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The effect of forest harvesting and climatic variability on runoff in a large watershed: The case study in the Upper Minjiang River of Yangtze River basin

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SUMMARY

Forest disturbance (or land cover change) and climatic variability are commonly recognized as two major drivers interactively influencing hydrology in forested watersheds. However, separating their relative contributions to hydrology is rarely examined, particularly in large watersheds (>1000 km^2). This study used a large watershed, the Upper Zagunao River watershed, situated in the upper reach of the Minjiang River, the Yangtze River basin, China as an example to demonstrate how the effects of forest harvesting and climatic variability on hydrology can be quantitatively separated. Long-term data on climate, hydrology and forest harvesting history are available from1953 to 1996. Time series cross-correlation analysis and non-parametric tests were performed first to identify possible responses of annual and seasonal runoff to forest harvesting, and to determine breakpoints of runoff change over its long-term time series. Then, modified double mass curve of accumulated annual effective precipitation (the residual of precipitation and evapotranspiration) and accumulated annual runoff was used to quantify the relative contributions of forest harvesting and climatic variability to annual runoff variation. Our analysis showed that the breakpoint of significant annual runoff change occurred in1969, about 10 yrs after the intensive harvesting period of 1955–1962, suggesting the delayed hydrological response in the studied large watershed. Over the period of 1970–1996, the average annual runoff increment attributed to forest harvesting was 38 mm/yr, while the annual runoff variation attributed to climatic variability was −38.3 mm/yr, clearly demonstrating that forest harvesting and climatic variability had offsetting effects on annual runoff. Our results also disclosed that the positive effect of forest harvesting on runoff decreased with forest recovery and eventually diminished about 20 yrs after intensive harvesting period.

1. Introduction

The impact of forest harvesting on runoff has been investigated for a century mainly using paired watershed experiments (Bosch and Hewlett, 1982; Stednick, 1996; Brown et al., 2005). The key conclusions drawn from small paired watershed (less than 100 km^2) studies show that forest harvesting can significantly increase annual runoff, magnify peak flow (particularly small magnitudes of peak flows) and change dry season low flow (Bethlahmy, 1974; Cheng, 1989; Stednick, 1996; Bruijnzeel, 2004; Jones and Post, 2004; Moore and Wondzell, 2005; Doerr and Shakesby, 2006; Scott and Prinsloo, 2008; Alila et al., 2009). But the research on impacts of forest harvesting on hydrology in large watersheds (>1000 km^2) is limited (Wei and Zhang, 2010a; Vose et al., 2011), and the results are less consistent (Ring and Fisher, 1985; Buttle and Metcalfe, 2000; Matheussen et al., 2000; Wilk, 2001; VanShaar et al., 2002; Costa et al., 2003; Sun et al., 2005; Siriwardena et al., 2006; Li et al., 2007a,b; Tuteja et al., 2007; Lin and Wei, 2008; Wei and Zhang, 2010b). However, many natural resource management practices and policies are operative at large landscape, watershed or even regional scales. Thus, large watershed studies on forest change and hydrological responses are critically needed to support designing of natural resource management strategies.

In large forested watersheds, forest disturbance and climatic variability are commonly recognized as two major drivers interactively influencing hydrology in forested watersheds (Buttle and Metcalfe, 2000; Sharma et al., 2000; Blöschl et al., 2007; Ma et al., 2010; Wei and Zhang, 2010b). The biggest challenge is how to separate their relative contributions to hydrology (Zhang et al., 2008a,b; Wang et al., 2009; Zheng et al., 2009; Wei and Zhang, 2010b). Without commonly-accepted methodology, physically-based hydrological modeling is often used to assess the relative effects of climate variability and forest change on hydrology (Tuteja et al., 2007; Juckem et al., 2008; Zégre et al., 2010; Zhao et al., 2010). But this modeling approach is only applicable for the watersheds that are well monitored with extensive, long-term available data on vegetation, soil, topography, land use, hydrology

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and climate (Wei and Zhang, 2010a,b). Moreover, time-consuming model calibration and validation impede us from making an efficient assessment on hydrological impacts of forest harvesting. In order to overcome the shortcomings of the modeling approach, some researchers employed non-modeling approach (e.g., statistical analysis) (Zhang et al., 2008a,b; McCormick et al., 2009; Wang et al., 2009; Zheng et al., 2009). The advantages of non-modeling approach include fewer requirements for data, quicker assessment and more reliable inferences. Unfortunately, the non-modeling approach suffers from lacking the ability to detect the underlining mechanisms and process linkages. Wei and Zhang (2010b) recently developed a combined methodology of statistical analysis (e.g. time series analysis) with graphical methods (e.g., modified double mass curves and flow duration curves) which successfully quantified the relative contributions of forest disturbance and climatic variability to annual runoff variation in the Willow River watershed of the central interior of British Columbia, Canada.

