Journal of Hydrology 546 (2017) 44–59

Contents lists available at ScienceDirect

Journal of Hydrology

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

Review papers

A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime

Mingfang Zhang [a,b], Ning Liu [b,c], Richard Harper [c], Qiang Li [d], Kuan Liu [e], Xiaohua Wei [d], Dingyuan Ning [a], Yiping Hou [a], Shirong Liu [b,*]

[a] Center for Information Geoscience, School of Resources and Environment, University of Electronic Science and Technology of China, Chengdu 611731, China
[b] Research Institute of Forest Ecology, Environment and Protection, Chinese Academy of Forestry, Beijing 100091, China
[c] School of Veterinary and Life Sciences, Murdoch University, 90 South Street, Murdoch 6150, Australia
[d] Department of Earth and Environmental Sciences, University of British Columbia (Okanagan), 3333 University Way, Kelowna V1X1R3, Canada
[e] Dalla Lana School of Public Health, University of Toronto, 155 College Street, Toronto M5T 3M7, Canada

A R T I C L E   I N F O

Article history:
Received 31 August 2015
Received in revised form 7 December 2016
Accepted 22 December 2016
Available online 26 December 2016
This manuscript was handled by Tim McVicar, Editor-in-Chief, with the assistance of Vazken Andréassian, Associate Editor

Keywords:
Forest change
Annual runoff
Scale
Climate
Forest type
Hydrological regime

A B S T R A C T

Despite extensive studies on hydrological responses to forest cover change in small watersheds, the hydrological responses to forest change and associated mechanisms across multiple spatial scales have not been fully understood. This review thus examined about 312 watersheds worldwide to provide a generalized framework to evaluate hydrological responses to forest cover change and to identify the contribution of spatial scale, climate, forest type and hydrological regime in determining the intensity of forest change related hydrological responses in small (<1000 km^2) and large watersheds ($\geqslant$1000 km^2). Key findings include: (1) the increase in annual runoff associated with forest cover loss is statistically significant at multiple spatial scales whereas the effect of forest cover gain is statistically inconsistent; (2) the sensitivity of annual runoff to forest cover change tends to attenuate as watershed size increases only in large watersheds; (3) annual runoff is more sensitive to forest cover change in water-limited watersheds than in energy-limited watersheds across all spatial scales; and (4) small mixed forest-dominated watersheds or large snow-dominated watersheds are more hydrologically resilient to forest cover change. These findings improve the understanding of hydrological response to forest cover change at different spatial scales and provide a scientific underpinning to future watershed management in the context of climate change and increasing anthropogenic disturbances.

Contents

* Corresponding author.
E-mail address: liusr@caf.ac.cn (S. Liu).

http://dx.doi.org/10.1016/j.jhydrol.2016.12.040
0022-1694/

1. Introduction

The interactions between forest change and water have been studied for over a century. Several classic reviews on hydrological responses to forest change in small watersheds (<1000 km^2) have been published, and these provide deep insights into the impact of forest change on annual runoff in small watersheds (Bosch and Hewlett, 1982; Sahin and Hall, 1996; Stednick, 1996; Andréassian, 2004; Bruijnzeel, 2004; Brown et al., 2005; Moore and Wondzell, 2005; van Dijk et al., 2012). A general conclusion drawn from small watershed studies is that deforestation (e.g., harvesting, urbanization, land cover change, wildfire, and insect infestation) can increase annual runoff while afforestation affects streamflow in the opposite way (David et al., 1994; Stednick, 1996; Neary et al., 2003; Bruijnzeel, 2004; Wu et al., 2007; Bi et al., 2009; Webb and Kathuria, 2012; Beck et al., 2013; Zhang et al., 2015; Carvalho-Santos et al., 2016; Buendia et al., 2016a). However, there have been some inconsistent responses, suggesting the response intensity of annual runoff to forest cover change can be variable among watersheds, especially for watersheds with afforestation or reforestation (Stednick, 2008; Lacombe et al., 2016).

