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Review papers

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

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ABSTRACT

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.

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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

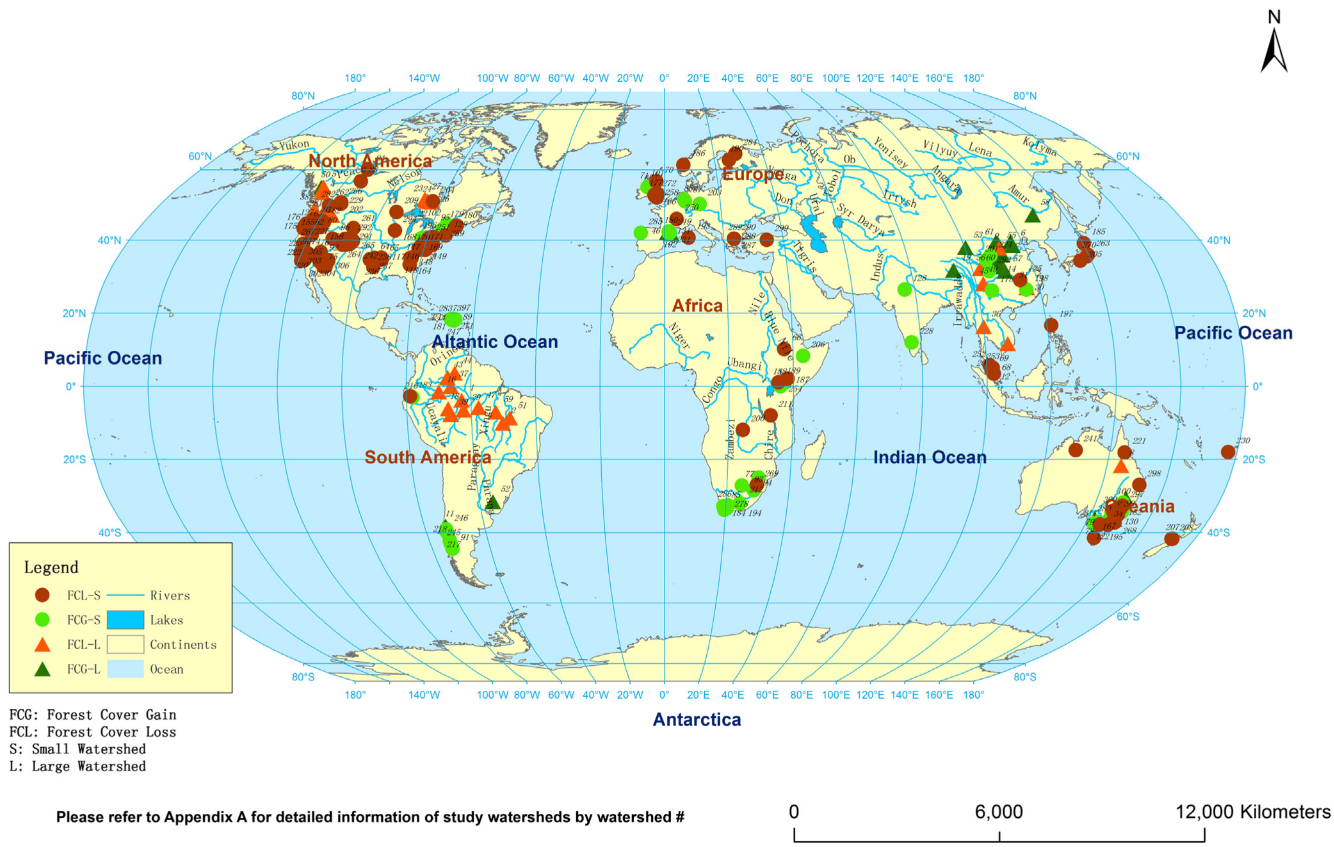

Fig. 1. The distribution of watershed studies on forest cover change and annual runoff.

Table 1
The number of selected watersheds across different categories of forest change, forest type and hydrological regime.

Watershed size	Forest type			Hydrological regime		Climate type			Forest change type	
	CF	BF	MF	RD	SD	EL	EQ	WL	FG	FL
Small	76	150	26	195	57	82	120	50	70	182
Large	11	34	16	50	11	14	22	23	31	30

BF, CF, and MF are broadleaf, coniferous, and mixed forests, respectively. EL, EQ, WL are energy-limited, equitant and water-limited watersheds, respectively. RD, and SD are rain-dominated and snow-dominated watersheds, respectively. FCG and FCL are forest cover gain and forest cover loss, respectively.

1,858,883 km^2 in size, while 251 of them are small watersheds (Fig. 1). 31 of the large watersheds have experienced forest cover gain by afforestation, or reforestation (with 3.6–46% forest cover change, Table 1), while 30 of them with forest cover loss (a 1–58% reduction in forest coverage) due to logging, slash-burn, fire, and insect infestation (Jones and Grant, 1996; Storck et al., 1998; Bowling et al., 2000; Chen et al., 2005; Li et al., 2007; Zhang et al., 2008; Mao and Cherkauer, 2009; Li et al., 2010; Ma et al., 2010; Jorge et al., 2012; Zhang and Wei, 2012a, 2012b; Iroumé and Palacios, 2013; Lima et al., 2014; Bieger et al., 2015). 182 of the small watersheds have forest cover losses due to logging, slash-burn, fire, and insect infestation, and only 69 of them with forest cover gain by afforestation, regrowth, or reforestation. This global dataset includes newly published small and large watershed studies on the annual runoff response to forest cover change (e.g., Webb et al., 2007; Webb, 2009; Bren et al., 2010; Gallart et al., 2011; Dung et al., 2012; van Dijk et al., 2012; Beck et al., 2013; Niedda et al., 2014; Carvalho-Santos et al., 2016; Winkler et al., 2015; Mahat et al., 2016), and small watersheds documented by several classic reviews (e.g., Bosch and Hewlett, 1982; Stednick, 1996; Sahin and Hall, 1996; Andréassian, 2004; Bruijnzeel, 2004; Brown et al., 2005; Moore and Wondzell, 2005). See Appendix A (Alexander and Watkilas, 1977; Alexander et al., 1985; Amatya and Skaggs, 2008; Bari et al., 1996; Bates and Henry, 1928; Bent, 2001; Blackie, 1993; Boggs et al., 2015; Borg et al., 1988; Bosch, 1979; Brantley et al., 2015; Brown, 1971; Bruijnzeel, 1990; Buendia et al., 2016; Buytaert et al., 2007; Cornish, 1993; Cornish and Vertessy, 2001; Cuo et al., 2009; Dale et al., 2000; Devito et al., 2005; Douglass and Swank, 1976; Edwards and Blackie, 1981; Fohrer et al., 2005; Fowler et al., 1987; Ganatsios et al., 2010; Gottfried, 1991; Haileyesus et al., 2011; Harr, 1982; Harr, 1980; Harr, 1976; Harr et al., 1979; Harris, 1977; Harris, 1973; Harrold et al., 1962; Hawthorne et al., 2013; Hewlett and Hibbert, 1961; Hewlett, 1979; Hewlett and Douglass, 1968; Hibbert, 1971; Hibbert, 1979; Hibbert and Ingebo, 1971; Hibbert et al., 1975; Hornbeck, 1975; Hornbeck et al., 1993; Hornbeck et al., 1970; Ide et al., 2013; Ingebo and Hibbert, 1974; Johnson and Kovner, 1956; Johnston, 1984; Jones, 2000; Jones and Post, 2004; Kabeya et al., 2015; Keppeler and Ziemer, 1990; Kochenderfer and Wendel, 1983; Kochenderfer et al., 1990; Koivusalo et al., 2006; Lane and Mackay, 2001; Lavabre et al., 1993; Lewis, 1968; Li et al., 2014; Lin and Wei, 2008; Liu et al., 2015; Lynch et al., 1980; Ma, 1980; Ma et al., 2009; Magilligan and Nislow, 2001; Matheussen et al., 2000; Miller et al., 1988; Molina et al., 2012; Nakano, 1971; Nänni, 1970; Ngo Thanh et al., 2015; Nguyen Khoi and Suetsugi, 2014; O'Shaughnessy et al., 1979; Patric, 1980; Patric and Reinhart, 1971; Pearce et al., 1976; Pearce et al., 1980; Peña-Arancibia et al., 2012; Pereira, 1962; Reinhart et al., 1963; Rich and Gottfried, 1976; Rich and Thompson, 1974; Robinson, 1993; Robinson and Dupeyrat, 2005; Robinson et al., 1991; Roche, 1981; Rodriguez Suarez et al., 2014; Rodriguez-Iturbe and Porporato, 2005; Rodriguez-Iturbea et al., 2001; Rothacher, 1970; Rowe, 1963; Ruprecht et al., 1991; Samraj et al., 1998; Schneider and Ayer, 1961; Serengil et al., 2007; Silveira and Alonso, 2009; Siriwardena et al., 2006; Sun et al., 2008; Swank and Helvey, 1970; Swank and Douglass, 1974; Swank and Miner, 1968; Swank et al., 1988; Swift and Swank, 1980; Tomer and Schilling, 2009; Troendle and Olsen, 1994; Troendle, 1988; Troendle and King, 1985; Troendle and King, 1987; Ukkola et al., 2015; Van der Zel and Kruger, 1975; Van Dijk et al., 2007; Van Haveren, 1988; Van Lill et al., 1980; VanShaar et al., 2002; Wang and Hejazi, 2011; Wang et al., 2012; Watson et al., 2001; Wei and Zhang, 2010a; Williamson et al., 1987; Yan et al., 2014; Yao et al., 2015; Yu et al., 2015; Zhao et al., 2010; Zheng et al., 2009; Zhou et al., 2010, 2015) for more details.

