Agricultural and Forest Meteorology 178–179 (2013) 66–74

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

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

The effect of site conditions on flow after forestation in a dryland region of China

Pengtao Yu[a], Yanhui Wang[a,*], Apeng Du[a,b], Wei Guan[a,c], Karl-Heinz Feger[d], Kai Schwärzel[d], Mike Bonell[e,f], Wei Xiong[a], Shuai Pan[a]

[a] Research Institute of Forest Ecology, Environment and Protection, Chinese Academy of Forestry, Beijing 100091, China
[b] China Eucalypt Research Centre, Zhanjian 524022, China
[c] Research Institute of Tropical Forestry, Chinese Academy of Forestry, Guangdong 510520, China
[d] Institute of Soil Science and Site Ecology, Dresden Water Center, Dresden University of Technology, 01735 Tharandt, Germany
[e] Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK
[f] The UNESCO Centre, University of Dundee, DD1 4HN Scotland, UK

ARTICLE INFO

Article history:
Received 17 May 2012
Received in revised form 2 February 2013
Accepted 14 February 2013

Keywords:
Water budget
Aspect
Slope
Soil thickness
BROOK90 Model
Sensitivity analysis

ABSTRACT

Although forestation has been encouraged worldwide for the benefit of forest ecosystem services, it can lead to a reduction in runoff. As site conditions also strongly contribute to this runoff reduction, site selection has been suggested in order to mitigate this negative effect of forestation. Up to now it is not clear, however, which catchment parameters play key roles in the water budget and runoff responses to forestation. In this study, two plots within an experimental basin in the Liupan Mountains, NW China, were chosen, and the eco-hydrological model BROOK90 (Version 3.25) was used to quantify the effects of slope (gradient, aspect) and soil (thickness) parameters on water flow after forestation. The simulation showed that the annual flow in a larch plantation was strongly affected by soil thickness and lightly affected by aspect and gradient. When the soil thickness increased from 30 cm to 70 cm, the annual flow in the larch plantation rapidly declined from 91 mm/yr to 56 mm/yr. When the soil depth was greater than 70 cm, however, the annual runoff was no longer sensitive to soil thickness. With respect to a forestation strategy, this means that trees preferentially should be planted on sites with thinner soil so as to lessen the impact of runoff reduction after forestation and, thus, alleviate the forest-water conflicts in dryland regions. The trade-off between a possible reduction in tree-growth on thinner soil on the one hand and an increase in runoff on the other, however, remains an open question for future interdisciplinary research.

1. Introduction

Forestation has been encouraged worldwide for the multiple benefits of forests (e.g. Scott et al., 2004; Malagnoux, 2007; Lamb, 2011), such as soil erosion control (CAE, 2000; Zhang and Liang, 1996), sediment reduction (Liu and Huang, 2003), hydrological regime regulation (Liu and Huang, 2003) and carbon sequestration (Winjum and Schroeder, 1997). This is particularly the case in China, where forestation has been carried out on a national scale through its Six Key Forestry Programs since 2000 (Wang et al., 2007). As a result, China's forest cover increased rapidly from 13.6% in 1995 (Zhang et al., 2000) to 21.4% in 2009 (http://www.forestry.gov.cn/portal/main/s/65/content-326341.html on April 1, 2012), and is further planed to increase to 26% by 2050 (Wang et al., 2007).

However, it has been widely found that forestation can cause a runoff reduction (Sahin and Hall, 1996; Wattenbach et al., 2007). For example, Farley et al. (2005) analyzed 26 catchment data sets by way of a comparison of forest plots and grassland plots and found that the reduction of mean annual runoff could reach up to 44% in humid regions. This runoff reduction was more notable in the semi-humid and semi-arid regions of China, where it can reach more than 50% after forestation (Sun et al., 2006; Wang et al., 2008, 2011; Yu et al., 2009, 2010). The negative effect was also suggested indirectly from the results of many forest hydrological studies at the plot scale (e.g., Wang et al., 2008; Wei et al., 2008). Forests consume more water by evapotranspiration than the other vegetation types do, e.g., natural grassland (Hou et al., 1999; Xiong et al., 2003; Zhang et al., 2001). Such findings imply that forestation at large scales may adversely affect drainage basin runoff and even threaten the water supply of communities in dryland regions.

On the other hand, there are a few studies in dryland regions, which have found that runoff did not decline remarkably when trees or woody plants increased in size or density. For example, Gaowa et al. (2010) found that runoff barely changed when

* Corresponding author. Tel.: +86 10 62889531; fax: +86 10 62884972.
E-mail addresses: wangyh@caf.ac.cn, wangyanhuicaf@gmail.com (Y. Wang).

0168-1923/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.agrformet.2013.02.007

grassland with coverage of 30–50% was converted to forests at a small sub-basin of the Jinhe river, Dongchuan, NW China. Another example is in the Edwards Plateau region (Texas, USA) where runoff has not been declining and the contribution of baseflow has doubled even though woody cover has expanded (Wilcox and Huang, 2010). Elsewhere, the annual runoff reduction after forestation strongly varied within a range from 35 mm/yr to 193 mm/yr among sites in a small basin, in the Liupan Mountains, NW China (Yu et al., 2009). Such a range of runoff responses to forestation suggested that apart from the vegetation itself (e.g. forest and grassland), there are other environmental factors which affect runoff in semi-arid regions (Obrist et al., 2003).

Most existing studies focusing on forestation effects on runoff, however, compared water yield changes from paired catchments (e.g. Brown et al., 2005; Wang et al., 2012) or the water budget components on plots (e.g. Farley et al., 2005; Wang et al., 2008; Huang et al., 1999) with the same or similar site conditions (e.g. topography, soils). This means that the effect on runoff of different site environmental conditions was usually ignored or excluded by these existing forest hydrological studies. The contribution of each site factor, e.g., aspect, gradient and soil thickness, has also not been quantified independently. This makes it difficult to forestation planning, notably with respect to site selection in order to lessen the water yield reduction after forestation.

