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ECO LETTER

Forest cover change and water yield in large forested watersheds: A global synthetic assessment

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Abstract

The effects of forest cover change on water yield have long been studied across the globe. Several reviews have summarized the impacts of forest change and water yield from the small and paired watershed experiments, but no any synthetic assessment has been conducted on the basis of studies of large watersheds (>1,000 km^2). We conducted a synthetic analysis on the basis of the studies from 162 large studied watersheds across the globe to explore how forest cover change affects annual water yield. Our first-ever assessment confirms that deforestation increases annual water yield and reforestation decreases it, which is consistent with results from paired watershed experiments. More importantly, we found that forest cover and climate variability play a coequal role in annual water yield variations. The effects of forest cover change and climate variability on annual water yield variations can be additive or offsetting. Thus, their interactions can critically determine the magnitudes and directions of water yield changes. We also found that the hydrological sensitivities to forest cover change in smaller and dryer watersheds are higher than those in larger and wetter ones. The implications of these findings for sustainable water and watershed management are discussed in the context of future land cover and climate changes.

KEYWORDS

annual water yield, climate change, forest cover change, hydrological sensitivity, large watersheds, relative contribution

1 | INTRODUCTION

The relationship between changes in forest cover and water yield has long been studied (Wei et al., 2008; Zhou et al., 2015). Our understanding of the effects of forest cover change on water resources in forest-dominated watersheds was mainly gained through the studies of paired watershed experiments (PWE). Various landmark reviews have summarized what we have learned in different eras (Andréassian, 2004; Bosch & Hewlett, 1982; Brown, Zhang, McMahon, Western, & Vertessy, 2005; Hewlett & Hibbert, 1967; Stednick, 1996). The general key messages from the PWE studies are that deforestation can increase annual runoff, magnify peak flows, and alter base flows, and reforestation can decrease annual runoff and reduce peak flows. However, the PWE studies are conducted at the small watershed scale (<100 km^2, most of which are less than 10 km^2), and their results cannot be simply extrapolated into large watersheds (>1,000 km^2) as large watersheds are characterized by more diverse landforms (e.g., forests, wetlands, and lakes), topographies, climates, and their interactions (Shaman, Stieglitz, & Burns, 2004; Shuttleworth, 1988; Woods & Sivapalan, 1997; Yang, Yang, Lei, & Sun, 2008). Recently, Zhang et al. (2017) reviewed the relationship between forest cover change and water yield across multiple spatial scales. However, their study only included 67 large watersheds, whereas this study used 162 large watersheds with the focus on relative contributions of the changes in forest cover and climate variability to annual water yield variations.

The relationship between forest cover change and water yield variations in large watersheds has been receiving growing attention in the past few decades mainly because of increasing demands on the scientific information on large-scale watersheds or landscapes to support sustainable natural resource management. However, studying such a topic in large watersheds is challenging as the classic PWE approach is not applicable at this spatial scale due to the difficulty in locating comparable controls to make paired watersheds (Wei, Liu, & Zhou, 2013; Zhang, 2013). Nevertheless, a significant number of studies employing different methods including advanced statistical approaches (e.g., Buttle & Metcalfe, 2000; Liu et al., 2015; Wei & Zhang, 2010; Wei et al., 2013; Zhang, Zhao, Chen, & Dixon, 2011) and hydrological modeling (e.g., Cuo, Lettenmaier, Alberti, & Richey, 2009; Fohrer, Haverkamp, & Frede, 2005; Schilling, Jha, Zhang, Gassman, & Wolter, 2008; Thanapakpawin et al., 2007; Zhang, Yang, Yang, & Jayawardena, 2016) have been conducted on this subject. These studies provide a solid basis for conducting this synthetic assessment.

Forest cover (or land cover) change and climate variability are commonly viewed as two major drivers for hydrological variations in forest-dominated watersheds. To assess the effects of changes in forest cover on water yields, the influences from climate must be either removed by possible methods such as the PWE approach or explicitly accounted for (Wei & Zhang, 2010; Zhang, Zhang, Zhao, Rustomji, & Hairsine, 2008). Because the PWE approach is not suitable for large watersheds, any research in large watersheds has to explicitly include climate into analysis so that the relative effects of forest cover change on hydrology can be quantified. Thus, the relative contributions of forest cover and climate variability to hydrology are often assessed in large watershed studies, although these are not normally available in the PWE studies. As far as we know, there is no a comprehensive synthesis on relative contributions of forest cover change and climate variability to water yield in large watersheds. The objectives of this paper are (a) to provide a synthetic assessment of the effects of changes in forest cover and climate on water yield on the basis of the studies of large-sized (>1,000 km^2) watersheds across the globe, (b) to evaluate relative contributions of changes in forest cover and climate to annual water yield, and (c) to explore the hydrological sensitivity to watershed properties and climate at this large spatial scale.