Data on spatial scale (watershed size), climate (dryness index), potential evaporation, annual runoff, forest cover change (%), annual runoff response to forest cover change (%), forest type (coniferous, broadleaf, and mixed forests), and hydrological regime (snow-dominated and rain-dominated) were derived or calculated from collected documents. See Appendix A for more details on the study watersheds.

It is important to note that these studies used a range of methods to quantify the change in runoff caused by forest cover change, including paired watershed experiments (e.g., Bart and Hope, 2010; Webb and Jarrett, 2013), quasi-paired watersheds (e.g., Buttle and Metcalfe, 2000; Mahat et al., 2016), hydrological modelling (e.g., Gallart et al., 2011; Beck et al., 2013), elasticity analysis (e.g., Zhang et al., 2008; Zhao et al., 2013), and a combination of statistical methods and hydrographs (e.g., Wang et al., 2009; Iroumé and Palacios, 2013). Paired watershed experiments are commonly used to measure runoff response to forest change in smaller watersheds (<100 km^2), where the influences on runoff from non-forest factors (e.g., climate variability) can be removed through comparisons between the impacted watershed and the control one. Quasi-paired watershed approach is applied to estimate runoff response to forest change in larger watersheds ($\geqslant$100 km^2) with more heterogeneities in landscape and climate. A watershed with a greater disturbance level is defined as the impacted watershed while its neighboring, intact, or less disturbed watershed is viewed as the control or partial control (Buttle and Metcalfe, 2000). Hydrological models (e.g., VIC, DHSVM, MIKE-SHE, SWAT) are often utilized to predict runoff response due to forest changes in well observed and monitored watersheds (e.g., Waterloo et al., 2007; Coe et al., 2009). In watersheds with limited data on forest, hydrology, climate, geology, and land cover, or lacking a suitable control watershed, a combination of statistical methods (e.g., non-parametric tests, ANOVA, time series analysis) and hydrographs (e.g., double mass curve, modified double mass curve, flow duration curve) are well-accepted strategies, especially in large watersheds (e.g., Costa et al., 2003; Zhang and Wei, 2012a).

3. Methods

Annual runoff response to forest cover change (ΔQ_f) is defined by Eq. (1). Additionally, the sensitivity of annual runoff to forest cover change (S_f) in a given watershed has been introduced as an indicator of the response intensity of annual runoff to forest cover change. S_f is defined as annual runoff response to forest change (ΔQ_f) normalized by forest cover change (ΔF) (Eq. (2)). Watershed properties such as watershed size, climate, forest type, and hydrological regime are potential determinants of the sensitivity of annual runoff to forest change (Kirchner, 2006; Donohue et al., 2010).

Budyko dryness index (*DI*), equal to the ratio of mean annual potential evaporation (*PET*) to mean annual precipitation (*P*) was adopted as an integrated indicator of climate conditions for a given watershed. Dryness index can effectively reflect the interactions between energy and water limitations on catchment annual ET, and thus can indicate the water availability for vegetation growth (Jones et al., 2012; van Dijk et al., 2012). Watersheds were then grouped into water-limited ($DI > 1.35$), equitant ($0.76 < DI < 1.35$), energy-limited ($DI < 0.76$) environments based on dryness index (McVicar et al., 2012). Forest types include coniferous, broadleaf (either evergreen or deciduous broadleaf forest), and mixed forests (a mixture of coniferous and broadleaf forests). The forest type for a given watershed was determined by its dominant tree species from the literature. Hydrological regime for a watershed can be snow-dominated or rain-dominated. Snow-dominated watershed is featured with most floods driven by snowmelt process while rain-dominated watershed with most floods driven by rainfall.