In contrast, the relationship between forest change and water yield has been less investigated in large watersheds ($\geqslant$1000 km^2). This is mainly due to the lack of high quality data on precipitation and streamflow or suitable methodology to exclude the hydrological impact of non-forest factors such as climate variability and human activities (e.g., dam construction, agricultural activities, and urbanization) (Wei and Zhang, 2010a, 201b; Vose et al., 2011). Unlike small watershed studies, a general conclusion on the relationship between forest change and annual runoff in large watersheds has not yet been drawn. Indeed, inconsistent responses, and high variations in response intensity of annual runoff to forest change, have often been reported in large watershed studies (Eschner and Satterlund, 1966; Ring and Fisher, 1985; Cheng, 1989; Buttle and Metcalfe, 2000; Costa et al., 2003; Tuteja et al., 2007; Adnan and Atkinson, 2011; Wu et al., 2015). For example, in Canadian boreal forests (watershed areas from 401 to 11,900 km^2), with disturbance levels ranging from 5% to 25% of the watershed areas, no definitive changes in annual runoff were found (Buttle and Metcalfe, 2000) while in the upper Yangtze River annual runoff was increased by a mean of 38 mm with only 15.5% of the watershed area logged (Zhang et al., 2012b).

In small watershed studies, large variations in the hydrological response to forest change are attributed to factors such as forest type, topography, climate, hydrological regimes, soil, geology, and landscape pattern (Moore and Wondzell, 2005; Zhang and Wei, 2014). However, an understanding on hydrological responses to forest change and on how those factors affect interactions between forest and water in large watersheds or across multiple spatial scales is limited. In most cases, the inconsistent findings from large watersheds are simply ascribed to the complexity in watershed processes and heterogeneity in landscape, climate and geology in large watersheds (Stednick, 1996; Moore and Wondzell, 2005; Vose et al., 2011). Although Peel et al. (2010) evaluated the vegetation impact on hydrology at both large and small watershed, they studied annual evapotranspiration rather than annual runoff. Similarly, some studies have investigated the climatic effects on water use efficiency of vegetation (Huxman et al., 2004; Troch et al., 2009; Yang et al., 2016), and this helps to disclose the mechanisms that explain the effect of precipitation on hydrological response to vegetation change.

Due to a lack of a generalized relationship between forest and water in large watersheds, the empirical relationships between different watershed processes and components from small watershed studies are largely used in hydrological models, and may be problematic when scaled to large watersheds (Kirchner, 2006). Similarly, watershed management often relies on a simple extrapolation of concepts and information generated from small watersheds to large watersheds, which can be misleading in decision-making (Yang et al., 2009; van Dijk et al., 2012; Xiao et al., 2013; Zhang et al., 2016). Since the design of natural resource management strategies is normally performed in large watersheds, a comprehensive understanding on the likely hydrological impact of forest change in large watersheds and the associated mechanisms is in critical need. This can be particularly true given the fact that climate change and anthropogenic activities (e.g., widespread afforestation, deforestation, forest harvesting, urbanization, and fire) are dramatically and extensively altering the watershed processes and ecosystem services (Keenan et al., 2013; Frank et al., 2015). Some of these forest disturbances are more frequent and catastrophic (e.g., insect infestation and wildfire) due to climate change (Schindler, 2001; Kurz et al., 2008). This critical scientific information gap, along with growing watershed management and planning needs in large watersheds calls for a substantial review of forest ecohydrology across multiple spatial scales.

This review aims: (1) to provide a generalized relationship between forest cover change and annual runoff response at multiple spatial scales; (2) to examine how the response intensity of annual runoff response to forest cover change varies along spatial scale and climatic gradients; (3) to investigate the effects of forest type and hydrological regime on hydrological responses to forest cover change in both small and large watersheds. Since annual runoff is the commonly investigated response variable to forest cover change, this paper focuses on this variable as a means to maximize the sample size.

2. Study sites and materials

This study synthesized quantitative assessments of annual runoff response to forest cover change from 312 watersheds worldwide in the literature. Collected watersheds are classified into large watersheds (watershed size $\geqslant$1000 km^2) and small watersheds (watershed size $\leqslant$1000 km^2) (Wei and Zhang, 2010a, 2010b). 61 of them are large watersheds, ranging from 1033 to