Separating the relative contributions of climate variability and forest or land use change to hydrology is essential for water resources management and watershed protection. Firstly, it may be the only way to understand the impacts of either forest change or climate variability on hydrology in large watersheds as both drivers interactively affect hydrology. Without such a separation, it is impossible to quantitatively determine the impacts of forest change (e.g., harvesting) on hydrology. Secondly, the separation has important management implications. For example, Wei and Zhang (2010b) showed that climate variability and forest harvesting can produce offsetting effect on runoff, and thus forest harvesting can be used to mitigate the negative impact of climate variability on runoff (also see Blöschl et al., 2007). Finally, there is a significant lack of understanding of the influence of climate variability and land use change in large watersheds, and the hydrological responses to those two drivers in large watersheds are likely watershed specific. Limited research has greatly constrained our ability to manage and protect water resources and watershed ecosystem services.

The Minjiang River is the largest tributary in terms of mean discharge in the Upper Yangtze River. It has strategic significance for environment, economy and social well-being to the downstream Chengdu plain. Due to historic mismanagement and large-scale deforestation in the upper reach watersheds, there are serious environment problems such as severe soil erosion, frequent floods and loss of habitat (Sun et al., 2008). Large-scale deforestation was claimed to be one of the major reasons responsible for the 1998 flood in the Yangtze River basin. Understanding the relative contributions of forest harvesting and climate variability to hydrology is critical for developing management and protection strategies for watershed integrity in the basin. The major purpose of this study was to use the Upper Zagunao River watershed of Minjiang River, located in the upper reach of Yangtze River basin as an example to demonstrate how an integrated non-modeling approach can provide an efficient evaluation of runoff alteration caused by forest harvesting and climate variability for large forested watersheds (greater than 1000 km^2 and less than 10,000 km^2).

2. The study watershed and data

2.1. Watershed description

The Upper Zagunao River watershed, located in the Northwest of Sichuan Province, China, flows into the Minjiang River, the largest tributary of the Upper Yangtze River (Fig. 1). The main watercourse is 113 km in length and its drainage area is approximately 2528 km^2. The watershed is situated in Southeast Tibet Canyon, the transitional zone from the Qinghai-Tibet Plateau to the Sichuan Basin. The elevation for the Upper Zagunao River watershed ranges from 1800 m to 5800 m above the sea level, with an average of 3676 m, and the area with the elevation above 3800 m accounts for 56.8% of the total watershed area. About 3.5% of the watershed area is covered by glaciers and permanent snow.

The climate in the Upper Zagunao River watershed is characterized by typical alpine climate with relatively cooler summers and mild winters (Fig. 2). Average annual temperature is 11.2 °C, and the maximum temperature can reach 26.9 °C (July), while the minimum temperature is −3.3 °C (January). The summer is mainly affected by the Southwest Monsoon from the Indian Ocean, which leads to a rainy season from May to September. The average watershed-scale precipitation in the rainy season comes up to 880 mm, accounting for 80% of the annual total. Unlike other monsoon influenced regions, rainfall events in the study watershed are normally featured with low intensity and long duration due to topographic effects. During the winter season from November to March, most of precipitation occurs in the form of snow, which usually contributes to runoff during the snow-melting season (April–May). The runoff in the winter season is mainly from groundwater discharge.

The major vegetation types include alpine meadow and subalpine coniferous forest, covering 46% and 32% of the total watershed

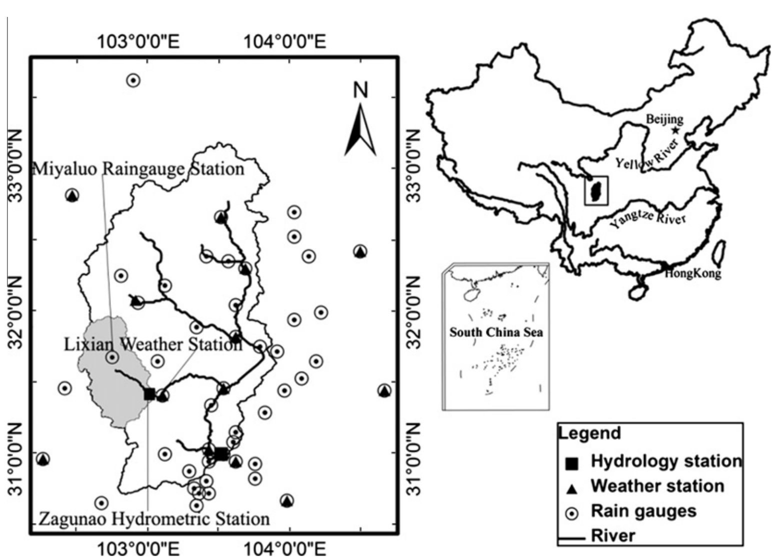

Fig. 1. Location of the Upper Zagunao River watershed.