2 | ASSESSMENT MATERIALS AND ANALYSES

Published global case studies that assessed the effects of changes in forest cover on water yield in large watersheds were collected. In total, we collected data from 162 studied large watersheds (>1,000 km^2), of which 17 with the areas from 500 to 1,000 km^2 are included to increase our sample size. Because the PWE is not applicable for large watersheds, various methods have been adopted for this subject (Wei et al., 2013). These methods can be classified into two broad categories: statistical analyses and hydrological modeling. Statistical analyses (e.g., double mass curves, trend analysis, and sensitivity-based approach) are based on long-term observation data and treat any individual watersheds as a whole entity (Zhang, 2013). Unlike the statistical approach, physical-based hydrological models explicitly represent spatial characteristics to some extent. For this synthetic analysis, 58 studied watersheds were from the researches by the statistical approach and 104 by hydrological modeling (Table S1). Among those 162 studied large watersheds, 89 are associated with deforestation and 73 with reforestation. Table S2 lists only 67 studied watersheds where the relative contributions of changes in forest cover and climate variability to annual water yield have been quantified.

For each published literature, the following data were collected: annual water yield (*AWY* [mm]), climatic variables (mean annual temperature *T*, °C), precipitation (P [mm]), potential evapotranspiration (*PET* [mm]), and watershed properties (forest cover change and watershed area [km^2]; Table S1). In order to have consistent comparisons, annual *PET* values were estimated using Hamon method (Equations 1–3) in this study for those watersheds where PET was not provided (Vörösmarty, Federer, & Schloss, 1998).

$$PET = 0.1651 \times D \times V_d \times K \times 365 \tag{1}$$

$$V_d = 216.7 \times \frac{V_s}{T + 273.3} \tag{2}$$

$$V_s = 6.108 \times \exp\left(17.26939 \times \frac{T}{T + 237.3}\right), \tag{3}$$

where *D* is the time from sunrise to sunset in multiples of 12 hr, varies with date, latitude, slope, and aspect of a watershed (average daily *D* of an entire year is 1); V_d is the saturated vapor density (g/m^3) at annual mean temperate (*T*, °C); V_s is saturated vapor pressure (mb); and *K* is the correction coefficient to adjust *PET* to realistic values. *K* ranges from 1.2 to 1.4, and the value of 1.3 is used for all *PET* calculations to keep consistency (Zhou et al., 2015).

In this study, the watershed area and changes in forest cover are selected as proxies for representing watershed characteristics. Dryness index (*PET/P*) and precipitation are treated as climate indicators. To assess the role of watershed characteristic and climate indicators in AWY variations, hydrological sensitivity (H_s) is defined as the absolute changes in AWY in response to one unit change in forest cover (Equation 4).

$$H_s = \frac{|\Delta AWY|}{|\Delta F|}, \tag{4}$$

where $|\Delta AWY|$ is the absolute changes in annual water yield and $|\Delta F|$ is the absolute changes in forest cover (%) in a watershed.

3 | RELATIVE CONTRIBUTIONS OF CHANGES IN FOREST COVER AND CLIMATE TO ANNUAL WATER YIELD VARIATIONS

The relative contributions of changes in forest cover (R_f) and climate (R_c) from 67 large studied watersheds were averaged to evaluate the impact magnitudes of forest cover and climate changes to AWY variations (Figure 1a). The histograms of R_f and R_c were also plotted to show the distributions of those two variables across the sampled watersheds (Figure 1b). Our analysis clearly shows that the averaged R_f and R_c to AWY variations are 50.1 ± 18.9% and 49.1 ± 19.5%, respectively (Figure 1a), suggesting that the changes in forest cover