Linear regression and Kendall rank correlation test were used: (1) to detect the statistical significance of relationships between ΔQ_f and ΔF; (2) to investigate the statistical significance of relationships between watershed size and the response intensity of annual runoff response to forest cover change (S_f); and (3) to examine how the response intensity of annual runoff response to forest cover change (S_f) varies with climatic gradients (DI). Two-sample nonparametric Kolmogorov–Smirnov test was performed on pairs of watershed groups classified by climate type (energy-limited (EL), equitant (EQ) and water-limited (EW) environments), forest

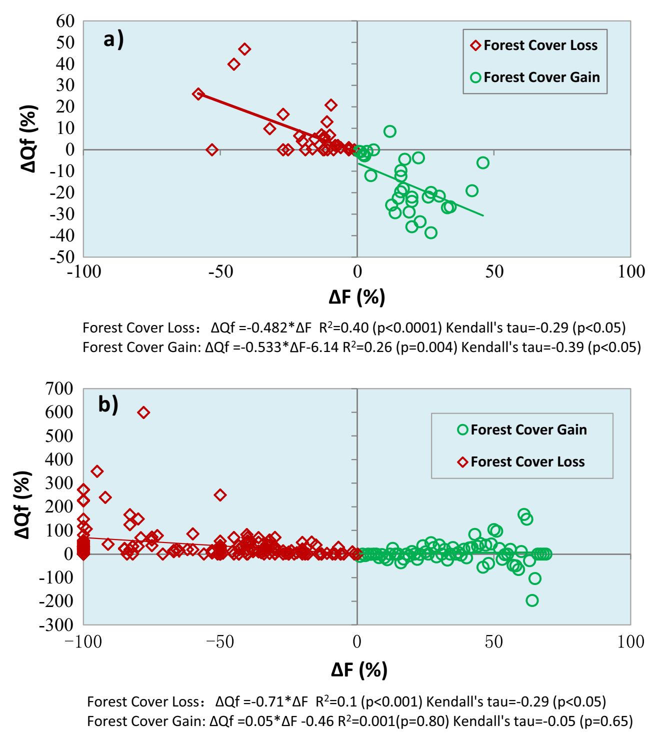

Fig. 2. The relationship between forest coverage change and annual runoff change in (a) large ($\geqslant$1000 km^2) and (b) small watersheds (<1000 km^2).

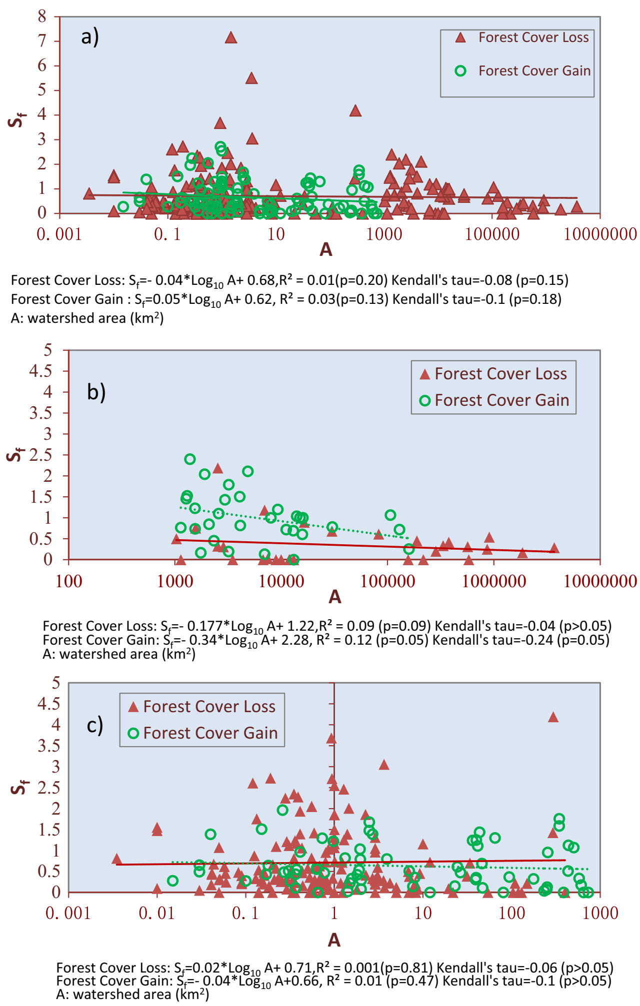

Fig. 3. The relationship between watershed size and the sensitivity of annual runoff to forest cover change across (a) all spatial scales, (b) in large (⩾1000 km^2) and (c) in small watersheds (<1000 km^2).

type (coniferous (CF), broadleaf (BF), and mixed forests (MF)) or hydrological regime (rain-dominated (RD) and snow-dominated (SD) watersheds) to test for significant differences between entire distributions of the sensitivity of annual runoff to forest cover change, while the Mann-Whitney *U* test was conducted on watershed groups to test for significant differences in the medians of distributions of the sensitivity of annual runoff to forest cover change. In this way, the effects of watershed size, climate, forest type, and hydrological regime on the sensitivity of annual runoff to forest cover change can be quantitatively analyzed.

$$\Delta Q_f = 100 \times \frac{\Delta Q_{f,m}}{\overline{Q}} \tag{1}$$

$$S_f = \left|\frac{\Delta Q_f}{\Delta F}\right| \tag{2}$$

where $\overline{Q}$ refers to the long-term mean annual runoff (mm); $\Delta Q_{f,m}$ is the amount of (mm). ΔQ_f is annual runoff response to forest change (%). S_f refers to the response intensity of annual runoff to forest cover change and ΔF is the watershed forest cover change (%).

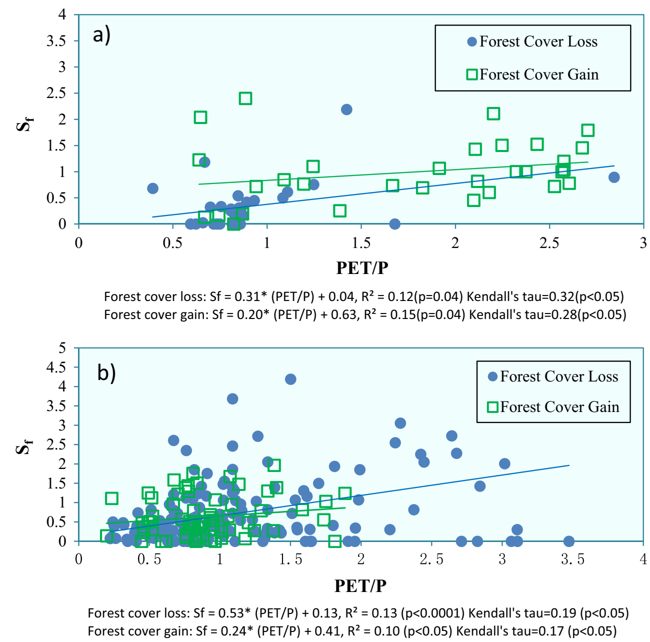

Fig. 4. The relationship between climatic gradient and the sensitivity of annual runoff response to forest cover change in (a) large (⩾1000 km^2) and (b) small watersheds (<1000 km^2).

