrology

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

Effects of surficial condition and rainfall intensity on runoff in a loess hilly area, China

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ARTICLE INFO

Article history:
Received 13 January 2014
Received in revised form 1 March 2014
Accepted 7 March 2014
Available online 20 March 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Ellen Wohl, Associate Editor

Keywords:
Runoff
Rainfall simulation
Water loss
Plant species
Vegetation position
Surface cover

SUMMARY

Knowledge of the so-called "source-sink" pattern of surface runoff is important for soil conservation, water resources management and vegetation restoration in the dry-land ecosystems. Micro-runoff plot and rainfall simulation are effective tools in quick understanding the relations between land surface and runoff dynamics. This study made full use of these tools to examine the effect of various factors (plant species, surface cover, vegetation distribution) on runoff generation in the semiarid loess hilly area of China. Two major simulated rainfall intensities ($52\ \text{mm h}^{-1}$ and $28\ \text{mm h}^{-1}$) were designed and conducted, which can represent heavy rainstorms and moderate rainfalls in the local region, respectively. Results showed that the responses of runoff generation and dynamics were far more sensitive to high-intensity rainfalls. Rainfall events with only 1.8 times an increase in intensity and 16% decrease in duration caused a sharp increase in total discharge (13.96 times), runoff depth (16.33 times), mean flow velocity (12.17 times), peak flow velocity (9.34 times) and runoff coefficient (9.23 times), respectively. The time to runoff generation however, was shortened by 70%, which raised the alarm to caution against the risks of hydrological disasters induced by potential rainfall variation in the context of climatic change. More importantly, different plant species and surface cover play various roles in runoff generation and processes. Due to the difference in plant morphology and effective surface cover, runoff delay, total discharge retention and peak-flow reduction with shrubs (seabuckthorn) were more effective than those with secondary natural grass, followed by biological crust and bare soil. Notably, the specific positions of shrub species along the slope affects the time to runoff, specific flow process and total volume significantly. Shrubs in the lower positions acted as more powerful buffers in preventing runoff generation and surface water loss. Such findings can provide important references for runoff control, water conservation and ecosystem restoration regarding plant selection and vegetative collocation in practice in the arid and semiarid environments.

1. Introduction

Water scarcity is the greatest problem in semiarid and arid regions such as the Loess Plateau, the Mediterranean and other similar areas around the world (Chen et al., 2007; Wang et al., 2011; Maetens et al., 2012). In the context of human accelerated global warming, many dry-land areas are suffering from warmer and drier climates (Richard, 2007), which further worsen the status of water–carbon contradiction, increase the difficulties of plant growth and threaten the sustainability of ecosystem restoration (Putten et al., 2013). More alarming is an increasing trend in destructive rainstorms with higher intensity and more severe erosivity, which may possibly continue on large scale, consequently increasing the potential risks of water loss in many fragile and mountainous regions (Weltzin et al., 2003; Sun et al., 2002; Zhao et al., 2009). Conserving scarce water resources *in situ* for better plant utilization thus becomes extremely important in such thirsty regions (Yang et al., 2012). Runoff and water flow along the hillslope conditions, on the other hand, has long been blamed for aggravating water shortage stress, causing soil nutrient loss and hampering the process of vegetation restoration (Sinoga et al., 2010). Consequently, a deep understanding of the mechanism regarding runoff performance and finding more valuable solutions to control runoff loss are significant for vegetation restoration and ecological rehabilitation, especially against the background of climatic change.

In general, runoff processes are characterized by high spatio-temporal variability in arid and semiarid ecosystems, resulting from the interaction among different environmental factors at

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http://dx.doi.org/10.1016/j.jhydrol.2014.03.022
0022-1694/

specific scales (Imeson and Prinsen, 2004; Sinoga et al., 2010). There is no-doubt that the dynamics of rainfall features such as intensity and depth contribute to runoff generation and hydrological variation (Wei et al., 2007, 2009; Shi et al., 2010, 2012). The deep rainfall-runoff relation however, is also largely regulated by such surface conditions as plant species, soil crusts, surface cover, antecedent soil moisture, vegetation buffer strips and specific positions (Sun et al., 2000; Wei et al., 2007; Sinoga et al., 2010; Chamizo et al., 2012), which makes the interactions among them uncertain over time and space. Consequently, the related factors and runoff generation processes were quite complex and difficult to quantify. For example, studies have confirmed that vegetation cover is a key factor influencing runoff generation (Cantón et al., 2011), but how the source and sink of runoff transfers with plant morphology and its spatial location remains unclear (Xu et al., 2008), particularly when experiencing stochastic rainfall pulses. No sufficient information was provided for selecting suitable plant species in terms of plant morphology and spatial distribution for runoff reduction and vegetation restoration in water-limited environments (de Baets et al., 2007; Xu et al., 2009). Moreover, in such arid and semiarid zones, local hill-slopes are always characterized by spatially discontinuous vegetation, which reflects the limited supply of soil water and nutrients. The specific plant species and vegetation position can influence the location of runoff "source-sink" areas markedly (Bochet et al., 1998; Ma et al., 2013). So far, few studies have actually linked spatial vegetation position to geo-hydrological processes (Imeson and Prinsen, 2004; Mayor et al., 2011). Clarifying how plant morphology and vegetation distribution reflect and respond to rainfall pulses is thus of great value. Although abundant studies regarding rainfall-runoff relations in different climatic zones were conducted across multiple scales, it still lacks a comprehensive understanding about the mechanism of runoff dynamics within different environments (Xiao et al., 2011; Chamizo et al., 2012; Shi et al., 2013).

