Journal of Hydrology 416–417 (2012) 50–59

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

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

An event-based approach to understanding the hydrological impacts of different land uses in semi-arid catchments

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ARTICLE INFO

Article history:
Received 26 January 2011
Received in revised form 6 October 2011
Accepted 16 November 2011
Available online 25 November 2011

This manuscript was handled by Philippe Baveye, Editor-in-Chief, with the assistance of Xunhong Chen, Associate Editor

Keywords:
Land use change
Event hydrological impacts
Re-vegetation
Semi-arid region
Loess Plateau

SUMMARY

In semi-arid catchments around the world re-vegetation is often implemented to reduce quick surface runoff, combat severe soil erosion, restore degraded ecosystem functionality, and, ultimately, improve ecosystem productivity. However, to date, in these water stressed regions, the event-based hydrological impact of different land uses induced by re-vegetation activities is not fully understood at the watershed scale. Traditional hillslope plot experiments and paired watershed experiments have proved difficult to up-scale to a watershed level. In 2006 and 2007, we used broad-crested weirs to measure event streamflow from six catchments within the Caijiachuan watershed (area = 40.1 km^2), located in the Loess Plateau, a semi-arid region in China. The six catchments have different land use compositions with functional combinations of crop, grassland, shrubland, secondary forest, and plantations. Over the same period, event rainfall was measured by a network of rainfall gauges deployed over the study site. We examined the difference in hydrological properties between the catchments using the non-parametric Firedman test, and differentiated the role of each land use in governing watershed hydrology using a numerical analysis technique. Our results showed important differences between the six catchments with respect to event runoff coefficients, normalized peak flow, and event duration. Each land use played a different role in catchment hydrology, as shown by the different mean runoff coefficients (rc) and mean representative surface flow velocities (V). Compared to secondary forest ($rc = 0.017$ and $V = 0.07$ m s^{-1}), plantations ($rc = 0.001$ and $V = 0.18$ m s^{-1}) provide a greater potential for increasing shearing force and had a larger impact on runoff reduction. Although shrubland ($rc = 0.096$ and $V = 0.20$ m s^{-1}) and grassland ($rc = 0.127$ and $V = 0.02$ m s^{-1}) have similar magnitude of mean runoff coefficients, grassland seems more capable of trapping sediment due to its lower surface runoff velocity. Cropland ($rc = 0.008$ and $V = 0.05$ m s^{-1}) exerted an important effect on runoff reduction and a moderate effect on flow retardation. We concluded that, to combat severe soil erosion while minimizing water use, re-vegetation in the semi-arid Loess Plateau should not overly, or even solely, rely on plantations. Alternatively, to produce the desired ecosystem functionality, preservation and establishment of grassland during re-vegetation processes should be encouraged, at least, in the early stage of ecological restoration within a "successional re-vegetation" framework.

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1. Introduction

Soil erosion is a serious problem in semi-arid catchments (Irvem et al., 2007; Dunjo et al., 2004), resulting in on-site productivity losses, ecological degradation, a poverty trap for local inhabitants, and severe downstream environmental problems (Fu and Gulinck, 1994; Kang et al., 2001; Hessel et al., 2003; McVicar et al., 2007a). In addition to key soil and rainfall properties (especially rainfall intensity), vegetation cover and land management are particularly important for controlling runoff generation in semi-arid catchments by directly determining the hydraulic roughness of the surfaces where overland flow occurs (Bryan and Campbell, 1986; Kosmass et al., 1997; Mitchell, 1990; Candela et al., 2005). To effectively control severe soil erosion, re-vegeta-

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doi:10.1016/j.jhydrol.2011.11.035

Table 1
Global distribution of arid and semi-arid regions[a].

Continent	Percentage of arid and semi-arid region (%)	Area of arid and semi-arid region ($^{a}10^4$ km^2)
Africa	57.2	1716
Asia	23.9	1052
North America	15.3	367
South America	15.0	270
Europe	36.3	363
Australia	77.8	700

[a] Percentage data are from Peel et al. (2007).

tion has been widely implemented in semi-arid catchments around the world (Sorriso-Valvo et al., 1995; Castillo et al., 1997; Li, 2004; Chirino et al., 2006; Porto et al., 2009; Nunes et al., 2011).

It has been increasingly observed that large catchment-scale re-vegetation does not provide effective erosion control in semi-arid regions (based on understanding generated from traditional hill slope plot and paired watershed experiments). Many of these observations have been reported from European countries with a Mediterranean climate (Sorriso-Valvo et al., 1995; Kosmass et al., 1997; Vacca et al., 2000; Chirino et al., 2006; Porto et al., 2009; Nunes et al., 2011). Whereas researchers in other semi-arid regions (see Table 1) make greater reference to erosion characteristics on arable land and rangeland (Wilcox and Wood, 1988, 1989; Gutierrez and Hernandez, 1996), than to natural vegetation or plantations. Understanding generated from traditional experiments is difficult to up-scale to larger watersheds. Moreover, a key finding is that the impact of plantations on erosion control was similar to, or even less effective, than that of natural shrubland (Maestre and Cortina, 2004;Chirino et al., 2006). The integrated assessment of large-scale ecological restoration programs has, thus, been called into question (Maestre and Cortina, 2004; Xu et al., 2006; Cao, 2008; Yin et al., 2009). Specific issues of concern are (i) potential water yield reduction due to re-vegetation (Sahin and Hall, 1996; Stednick, 1996; Huang et al., 2003; Sun et al., 2006; McVicar et al., 2007a; Zhang et al., 2008b); and (ii) the ability of re-vegetation in semi-arid regions to control soil erosion (Vacca et al., 2000; Chirino et al., 2006; Huang and Zhang, 2004; Li et al., 2007; Chen et al., 2007a; Zhang et al., 2008c).