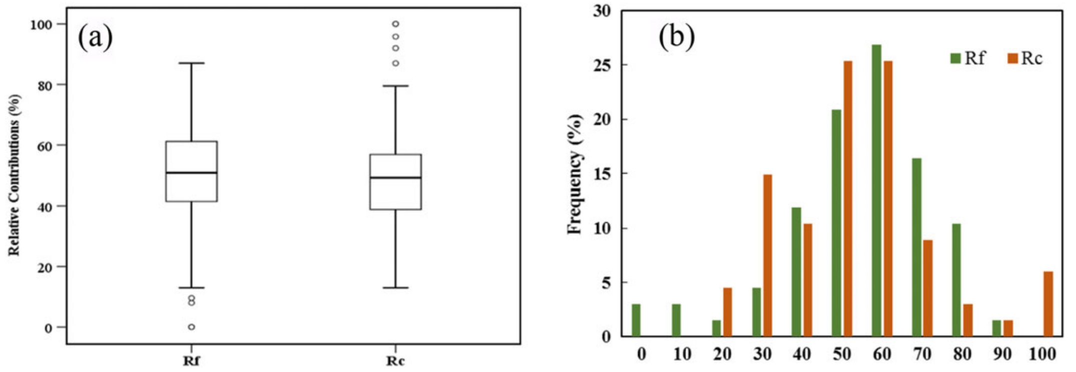

FIGURE 1 (a) Boxplot of the relative contributions of forest cover change (R_f) and climate variability (R_c) to annual water yield variations, and (b) histogram of relative contributions of forest cover and climate variability to annual water yield variations. The averaged R_f and R_c are 50.1 ± 18.9% and 49.1 ± 19.5%, respectively

and climate are equally important to AWY variations. Three key reasons may contribute to our finding. First, when conducting large watershed studies, researchers normally selected watersheds that have experienced dramatic changes such as severe forest disturbance (e.g., logging and wildfire) so that the hydrological effects of forest cover change can be easily detected. As such, AWY variations due to changes in forest cover might be more pronounced in the studied watersheds. Second, there are distinctions regarding their impact directions. The effects of deforestation or reforestation on AWY variations are monodirectional, and their effects are cumulative over a specific period of either deforestation or reforestation. In contrast, the effects of climate variability on AWY variations tend to be fluctuated or multidirectional and, consequently, may lead to possible cancelations over the deforestation or reforestation period (also see Figure 2). Thus, the difference in the impact directions may make the hydrological effects of forest cover change more pronounced. Third, our selected hydrological variable is AWY variation rather than its total magnitude. There is no doubt that total annual water yield in any given years are normally determined by climate, but their variations can be associated with both the changes in forest cover and climate.

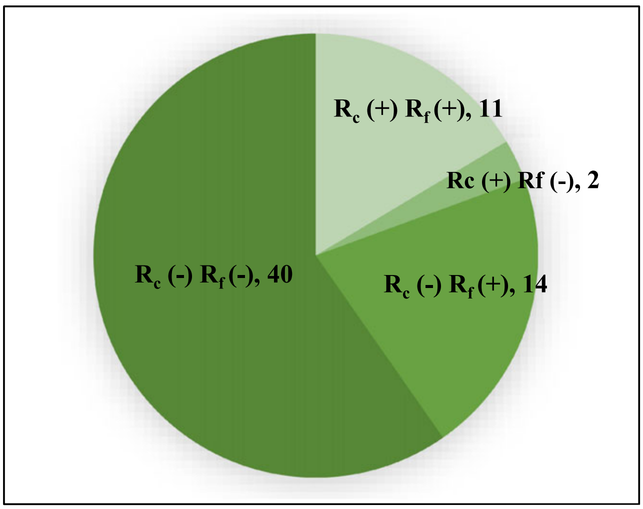

FIGURE 2 Directional responses of relative contributions of forest cover changes (R_f) and climate variability (R_c) to variations of annual water yield. + and − indicate positive and negative effects of R_f and R_c to variations of annual water yield. (Note that numbers in graph denote the numbers of case studies in different categories)

The effects of changes in forest cover and climate to AWY are directional (either positive or negative). As a result, their integrated effects on AWY variations can be additive or offsetting. Among 67 studied watersheds, 51 studied watersheds exhibited additive effects and 16 showed offsetting effects (Figure 2). Generally, high risk of extreme cases (floods or droughts) may happen if there are additive effects between the changes in forest cover and climate. On the contrary, limited or no significant water yield changes may occur if their effects are offsetting. Thus, both change magnitudes and directions of forest cover and climate must be considered in predicting and assessing future water resource availability.