Unfortunately, due to water limitation and infrequent rainfalls in dry-lands, getting enough field data is always restricted by the fact that there are few naturally occurring runoff events, which hinders the progress in basic research regarding this topic. Rainfall simulation experiments, however, can overcome this drawback and provide huge amounts of data for model calibration and mechanism exploration within short periods, only because such experiments are easily conducted in the fields (Shi et al., 2012; Huang et al., 2013). Studies across different regions have pointed out that rainfall simulation by portable simulator at a fine scale is a powerful tool in surface hydrological studies (Cerdà, 1998; Abudi et al., 2012). Furthermore, rainfall simulators can create different scenarios regarding variations in rainfall variables, helping to ascertain runoff response to rainfall and soil surface conditions. Since the end of 1930s, more than 100 rainfall simulators with less than 5 m^2 plot areas as the land surface were developed (Pérez-Latorre et al., 2010). So far, such fine-scale studies are more focused on the semiarid Mediterranean region in Europe and other areas such as the dry-hot valleys in southwest China (Borin et al., 2005; Xu et al., 2008, 2009). Systematic research regarding the role of plant species and vegetation distribution in runoff at micro-scales was rarely conducted in the Loess Plateau of China.

The semiarid Loess Plateau in China, which covers 0.64 million km^2 of the land territory, has long been criticized as one of the most degraded regions around the world due to its severe droughts and fragile ecosystem (Chen et al., 2007; Wang et al., 2011; Yang et al., 2012). Recent studies declared that water resources may become more inadequate in many areas of the plateau due to social development and global warming (Li et al., 2009; Wang et al., 2011). In general, precipitation has been detected to decline while temperature and evapotranspiration have increased, although such variations remain across time and space. Meanwhile, heavy rainstorms with higher intensities in this region may possibly increase by about 8–35% (Zhang and Liu, 2005), which can further raise the sensitivity of land surface to rainfall pulses and thus cause higher risks of runoff loss. Although we know that plant species and vegetation patterns may play a key role in water dynamics, it is still unclear which species and what kinds of spatial patterns are more effective in runoff control. As a consequence, conserving limited water resources through enhancing infiltration *in situ* and reducing overland-flow at slopes becomes more challenging. Facing these issues, fine-scale studies, rather than coarse scale, can focus on specific hydrological processes and may help to answer this question (Bochet et al., 1998; Ellis et al., 2006; Chamizo et al., 2012).

In this study, 16 micro-plots were established in the growing season of 2010, in Dingxi, a semiarid loess hilly area of China. Rainfall simulation experiments were implemented for analyzing different land surface conditions (plant species, surface cover and vegetation distribution) and rainfall characteristics on runoff generation and water discharge dynamics. Specifically, three major sub-objectives were expected to be achieved: (1) to analyze the response of runoff generation, surface flow rates and total runoff reduction to two major simulated rainfalls, (2) to determine how different runoff indicators respond to plant species and surface coverage, and (3) to analyze the role of plant position and spatial vegetation distribution on runoff dynamics.

2. Materials and method

2.1. Study area

Our rainfall-simulation experiments were designed and conducted in the Anjiapo catchment (35°33′–35°35′N, 104°38′–104°41′E) in Dingxi county of Gansu province, in the western part of the Chinese Loess Plateau (Fig. 1). In this rain-fed and semiarid catchment, a field meteorological station was established in 1985, which belongs to the Dingxi Institute of Soil and Water Conservation. According to the water deficit index (WDI) and the aridity index (ARI), this region is located in a semiarid climatic zone and is dominated by the warm-humid summers and cold-dry winters. The mean annual precipitation (based on local recorded data from 1956 to 2010) is 421 mm/year, of which about 78% total rain falls during the growing season, i.e., from May to September (Wei et al., 2009). The mean annual pan evaporation however, can reach about 1515 mm. According to over 50 years (1954–2004) of monitored data in the field station, the precipitation experienced a decreasing trend while the temperature continued to increase during the past decades, which means that the local climate is becoming drier and warmer. Such a situation may further aggregate water pressure and do harm to vegetation restoration in this region.

Local soil is developed from loess material, with a mean soil depth ranging from 40 to 60 m. The deepest soil layer in some areas, however, can reach and even exceed more than 100 m. According to the soil classification system, the soil in this area is dominated by calcic Cambisol (FAO-UNESCO, 1974) with a clay content of 33–42%, organic matter of 4–13 g/kg, and a bulk density from 1.09 to 1.36 g/cm^3 within a 2 m soil depth (Chen et al., 2007). No available groundwater can be used for vegetation growth and restoration, mainly due to deep loess soil and severe drought. Limited annual rainfall is thus the only usable water resource for plants. Deep percolation can be neglected in most cases (Wang et al., 2011).

In general, the local climate is more suitable for shrub and grass species to grow, although some tree species (e.g. Chinese pine, Chinese arborvitae, poplar and willow) were planted widely in the