The Liupan Mountains (104°30′–107°10′ E, 34°30′–37°30′ N), located in NW China, is an important regional headwater area. In order to understand the hydrological impacts of forestation in this region, an eco-hydrological study has been carried out since 2000 (Wang et al., 2008). The hydrological processes (precipitation, interception, evaporation, transpiration, and runoff) and ecological processes (e.g. vegetation dynamics) have been monitored at three scales: single tree, plot, and small drainage basin. Previous studies have found that forestation in the Liupan Mountains would decrease the annual runoff at the plot scale (Wang et al., 2008) and small basin scale (Yu et al., 2009).

In this study, we try to evaluate how hydrological processes response to different site environmental factors. Furthermore, there might be a dominant site factor crucial to runoff change after forestation in dry regions. Data sets based on measurements at two permanent plots in the Liupan Mountains were used to calibrate and validate BROOK90 (Federer, 1995, 2002) a widely used eco-hydrological model, notably for forested environments (e.g. Wellpott et al., 2005; Schwärzel et al., 2009). In a second step, we made systematic model runs to test to what extent a variation in site conditions (i.e. aspect, slope and soil thickness) affect the dynamics of hydrological processes. Finally, the relationships between these site conditions and water flow after forestation were quantified.

2. Study area and methods

2.1. Study area

2.1.1. The environmental setting

Being an important regional head-water area, the Liupan Mountains are termed as a "wet island" of Loess Plateau in NW China. Massive forestation or reforestation has been carried out there for several decades, mainly for erosion control and timber production.

Diediegou (106°4′ E, 35°55′ N) is a representative small drainage basin (25.4 km^2; 1795–2615 m above sea level, Fig. 1) situated in the NW part of the Liupan Mountains. It has a temperate monsoon climate characterized by a cold-dry winter and warm-wet summer. The mean annual air temperature is 5.9 °C and the mean annual precipitation is 428 mm, >80% of which is concentrated in the rainy season from June to October.

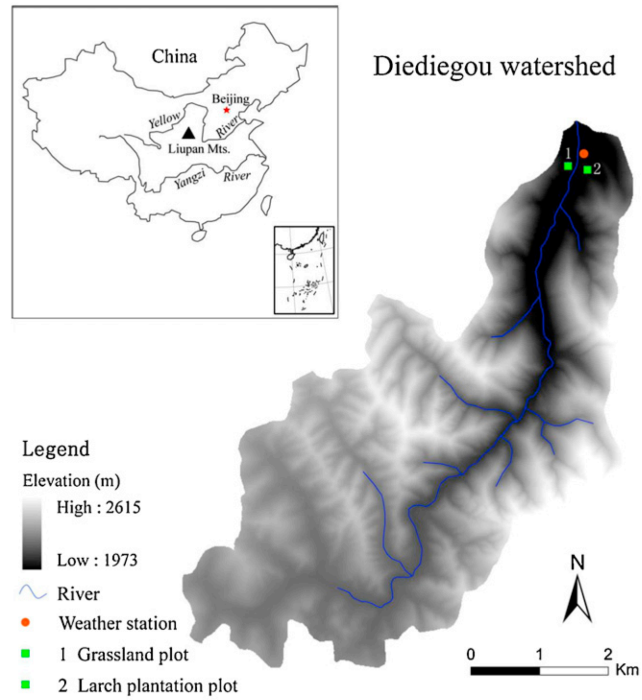

Fig. 1. Location of the study area in the Liupan Mountains, NW China.

Diediegou is mainly composed of steep slopes, which predominantly consist of Haplic Luvisols overlying fissured shale. The soil thickness varies from 20 cm over the upper slopes to more than 2 m at the foot of the slopes. In the past these steep slopes have been used as pasture. Nowadays, some of these slopes have been afforested with larch (*Larix principis-rupprechtii*) (Wang et al., 2008).

2.1.2. The experimental setting

One grassland plot and one larch plantation plot (Table 1) were established on the steep slopes located in the lower reaches of the Diediegou basin. The grassland plot lies in the middle part of a SW slope with a gradient of 30°, and its predominant species of vegetation are *Stipa bungeana* and *Bothriochloa ischaemum*. The soil there is a Haplic Luvisol, with a thickness of ≈40 cm. The soil texture is a sandy loam with a stone content of ≈10%. The total porosity is 57.3%. Permeability is high so that the saturated hydrological conductivity attains 1.0 mm/min (60 mm/h) (Table 1). Thus, surface flow has been rarely observed during the last 10 yr of investigation (Guo, 2005; Guan, 2007; Liu, 2008; Du, 2009).

The larch plantation plot is located on a NW facing slope (Table 1). The overstory of vegetation is composed of only larch (*L. principis-rupprechtii*) trees planted in 1982, and the understory is mainly made up of several grass species, such as *Artemisia* spp. No shrubs grow there. The soil type is comparable to the grassland plot. In this larch plantation plot, soil thickness is >1 m and saturated hydraulic conductivity reaches 2.8 mm/min (168 mm/h), which is higher than that in the grassland plot. The amount of stones within the soil in this larch plantation plot is less than that in the grassland plot.

2.1.3. Field measurements

On larch plantation plot, the hydrological components, i.e. overland flow, subsurface flow in soil layer of 0–50 cm, canopy interception, tree transpiration (T), floor evapotranspiration (which includes soil evaporation and grass transpiration), and soil moisture at the soil proflie (0–90 cm), were simultaneously monitored with