4 | ANNUAL WATER YIELD VARIATIONS IN RESPONSES TO FOREST COVER CHANGE

The significant relationships between AWY and forest cover change were found in all three forest cover change categories: deforestation, reforestation, and general forest cover change (or their combinations; Figure 3). As expected, deforestation increases AWY, but reforestation decreases it. Figure 4 further shows that larger forest cover change can lead to greater AWY variations. Those results in the large watersheds are consistent with the results from multiple watershed scales (e.g., Andréassian, 2004; Bosch & Hewlett, 1982; Stednick, 1996; Zhang et al., 2017).

Although significant relationships exist between forest cover change and AWY variations, there are large variations in AWY responses (Figures 3 and 4). This is because (a) many variables such as climate, forest cover, and watershed properties can affect hydrological responses; (b) the studied watersheds of this assessment are from a wide range of climates across the globe (i.e., the dryness index [PET/P] ranges from 0.5 to 4.5 or from the very wet to very dry); (c) there are large variations on watershed properties such as soil types, topographies, and watershed sizes; and (d) the assessment involved various types of global forests whose significant but different

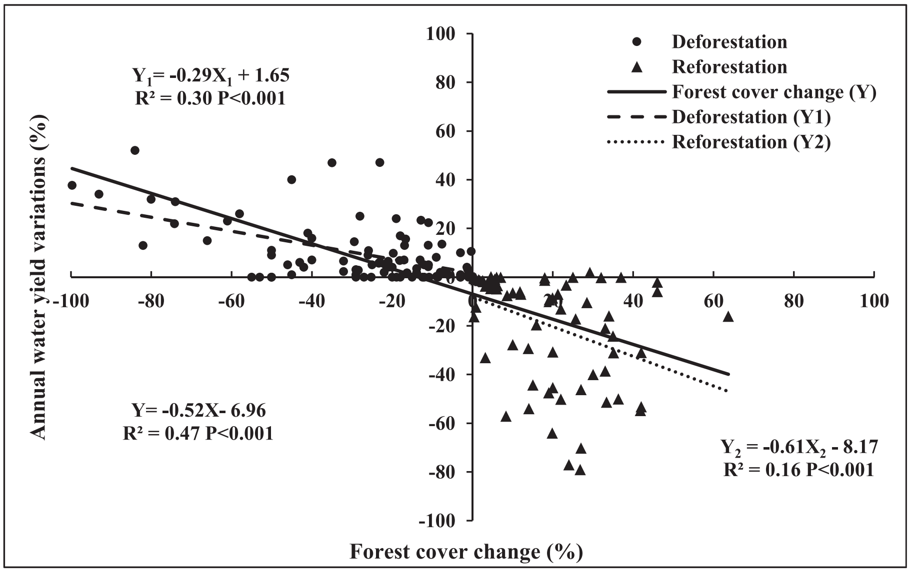

FIGURE 3 The relationships between annual water yield variations and the changes in forest cover in 162 large watersheds, among which 89 studied watersheds are in the deforestation category and 73 in the reforestation category

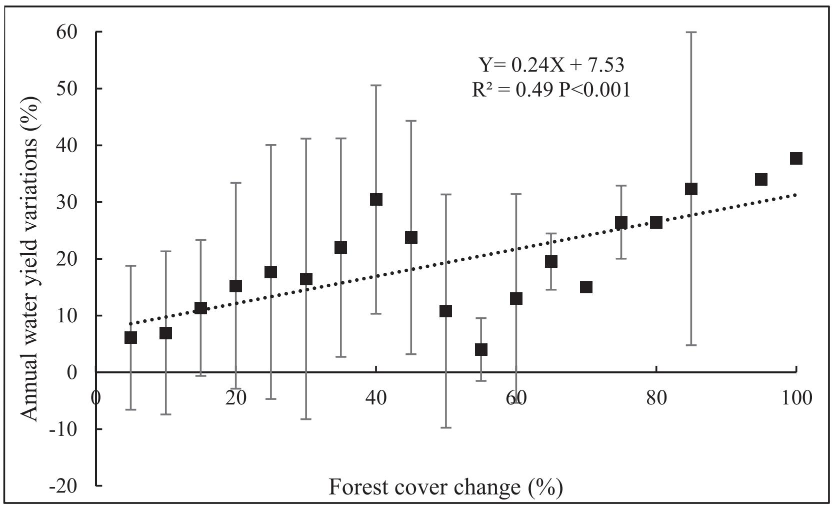

FIGURE 4 Absolute changes in annual water yield responding to the absolute changes in forest cover (in every 5% increment). Bars are standard deviations within the intervals