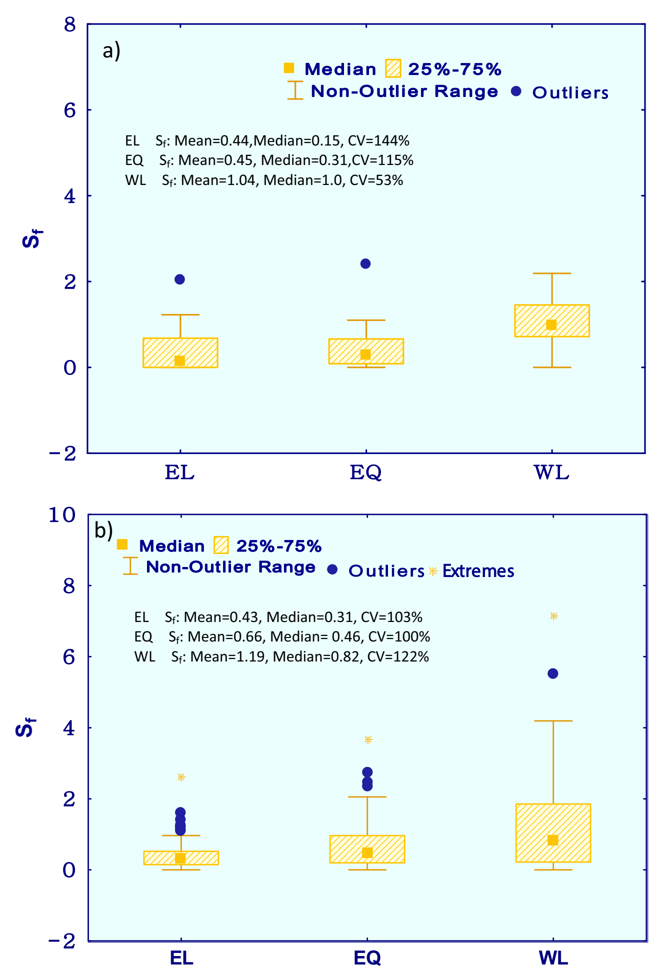

Fig. 5. A comparison of the sensitivity of annual runoff response to forest cover change grouped by energy-limited (EL), equitant (EQ), and water-limited (WL) environments in (a) large (⩾1000 km^2) and (b) small watersheds (<1000 km^2).

4. Results

4.1. Forest and water relationships at multiple spatial scales: forest cover gain vs. forest cover loss

Results from the majority of watersheds show that forest cover loss can increase annual runoff ((21 large watersheds ($\geqslant$1000 km^2) and 202 small watersheds (<1000 km^2)). Both linear regression analysis and the Kendall correlation test suggest a significant negative relationship ($\alpha = 0.05$) between forest cover loss (ΔF) and its associated annual runoff change (ΔQ_f) in both large and small watersheds (Fig. 2a and b). In other words, there is significant tendency across multiple spatial scales for more forest cover loss to lead to increases in annual runoff. However, the effect of forest cover gain (e.g., afforestation, reforestation or regeneration) tends to be more complicated and inconsistent. We failed to detect a statistically significant relationship ($\alpha = 0.05$) between forest cover change (ΔF) and annual runoff response (ΔQ_f) in small watersheds with forest cover gain (Fig. 2b), while there is a significant negative relationship between ΔF and ΔQ_f in large watersheds (Fig. 2a). This suggests that the tendency for an increase in forest cover to lead to a reduction in annual runoff is only significant in large watersheds.

4.2. Spatial scale and the sensitivity of annual runoff to forest cover change

Fig. 3 shows how the sensitivity of annual runoff to forest cover change varies across spatial scales. As suggested by the linear regression and the Kendall correlation test, the relationship between watershed area and the sensitivity of annual runoff to forest cover loss is statistically insignificant ($\alpha = 0.05$) across all spatial scales (Fig. 3a). Similarly, the relationship between watershed area and the sensitivity of annual runoff to forest cover gain is also insignificant across multiple spatial scales. However, when large watersheds and small watersheds were investigated separately, different results were found. For large watersheds, there is a significant negative relationship between watershed area and the sensitivity of annual runoff to forest cover change (forest cover loss and forest cover gain) at $\alpha = 0.05$ (Fig. 3b). That is, there is a significant tendency for the response intensity of annual runoff to forest cover change to decline with increased watershed size in large watersheds. In contrast, the relationship between watershed area and the sensitivity of annual runoff to forest cover change is statistically insignificant for small watersheds (Fig. 3c).

4.3. Climate gradient and the sensitivity of annual runoff to forest cover change

The general tendency that the sensitivity of annual runoff to forest cover change can increase with elevated dryness index is significant across multiple spatial scales. As shown by the regression analysis and the Kendall correlation test, there is a significant positive relationship between dryness index and the sensitivity of annual runoff to forest cover change in both small and large watersheds at $\alpha = 0.05$ (Fig. 4).The drier a watershed, the more pronounced is the response intensity of annual runoff to forest cover change and vice versa.

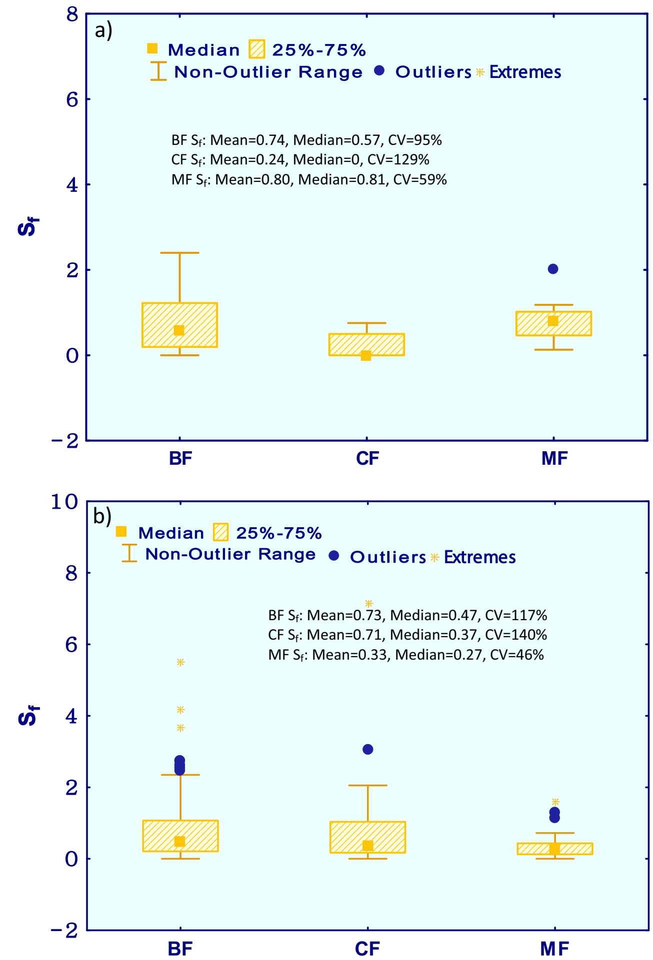

Fig. 6. A comparison of the sensitivities of annual runoff to forest cover change in (a) large and (b) small watersheds dominated by different forest types (BF, broadleaf forest, CF, coniferous forest, MF, mixed forest).

Fig. 5 compares the sensitivity of annual runoff to forest cover change in water-limited (WL), equitant (EQ), energy-limited (EL) environments. In large watersheds, the Kolmogorov–Smirnov and the Mann-Whitney *U* tests (Table 2) suggest insignificant differences between EL and EQ watersheds in the distributions and medians of the sensitivity of annual runoff to forest cover change,

Table 2
Statistical tests for the effect of climate type on the sensitivity of annual runoff to forest cover change.