Although numerous studies have explored the hydrological impacts of land use and vegetation change (Bosch and Hewlett, 1982; Bruijnzeel, 1988; Sahin and Hall, 1996; Zhang et al., 2001; Brown et al., 2005; Robinson et al., 2003; Grant et al., 2008), our current understanding of land use and water interactions is mainly derived from traditional paired watershed experiments conducted across the globe. These findings are usually summarized as the relationship between forest cover and long-term annual water yield (Zhang et al., 2008b,c; Li et al., 2007; Li et al., 2009). The specific effect of land uses, other than forest, on watershed hydrology is rarely considered. As species composition (Wattenbach et al., 2007), forest age (Cornish and Vertessy, 2001), stand regeneration, and successional stages (Rab, 1996) representing different chronosequences of vegetation regeneration, succession, and disturbances, are all important to watershed hydrology, with only the traditional conclusions available, the difference in hydrological functioning between plantations and other land covers (e.g., shrubland, grassland, and crops) is not fully understood. On the other hand, since most annual precipitation in semi-arid catchments usually falls in short-duration and high-intensity thunderstorms (Hessel et al., 2003; McVicar et al., 2007a,b; Zhang et al., 2008e; Wang et al., 2008, 2009), which is likely to cause severe soil erosion, it is imperative to understand how each land use affects watershed hydrology at the event basis.

Plot scale investigations may provide practical information on the specific effect of different tree species and land uses on runoff, particularly at the event scale (Wheater et al., 1991; Descheemaeker et al., 2006; Chen et al., 2007b; Molina et al., 2007). However, such results cannot be up-scaled to the watershed level due to non-linear scaling effects (Cerdan, et al., 2004). The spatial pattern and disposition of land use are important for watershed hydrology (Schulze, 2000). Hydrological impacts of land use change can be small due to complex compensating effects between water storage and release in a watershed (Fohrer et al., 2001). To provide solid scientific support for watershed ecological restoration it is thus necessary to examine the general role that each land use has in modulating hydrologic processes at the watershed scale.

We have monitored event rainfall runoff in a watershed in the semi-arid Loess Plateau (LP) China to examine hydrological functioning of different land covers. Soil erosion rates of the LP are typically 20,000–30,000 t/km^2/year, with rates up to 60,000 t/km^2/year (Hessel et al., 2003). To effectively improve the degraded environment of the LP, several large-scale re-vegetation programs have been implemented since the 1970s such as “Three North (Northwest, Northern China, West of the Northeast) Shelterbelt” program and most recently the influential “Grain for Green” program (McVicar et al., 2007a), launched in 1999 aiming to convert slope cropland exceeding 25° to either forest or grassland (Wu et al., 2007). However, such programs do not totally meet expectations because of: (i) trivial impacts on erosion control (Bellot et al., 2001; Chirino et al., 2006); and (ii) reduced downstream water availability (Huang et al., 2003; Sun et al., 2006; McVicar et al., 2007a; Zhang et al., 2008b). To effectively improve erosion control and restore degraded ecosystem functionality of the LP it is necessary to understand how different land uses govern watershed-scale hydrology at a storm event basis. Specifically, our objectives were to: (i) test for important differences in event runoff response between the catchments of different land uses; (ii) differentiate the role each land use has in governing the catchment-scale event hydrological response; and (iii) discuss the implications for vegetation-based ecological and environmental restoration programs conducted in semi-arid regions.

2. Methods

2.1. Study area and experimental design

The Caijiachuan watershed (110°39′45″E–110°47′45″E, 36°14′27″N–36°18′23″N) located in Jixian County, Shanxi Province, China is a third-order tributary of the Yellow River (area 40.1 km^2, elevation 904–1592 m) (Fig. 1). The mid- and down-stream landscapes are characterized by gently sloping areas (typical slopes of 12.8°), whereas the up-stream landscape is characterized by soil truncation and weathered bedrock outcrops. The soils are carbonated (Zhang et al., 2008a) and the climate is temperate continental monsoon with an average (1957–1979) annual precipitation of 580 mm and an average daily temperature of 10 °C (Zhang et al., 2008a). Approximately 70% of rainfall occurs from June to September with high rainfall intensity (maximum 5-min rainfall intensity is ~50 mm/h, Zhang et al., 2008d). The average annual pan evaporation is 1729 mm, which causes severe aridity and regional ecological and economic problems.

The watershed has different land use and vegetation compositions as interpreted from 2003 Quickbird imagery (Table 2). The land use and vegetation composition within the watershed was constant over the study period. In general, the watershed is well vegetated, with 72% in forest. A large area of secondary re-growth is distributed in the upper watershed.

During the 2006 and 2007 growing seasons (1 April–31 October), we used a nested catchment system to measure watershed stream flow (see Fig. 1). Automatic water-stage recorders were

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