roles in hydrological responses have been demonstrated by various studies (e.g., Andréassian, 2004; Bruijnzeel, 2004; Ellison, Futter, & Bishop, 2012; Zhang, Dawes, & Walker, 2001). The large variations in hydrological responses to forest cover change clearly suggest that forest cover is one of the important various variables for influencing hydrological responses, and assessing the effects of forest cover change on hydrology needs to be conducted in a broad ecosystem context considering other important variables.

5 | ANNUAL WATER YIELD VARIATIONS IN RESPONSE TO WATERSHED PROPERTIES AND CLIMATE

Watershed properties (e.g., watershed size and slope) can determine flow path and residence time and, consequently, water storage capacity and hydrological response magnitude (Zhou et al., 2015). As shown in Figure 5, hydrological responses or sensitivities significantly decrease with increasing watershed size (P < .01), suggesting that larger watersheds are more resilient to hydrological alterations caused by forest cover change. This is because larger watersheds are normally characterized by more diverse land uses, landforms (e.g., wetlands and lakes), topographies, soil types, and so on, which buffer hydrological changes in responses to the changes in forest cover and climate (Woods, 2003; Yang et al., 2008; Zhang & Wei, 2014). Because of different hydrological sensitivities in different sized watersheds, any conclusions drawn from one watershed at a specific spatial scale may not be directly extrapolated to those at other spatial scales (Blöschl & Sivapalan, 1995).

Figures 6 and 7 show significantly increased hydrological sensitivities with increasing dryness, demonstrating that hydrological sensitivities in drier regions are higher than those in wetter regions. This result is consistent with previous studies (Farley, Jobbágy, & Jackson, 2005; Sun et al., 2006; Yang et al., 2009; Zhang et al., 2016;

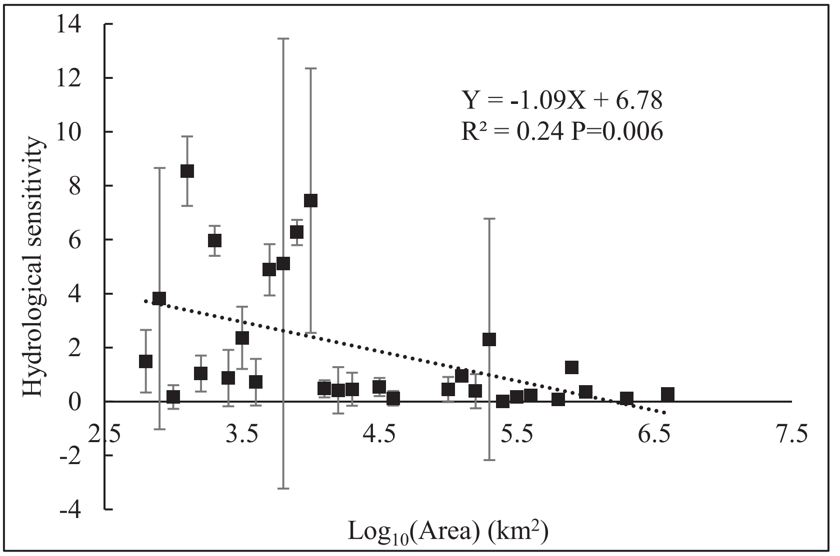

FIGURE 5 Hydrological sensitivity responds to watershed sizes (in logarithm scale) with an interval of $\log_{10}$ (area) of 0.1. Bars are the standard deviations within the intervals