Climate type	Watershed type	Kolmogorov–Smirnov test			Mann-Whitney *U* test	
		Max Neg difference	Max Pos difference	p	Z	P
EL-EQ	Large	−0.20	0.30	>0. 1	0.7	0.51
	Small	**−0.22**	0.01	**<0.02****	**−2.4**	**<0.02****
EL-WL	Large	**−0.60**	0.00	**<0.005****	**−2.9**	**0.004****
	Small	**−0.37**	0.11	**<0.001****	**−2.8**	**<0.006****
EQ-WL	Large	**−0.57**	0.04	**<0.005****	**−3.8**	**0.0002****
	Small	−0.23	0.11	0.07	−1.56	0.12

EL, EQ, WL are energy-limited, equitant and water-limited watersheds, respectively.
** Significant at $\alpha = 0.05$.

Table 3
Statistical tests for the effect of forest type on the sensitivity of annual runoff to forest cover change.

Forest type	Watershed type	Kolmogorov–Smirnov test			Mann-Whitney *U* test	
		Max Neg difference	Max Pos difference	p	Z	P
BF-CF	Large	−0.40	0.00	>0.1	**−2.3**	**0.02**[**]
	Small	−0.03	0.09	>0.1	−0.57	0.57
CF-MF	Large	**−0.57**	**0.00**	**<0.05**[**]	**−3.2**	**0.001**[**]
	Small	**−0.35**	**0.00**	**<0.05**[**]	**−2.2**	**0.03**[**]
MF-BF	Large	−0.21	0.29	>0.10	0.83	0.40
	Small	**−0.32**	**0.00**	**<0.05**[**]	**−2.4**	**0.02**[**]

BF, CF, and MF are broadleaf, coniferous, and mixed forests, respectively.
[**] Significant at $\alpha = 0.05$.

whereas the distribution and median of the sensitivity of annual runoff to forest cover change in WL watersheds are significantly different from those in EQ or EL watersheds ($\alpha = 0.05$). In large water-limited watersheds 1% forest cover change can lead to 1.04% change in annual runoff, while it can only cause about 0.44% and 0.45% change in annual runoff in large EL and EQ watersheds, respectively (Fig. 5a). In small watersheds, the distributions and medians of the sensitivity of annual runoff to forest cover change in EL watersheds are significantly different from those of WL and EQ watersheds, while there are insignificant differences between EQ and WL watersheds ($\alpha = 0.05$). For small EL watersheds 1% forest cover change can cause about 0.43% change in annual runoff, while in small EQ and EL watersheds that value can be up to 0.66% and 1.19%, respectively (Fig. 5b).

4.4. Forest type and the sensitivity of annual runoff to forest cover change

Fig. 6 compares the sensitivity of annual runoff to forest cover change in watersheds dominated by different forest types. As suggested by the statistical tests (Table 3), in large watersheds, the median of the sensitivity of annual runoff to forest cover change in coniferous forest dominated watersheds is significantly different from that in broadleaf or mixed forest dominated watersheds ($\alpha = 0.05$). In large mixed and broadleaf forests dominated watersheds, 1% forest cover change can result in 0.80% and 0.74% change in annual runoff, respectively, while in large coniferous forests dominated watersheds, that value is only 0.24%. In small watersheds, the distribution and medians of the sensitivity of annual runoff to forest cover change in mixed forest dominated watersheds are significantly different from those of broadleaf and coniferous forest dominated watersheds, while there are no significant differences in the distribution and medians of the sensitivity of annual runoff to forest cover change between broadleaf and coniferous forest dominated watersheds ($\alpha = 0.05$). In small broadleaf and coniferous forests dominated watersheds, 1% forest cover change can result in 0.73% and 0.71% change in annual runoff while in small mixed forests dominated watersheds, respectively, that value is only 0.33%.

4.5. Hydrological regime and the sensitivity of annual runoff to forest cover change

Fig. 7 compares the sensitivity of annual runoff to forest cover change between rain-dominated and snow-dominated watersheds. As suggested by the statistical tests (Table 4), in large watersheds, the distribution and medians of the sensitivity of annual runoff to forest cover change (S_f) in rain-dominated watersheds are significantly ($\alpha = 0.05$) different from those in snow-dominated watersheds (Table 4). In rain-dominated large watersheds, 1% forest cover change can lead to up to mean 0.74% change

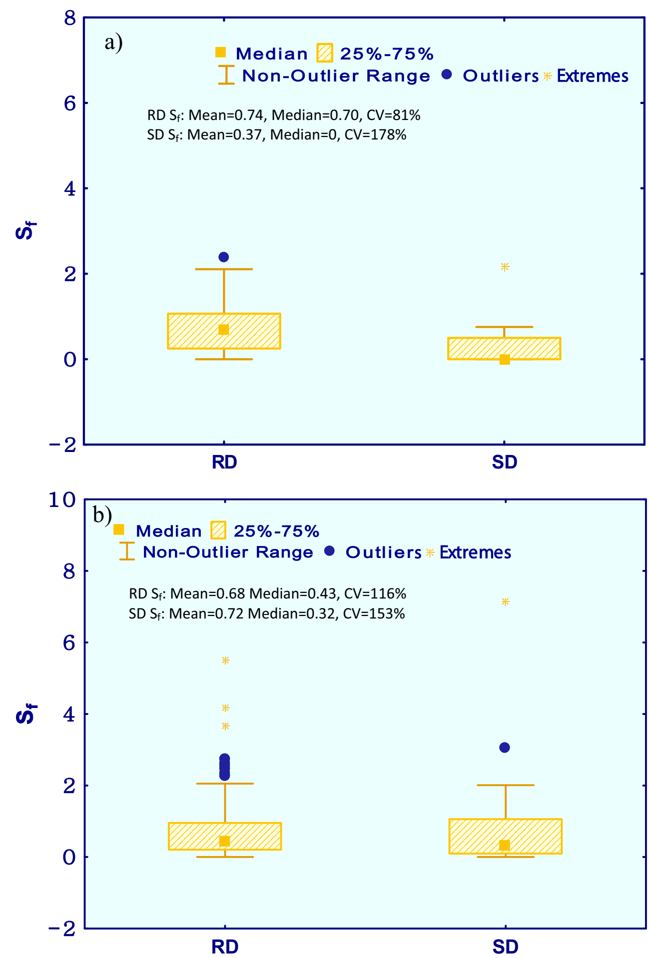

Fig. 7. A comparison of the sensitivities of annual runoff to forest cover change in (a) large and (b) small watersheds dominated by different hydrological regimes (RD, rain-dominated, SD, snow-dominated).

in annual runoff while in snow-dominated watersheds, this value is only 0.37%. However, in small watersheds, there are no statistically significant differences ($\alpha = 0.05$) between rain-dominated and snow-dominated watersheds in the distribution and medians of the sensitivity of annual runoff to forest cover change (Table 4).

5. Discussion

5.1. Forest cover change and annual runoff response: consistency and variations

There is a general understanding that forest cover loss can increase annual runoff due to a reduction in interception and evap-

Table 4
Statistical tests for the effect of hydrological regime on the sensitivity of annual runoff to forest cover change.

Hydrological regime	Watershed type	Kolmogorov–Smirnov test			Mann-Whitney *U* test	
		Max Neg difference	Max Pos difference	p	Z	P
RD-SD	**Large**	**−0.07**	**0.43**	**0.05****	**2.40**	**0.01****
	Small	−0.07	0.13	>0.1	0.76	0.45

RD and SD are rain-dominated and snow-dominated watersheds, respectively.
** Significant at $\alpha = 0.05$.

otranspiration in small watersheds while a similar conclusion has not yet been drawn in large watersheds (Andréassian, 2004; Stednick, 2008; Oudin et al., 2008). Our analysis suggests that the tendency for forest cover loss to increase annual runoff is valid across watersheds of all sizes: simply put, increasing forest cover loss will lead to an increase in annual runoff. This is consistent with a few studies on the effect of vegetation change on annual evapotranspiration (e.g., see Brown et al., 2005; McVicar et al., 2007 and the relevant references in both), which show a negative relationship between vegetation coverage and annual evapotranspiration at multiple spatial scales.

Despite this general trend, the annual runoff response to forest change is variable among watersheds. There is a sub-set of watersheds with insignificant changes in annual runoff to forest cover change in 12 (of 61) large watersheds with forest cover loss from 1 to 53% and 33 (of 252) small watersheds with forest cover loss from 0 to 100%. In some watersheds, insignificant changes in annual runoff are associated with a small amount of forest cover change. For example, a study in Canadian boreal forests (with six watersheds ranging from 401 to 11,900 km^2), with forest cover loss ranging from 5% to 25% of watershed areas, failed to find definitive changes in annual runoff (Buttle and Metcalfe, 2000).

However, there are several non-responsive watersheds (10 of the 45 non-responsive watersheds) with forest cover loss >50%. More surprisingly, in some small watersheds, even with a 100% forest cover loss, insignificant changes in annual runoff have been detected (Scott, 1993; Stednick, 1996; Bart and Hope, 2010). The reasons for these non-responsive cases could be their differences in hydrological regimes. For example, in the Nam Pong River Basin (12,100 km^2) of Northeast Thailand, a rain-dominated tropical watershed with forest cover reduced by 53%, Wilk et al. (2001) did not detect any significant change in annual runoff. Part of the explanation is associated with the land classification of forested land and non-forested land. Land with a low density of trees can be classified as forested land, and this may mask the actual effect of a particular land use on watershed hydrology. Another important reason is that in this large watershed deforestation occurred gradually over time with vegetation regrowth occurring in parts of the watershed at the same time. The rapid vegetation regrowth in these subtropical or tropical rain-dominated regions may consume more water than reduced evapotranspiration by cleared trees (Bruijnzeel, 2004). In snow-dominated watersheds, the non-response is likely to be related to snowmelt processes that are affected by aspect, elevation range, soil, and energy input (Schnorbus and Alila, 2013). For example, in the 242 Creek in the interior of British Columbia in Canada, where forest was logged by 50%, annual runoff change was insignificant while runoff in May was greatly increased by 100% followed by a significant reduction in June and July. That is, more water leaves the watershed in terms of spring snowmelt runoff, resulting in less water recharge for the drier soils during summer and autumn (low flow seasons in the Pacific Northwest) with high evapotranspiration and low precipitation, and consequently leading to insignificant changes in annual runoff (Winkler et al., 2015).

In addition, the non-response in runoff to forest changes can sometimes be related to dominating impacts of climate conditions during post-forest change years. For example, Bart and Hope (2010) investigated the post-fire runoff response in six California catchments (54–632 km^2) with forest burnt by 23–100% and found insignificant changes in annual runoff in four catchments (Sespe, Santa Paula, San Antonio, and Lopez). In particular, the Lopez catchment was completely burned. These four catchments experienced a prolonged drought during the second to fifth post-fire years when no streamflow increases were detected. In this region, soil moisture was the determinant of the runoff response to vegetation change during droughts. Differences in vegetation cover and transpirational capacity of the control and treated catchments may have limited effects on evapotranspiration and hence on runoff. Thus, soil moisture deficit due to the post-fire prolonged drought may offset the increases in runoff due to reduced ET after fire (Stednick, 2008; Bart and Hope, 2010).

The response of annual runoff to forest cover gain tends to be even more variable and complicated when compared to forest cover loss. In large watersheds, more forest cover gain is likely to result in more reduction in annual runoff while in small watersheds, insignificant relationship between forest cover gain (ΔF) and annual runoff response (ΔQ_f) has been detected. There are many watersheds where the response of annual runoff to forest cover gain is insignificant. There are about 19 small watersheds and one large watershed even with quite distinct hydrological responses - increased annual runoff due to forest cover gain. Such an example occurs in the headwater of Heihe River Basin in China where a 12.6% increase in forest cover due to spruce reforestation was predicted to increase annual runoff by 8.6% (Wu et al., 2015). In this mountainous watershed, old-growth spruce forests (*Picea crassifolia*) dominated at higher elevation areas (with an altitude of 3000 m above sea level) are featured by lower evapotranspiration than grassland as suggested by the modelling. In addition, these subalpine forests can increase soil water storage by intercepting both rainfall and cloud water (Wei et al., 2005; Zhang et al., 2008b). Thus, an increase in annual runoff after the conversion of grassland to spruce forest in this watershed will be expected.

In general, we can only draw a statistical inference that more forest cover loss can lead to more pronounced changes in annual runoff in both small and large watersheds. Moreover, despite this general tendency, the annual runoff response to forest cover change is highly variable. These variations are not simply determined by the change in forest cover rate, but largely related to many confounding factors such as forest characteristics (e., tree species, stand age and structure, vegetation regeneration, and forest change pattern), topography (e.g., aspect, elevations), geology (e.g., surface-groundwater interactions), hydrological regimes (e.g., snow-dominated, rain-dominated), landscape pattern (e.g., lakes, wetlands) and water availability (precipitation) rather than watershed size (Farmer et al., 2003; Williams and Albertson, 2005; Blöschl et al., 2007; Bart and Hope, 2010; Karlsen et al., 2016). This highlights the need for a more detailed investigation on how these factors affect the response of annual runoff to forest cover change across multiple spatial scales.

5.2. Scale issue in annual runoff response to forest cover change

Theoretically, more heterogeneities in landscape, topography, climate, geology and vegetation will occur as watershed size increases, resulting in greater buffering ability to watershed disturbances such as forest cover change, and thus being less sensitive to a given level of forest cover change as compared to smaller watersheds (Huff et al., 2000; Andréassian, 2004; Crouzeilles and Curran, 2016). Is the response of annual runoff to forest cover change really scale-dependent? Our analysis shows that the response intensity of annual runoff to forest cover change declines with increasing watershed size is only valid in large watersheds. A definite conclusion that the impact of forest cover change on annual runoff attenuates with watershed size cannot be drawn in small watersheds or across multiple spatial scales.

The differences in scale effects on the hydrological responses to forest cover change between large watersheds and small watersheds indicate that dominant eco-hydrological processes and interactions between forests and water in large watersheds can be quite different from those in small watersheds (Arrigo and Salvucci, 2005; Kirchner, 2006). Therefore, extrapolating the findings from small watersheds to large watersheds or vice versa can be very challenging and complicated (Best et al., 2003; Popp et al., 2009). A simple extrapolation of findings from a small watershed to a large watershed could be problematic given the differences in eco-hydrological processes between small and large watersheds (Bracken and Croke, 2007). This calls for more large watershed studies on the mechanisms underlying forest and water interactions and feedbacks.