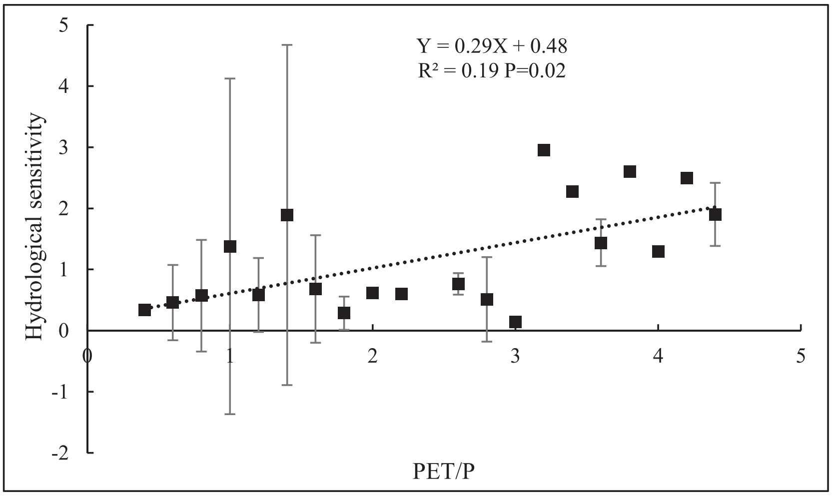

FIGURE 6 Hydrological sensitivity responds to the aridity index (PET/P) with the PET/P interval of 0.1

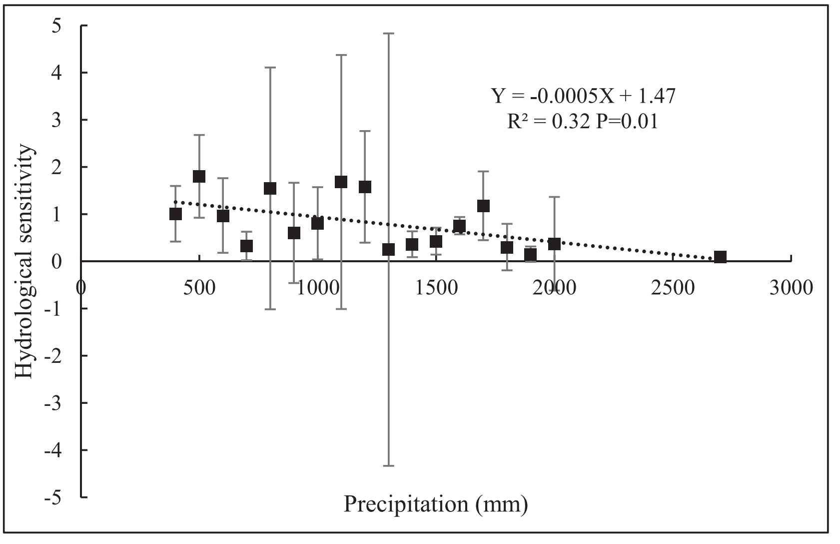

FIGURE 7 Hydrological sensitivity responds to precipitation with the precipitation interval of 100 mm

Zhang et al., 2017; Zhou et al., 2015). The reason may be that water is limited in dryer regions, and the changes in evapotranspiration caused by forest cover change could have a larger impact on water yield in terms of percentage change.

Our above analyses clearly demonstrate that forest cover change plays a coequal role in AWY changes as climate does. Our analyses also suggest that forest cover change, climate variability, and watershed properties all interactively affect AWY change. Those results have important implications for understanding and managing future water resources. First, it is important to consider both forest cover and climate changes in predicting future water resource changes in any forested watersheds as the interactions of both drivers determine magnitudes and directions of water resource changes. Second, a broader context considering various key drivers such as forest cover change, climate, and watershed property is needed to understand hydrological effects of either forest cover or climate changes. The interplays of those drivers also indicate that the effects of forest cover change on hydrology in large forested watersheds is likely watershed specific, and any extrapolation of results from one watershed to others requires integrated assessment of forest cover change, climate, and watershed properties. Finally, our results of higher hydrological sensitivities in smaller and drier watersheds suggest that any management practices in those more sensitive landscapes need extra caution to minimize negative hydrological effects.

6 | CONCLUSIONS

Our synthetic assessment of the effects of forest cover change and climate variability on annual water yield variations in large forested watersheds clearly indicates that forest cover change and climate variability are equally important to annual water yield variations. Because those effects can be additive or offsetting, both forest cover changes and climatic variability, together with their interactions must be considered in assessing and managing future water resources. We also found that smaller and dryer watersheds are more hydrologically sensitive to forest cover change. The large variations in the hydrological effects of forest cover change in large forested watersheds suggest that hydrological responses to forest cover change are likely watershed specific, and thus, a broader context considering forest cover, climate, and watershed properties is needed to fully understand and effectively manage annual water yield variations.

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SUPPORTING INFORMATION

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