5.3. Differences among water-limited, equitant, and energy-limited watersheds in hydrological responses to forest cover change

It is well-recognized that climate conditions in terms of water and energy are critical for forest growth (Jackson et al., 2005; Rodriguez-Iturbe et al., 2007; Asbjornsen et al., 2011). The interactions between ecological and hydrological processes can be quite different across climatic gradients (Rodriguez-Iturbe et al., 2007; Farmer et al., 2003; Donohue et al., 2011; Liu and McVicar, 2012; Zhou et al., 2015). Our analysis showed that the sensitivity of annual runoff to forest cover change will increase with dryness index across multiple spatial scales. A water-limited watershed tends to be more hydrologically sensitive to forest cover change than an energy-limited watershed. This is in accordance with a global study on the impact of afforestation on annual runoff, where afforestation in drier regions (mean annual precipitation <1000 mm) was found to have greater impact on runoff than in wetter regions (Jackson et al., 2005). Similarly, modelling by Sun et al. (2006) in China also showed that annual runoff reduction due to reforestation can be up to 50% in semi-arid regions while the reduction is only 30% in humid regions. The findings above suggest that the sensitivity of annual runoff to forest cover change is not constant but may vary along climatic gradients (Asbjornsen et al., 2011; Donohue et al., 2011). The mechanism controlling interactions between forest and water in water-limited watersheds is likely to be different from that in energy-limited watersheds (Newman et al., 2006; Zhang and Wei, 2012a). In water-limited watersheds, forest growth is often controlled by the spatial-temporal distribution of water, and the dryness index is often viewed as the best predictor of forest growth (Das et al., 2013). In turn, forest structure, age, and species composition affect water flux across multiple spatial scales (Schwinning and Sala, 2004; Asbjornsen et al., 2011), and the sensitivity of water-limited forests to water availability is expected to be maximal (Huxman et al., 2004; Scanlon et al., 2005). Accordingly, forest cover change in water-limited watersheds can cause more significant hydrological responses. On the contrary, in energy-limited watersheds where saturated soils are prevalent (Asbjornsen et al., 2011), forest growth tends to be less dependent on water availability but responds more strongly to temperature (Rodriguez-Iturbe et al., 2007; Troch et al., 2009; Wohl et al., 2012). Consequently, forest cover change tends to generate less pronounced hydrological impacts in these water-abundant environments.

5.4. Differences between large and small watersheds in the effects of forest type and hydrological regime

In small watersheds, mixed forests dominated watersheds tend to be less hydrologically sensitive to forest cover change than coniferous or broadleaf forest-dominated watersheds (Table 3 and Fig. 6). This finding is supported by several studies, showing that a 10% reduction in coniferous forest, deciduous forest and eucalypt forest can lead to about 20–25, 17–19, and 6 mm increase in water yield, respectively (Bosch and Hewlett, 1982; Brown et al., 2005). A small watershed study regarding global warming also suggests that mixed forest dominated catchments have higher resilience and stable water yield in response to global warming while coniferous forested ones have the lowest resilience (Creed et al., 2014). However, large coniferous forest dominated watersheds have been found to be least hydrologically sensitive to forest cover change, suggesting more hydrological resilience of large coniferous forest dominated watersheds to forest cover change. The differences between small and large watersheds may be due to more complexities in controls of the hydrological responses to changes at a larger spatial scale.

Unlike the important role that forest type plays in annual runoff response to forest cover change, hydrological regime tends to be a less influential factor in small watersheds but is a factor in large watersheds. The sensitivity of annual runoff to forest cover change in large snow-dominated watersheds is significantly lower than in rain-dominated watersheds. In other words, large snow-dominated watersheds are generally more resilient to forest cover change as compared with large rain-dominated watersheds. This is in accordance with small watershed studies: logging in snow-dominated hydrological systems can produce less pronounced impacts on annual runoff than in rain-dominated hydrological systems in the Pacific Northwest (Moore and Wondzell, 2005). The differences in S_f between large snow-dominated and rain-dominated watersheds maybe due to their different hydrological processes. In snow-dominated watersheds, annual runoff is mostly from snow-melt water in spring, affected by energy input and winter snow accumulation. Factors including not only forest but also topography (e.g., elevation, aspect) can produce significant impacts on evapotransipration and snow-melting, and eventually on annual runoff (Jost et al., 2007; Gleason et al., 2013). For example, forest cover loss at higher elevations or on slopes with southern aspects can have more pronounced hydrological impact than those at lower elevations or on slopes with northern aspect mainly because ET can be increased and snow-melting processes can be accelerated due to more energy input after forest cover loss, leading to more advanced snow-melt water input from higher elevation areas to streams (Boon, 2009; Bewley et al., 2010). Sometimes, even with similar level of forest cover change in snow-dominated watersheds, contrasting responses in annual runoff may be detected due to differences in topography, landscape pattern, and spatial heterogeneity in climate. For example, Zhang and Wei (2014) studied two large deforested watersheds (the Willow and Bowron) with the ΔF about 30% in British Columbia, Canada. They found forest harvesting in the Willow watershed significantly increased annual runoff but caused insignificant hydrological change in the Bowron watershed. The relative uniform topography and climate in the Willow watershed may promote hydrological synchronization effects, while larger variation in elevations, together with more forest harvesting occurred at lower elevations may cause hydrological de-synchronization effect in the Bowron watershed (Wei and Davidson, 1998; Whitaker et al., 2002). In general, heterogeneities in topography grow with the watershed size, resulting in more confounding effects to offset the annual runoff response to forest cover change (Jothityangkoon and Sivapalan, 2009), and thus annual runoff in large snow-dominated watersheds can be less sensitive to forest cover change.

5.5. Implications for future research

Forest hydrological studies in large watersheds are limited mainly due to the lack of an efficient, commonly-accepted methodology. Physically based hydrological models, such as the Distributed Hydrology Soils and Vegetation Model (DHSVM), MIKE-SHE (an integrated water simulation model designed by Danish Hydraulic Institute) and the Variable Infiltration Capacity (VIC) model are often used in large watershed studies (Stonesifer, 2007; Thanapakpawin et al., 2007; Franczyk, 2008; Wei and Zhang, 2010a, 2010b; Kuraś et al., 2012). However, these models mainly depend on scientific information derived from small watershed studies, and this can be problematic when applied to large watersheds (Kirchner, 2006). This review provides a generalized relationship between forest cover change and annual runoff response in large watersheds (Fig. 3), and can be directly applied in future hydrological modelling of large watersheds to generate more reliable predictions. Moreover, the selection of assessment techniques must consider the differences in ecohydrological processes between large and small watersheds since dominating factors that determine annual runoff response to forest cover change in large and small watersheds can be quite different (Jencso and McGlynn, 2011; Sivapalan et al., 2011). Similarly, given contrasting hydrological sensitivities and responses to forest changes in water-limited and energy-limited watersheds, future watershed hydrology studies should focus on identifying the dominant ecohydrological processes in both situations (Gentine et al., 2012). A better understanding of the interaction and feedback mechanisms between forest and water along climate gradients would improve the current hydrological models or help in the development of new hydrological models for more accurate simulation and prediction of ecohydrological processes under a changing environment.

5.6. Implications for future forest and water management

According to our analysis, the responses of annual runoff to forest change are determined not only by the proportion of forest cover change but also by watershed properties such as climate conditions, hydrological regime and forest type. The interactions of these factors with each other lead to diverse and inconsistent results (Lima et al., 2014). Thus, the transfer of results from one large watershed to another will have to be adjusted by considering similarities in climate, hydrological regime, and forest type between the two watersheds.

Since runoff responses are more sensitive to forest change in water-limited watersheds than in energy-limited watersheds, forest management in water-limited watersheds must be designed with caution (Porporato et al., 2001; Krishnaswamy et al., 2012). The trade-off between forest growth (carbon sequestration) and water use in watersheds across climatic gradients must be recognized in order to ensure water supply for both human and ecosystems (Jackson et al., 2005; Williams and Albertson, 2005; Keenan et al., 2013; Frank et al., 2015). This is particularly important and complicated under climate change given that more catastrophic forest disturbances such as fire, drought, flood, and insect outbreak are intensified (Anderegg et al., 2012; Pretzsch et al., 2014; Jolly et al., 2015). Climate change is very likely to yield significant impacts on water resources and in general, dry areas will tend to become drier while wet areas will become wetter (IPCC, 2007). Large-scale afforestation in water-limited environments will inevitably exacerbate water scarcity while afforestation in energy-limited environment will help to reduce flood risks (Calder, 2007). In addition to direct impacts on water resources, climate change will produce indirect impacts on water by altering forest, for example, altering the interactions and feedbacks between forest and water due to increasing temperature, changing seasonal precipitation patterns, and prolonged phenology and increased growth potential due to climate change (Bearup et al., 2014; Doughty et al., 2015; Swann et al., 2016). Thus, current understanding of the interactions between forest and water may be inadequate to support natural resources management in the context of climate change. In brief, forest practices must be designed with a full consideration of future climate, water availability, water consumption of different forest types, and hydrological regime, as well as topography and watershed size.

5.7. Limitations

A successful study on the quantification of hydrological response to forest cover change normally relies on the availability of long-term data on hydrology and climate, the quantification of watershed-scale forest changes, and an appropriate method to exclude the effect of non-forest drivers on runoff, e.g., climate variability and human activities (Wang et al., 2013; Liang et al., 2015). This review is a synthesis of many world-wide studies on hydrological responses to forest cover change across multiple spatial scales. Uncertainties associated with data collection, the quantification of forest changes and methods for excluding non-forest related hydrological impact in the literature are inevitable (Patterson et al., 2013).

For example, although precipitation data were derived from the literature, precipitation data sources (i.e., observed, spatial grids, and modelled) may differ among watersheds. Observed data from local climate stations are often used in small watershed studies while modelled or gridded data are normally applied in large watersheds due to a lack of sufficient climate stations (Coe et al., 2011; Lima et al., 2014). This strategy allows for a better representation of mean annual precipitation across multiple spatial scales, but associated uncertainties from various data sources may occur (Biederman et al., 2015). An ideal way is to apply a global gridded precipitation dataset with high resolution. Similarly, the length of streamflow record varied from one study to another. A short streamflow record may incompletely capture long-term cumulative hydrological responses after forest change (Brown et al., 2005). Although it would be helpful if the length of record could be standardized across all study watersheds in order to represent a full stand rotation for example, the number of study watersheds would be greatly reduced given great differences in data collection across the dataset.

The quantification of forest change at a watershed scale is very challenging since different types of forest changes due to natural (e.g., wildfire, flood, drought, hurricane, insect) and anthropogenic disturbances (e.g., logging, road construction, agricultural activities, urbanization, mining, and recreation) are accumulated over space and time (Logan et al., 2003; Bebi et al., 2016). The most direct way to quantify forest changes in a watershed is to compute the forest cover change (%), mainly because these data are normally available and relatively easy to derive (Buttle and Metcalfe, 2000; Zhang et al., 2008a). In this review, to maximize sample size, we also used forest cover change (%) as the indicator of forest change level. However, this indicator merely serves as a basic indicator without differentiating forest species, stand age and structure, growth potential, and disturbance types, and fails to express the spatial pattern of forest changes and subsequent forest recovery processes (Lewis and Huggard, 2010). A suitable forest change indicator for a watershed should not only express forest cover changes due to all types of disturbances, and their intensities and severities, but also account for forest characteristics (e.g., species, stand age, structure), disturbance history, and subsequent recovery processes over space and time.

The most challenging consideration in quantifying hydrological response to forest cover change is to exclude the effect of non-forest drivers on runoff, e.g., climate variability and human activities (Renner et al., 2014). This can be even more challenging for large watershed studies with various confounding factors including climate variability, dams, irrigation, and urbanization (Wang and Hejazi, 2011; Feng et al., 2016). As mentioned before, the responses of annual runoff to forest cover change in these watersheds are quantified by different methods such as paired watersheds, quasi-paired watersheds, hydrological modelling, elasticity analysis and a combination of statistical analysis and hydrographs. The paired watershed experiment is commonly accepted as an effective approach to exclude climatic effect on runoff in the treated or disturbed watershed through comparison against the control watershed (Biederman et al., 2015). However, the quasi-paired watersheds study, designed for larger watersheds may fail to completely remove the effect of climate variability on runoff given great variations in climate, especially precipitation in larger watersheds, leading to less reliable results as compared to a paired watersheds study (Loáiciga et al., 2001; Liu et al., 2004). Most hydrological models are still based on current theories that are deeply rooted in the physics of small-scale processes. This gives rise to difficulties in representing nonlinear hydrological processes and their interactions at all scales across heterogeneous landscapes (Kirchner, 2009). In addition, models are often over-parameterized to meet high accuracy levels, potentially leading to the equifinality problem because of an excessive number of free parameters (Beven, 1992; Kirchner, 2006). Similarly, the elasticity analysis or the combination of statistical methods and hydrographs may sometimes remove the effect of non-forest change on runoff incompletely since most studies only considered climate variability and forest change or land cover change as two major drivers, and ignored other confounding factors (Costa et al., 2003; Wei and Zhang, 2010; Wang et al., 2013; Xu et al., 2013; Liang et al., 2015). Obviously, none of these methods is perfect but characterized by different levels of uncertainties, especially for larger watershed studies. These method-related uncertainties may lead a certain level of bias in our synthesized analysis. Although a better solution could be to develop a standardized and efficient method that can be applied widely in both small and large watersheds to quantify annual runoff response to forest cover change, this approach is not possible with the current array of available data.

6. Conclusions

This review shows that dominant ecohydrological processes and associated drivers are variable across spatial scales. Climate is a key factor in determining annual runoff response to forest change at multiple spatial scales. Annual runoff in water-limited watersheds is more sensitive to forest cover change than in energy-limited watersheds. Forest type is an important factor affecting annual runoff response to forest cover change in small watersheds while hydrological regime tends to be a more influential factor in large watersheds. These findings above have profound implications for upscaling issues and model development in forest hydrology and also provide useful scientific information to guide future watershed management in the context of climate change.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2016.12.040.

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