Scale effects and variability of forest–water yield relationships on the Loess Plateau, China

by Chao Bi[1], Huaxing Bi[1,*], Ge Sun[2], Yifang Chang[1] and Lubo Gao[1]

ABSTRACT

The relationship between forests and water yield on the Loess Plateau is a concern to forest hydrologists and local governments. Most research indicates that forests reduce runoff but the degree of reduction is different at different sites. Data on precipitation, runoff depth, evapotranspiration and forest cover were collected for 67 watersheds through synthesizing published literature. Results suggest that afforestation on sparsely vegetated catchments reduces runoff and that this effect decreased with increasing forest cover. Annual runoff coefficients fluctuate around 4.1%. Catchment scales influence the relationship between percent forest and runoff coefficient. We believe that afforestation–water yield relationships are variable. Large-scale watersheds may have a relatively high buffering capacity that masks forest cover effects on runoff because of a number of interacting factors. Results from this research will support the implementation of large-scale afforestation programs on the Loess Plateau.

Keywords: afforestation, hydrologic impact, water yield

RÉSUMÉ

La relation entre les forêts et l'apport en eau sur le Plateau de Loess est au cœur des interrogations des hydrologistes forestiers et des gouvernements locaux. La plupart des recherches indiquent que les forêts réduisent le ruissellement mais le niveau de réduction est différent selon les sites. Les données sur les précipitations, la profondeur du ruissellement, l'évapotranspiration et le couvert forestier ont été recueillies dans 67 bassins hydrographiques à partir de la synthèse des documents publiés. Les résultats indiquent que le boisement effectué sur des bassins hydrographiques à végétation rare réduit le ruissellement et que cet effet diminue selon l'accroissement du couvert forestier. Les coefficients de ruissellement annuel fluctuent aux environs de 4,1%. La taille du bassin hydrographique influence la relation entre le pourcentage de forêt et le coefficient de ruissellement. Nous croyons que les relations entre le boisement et le ruissellement sont variables. Les bassins hydrographiques de grandes dimensions peuvent présenter un pouvoir tampon relativement supérieur qui masque les effets du couvert forestier sur le ruissellement à cause de l'interaction de plusieurs facteurs. Les résultats de cette recherche aideront à la mise en place de programmes de boisement de grande envergure sur le Plateau de Loess.

Mots clés : boisement, impact hydrologique, apport en eau

Introduction

Forests provide goods and services that play an important positive role in environmental rehabilitation, biodiversity maintenance, carbon sequestration, bio-fuel, timber production, amenities and social benefits (Calder 2007). However, several studies (Sun *et al*. 2006; Wang *et al*. 2011a,b; Feng *et al*. 2012) demonstrated that forests decrease water yield, i.e., they reduce runoff. This effect of forests on water yield is important, especially on the Loess Plateau, an arid/semi-arid region of China. Water shortages here are a major limiting factor for ecological improvement and social-economic development. Afforestation on the Loess Plateau is necessary to control soil erosion but at the same time may aggravate water shortages.

Li (2001) stresses an urgent need to examine how current large-scale afforestation efforts throughout China affect water resources at the watershed and regional levels. Understanding hydrological effects of afforestation is critical in the Loess Plateau. Trade-offs between afforestation and water yield are significant and a clear understanding of the relationships between forests and runoff is important to local land managers (Sun *et al.*2006).

During the past few decades, with changes in forest management principles and strategies, China has implemented several large-scale afforestation programs that increased forest cover from 16.0% in the early 1980s to 20.4% by 2008 (Li *et al.* 2009). Implementation of these large-scale programs has generated significant growth in forest resources. Forest cover has increased by 20.5 million ha since 2003. The extent of the country's forest plantations is approximately 54 million ha, accounting for one-quarter of the world's total forest area (Raloff 2009).

Much progress has been made in understanding forest and water yield relationships. One of the first influential reviews was published by Bosch and Hewlett (1982). Andréassian (2004) synthesized experimental results from 137 paired watersheds located in various geographic regions. A review by Robinson *et al*. (2003) focused on Europe, Scott *et al*. (1998) in South Africa, and Bruijnzeel (2004) and Scott *et al*. (2004) for the tropics. Although there is a large variability due to differences in climate, soils and vegetation, these studies concluded that deforestation generally increases water yield and base flow for most watersheds.

[1] College of Soil and Water Conservation, Beijing Forestry University, Beijing, 100083, China.
[2]Southern Global Change Program, USDA Forest Service, Raleigh, North Carolina, 27606, USA.
* Corresponding author. E-mail: bhx@bjfu.edu.cn

There have been similar studies carried out in China. Liu and Zhong (1978) reported that forested watersheds on loess soils had lower water yields (25 mm per year) and lower yield:precipitation ratios than adjacent basins with less forest cover on the upper reaches of the Yellow River, northwestern China. They concluded that forests may reduce stream flow by 37% based on data from a number of hydrological stations throughout the Loess Plateau. Ran (1992) found a much smaller reduction of 7.5% on the Jinghe watershed (43 000 km^2). Sun *et al.* (2006) examined the sensitivity of water yields to afforestation across China by employing a simple evapotranspiration model and a set of continental-scale databases, including climate, topography and vegetation. They suggested that the reduction in water yields due to afforestation was on average approximately 50% (or 50 mm) each year. McVicar *et al.* (2007) conducted a literature review of land use–hydrology studies in the Loess Plateau region and confirmed that the annual stream flow is reduced by afforestation. Bi *et al.* (2009) showed that afforestation reduced stream flow by 49.6% (or 6.5 mm) each year in paired catchments on the Nanxiaohegou watershed on the Loess Plateau. Wang *et al.* (2011b) reported that the regional average annual runoff from forestlands was only 16 mm, 58% lower than that of 39 mm from lands without forest cover. They suggested that large-scale afforestation may have serious consequences for water management and sustainable development on the Loess Plateau due to runoff reduction.

However, studies have shown that the magnitude of flow reduction may differ. Wang *et al.* (2011a) examined forest cover and runoff in northern China and concluded that forest cover was negatively correlated with the runoff coefficient ($r = 0.64$, $P < 0.05$). They estimated that forests might reduce annual water yields by 37%. Feng *et al.* (2012) found that yields of water on almost 40% of the Loess Plateau might have decreased by up to 48 mm per year as a result of cover change alone.

Some studies (Li 2001, Huang and Liu 2002, Huang *et al.* 2003) have reported an obvious decline in water yield as forest cover increased. However, these studies also observed that forests might increase flow in low flow seasons, indicating that forested catchments produce greater base flows and more natural springs. A comparison of stream flow from 10 large basins (674–5322 km^2) in the Yangtze River basin suggested that ones with higher forest cover generally had higher runoff/rainfall ratios (>0.9). Similar positive correlations between forests and water yield for large basins (>100 km^2) were reported for northern China (Wei *et al.* 2003). However, Wei *et al.* (2008) stated that afforestation campaigns were not likely to lead to large-scale changes in annual water yields, low flows or flood peaks before the hydrologic properties of degraded soils were fully improved. These findings were corroborated by Russian literature, which suggests stream flow is generally higher for large forested basins (Wei *et al.* 2003). More rigorous studies suggested these seemingly contradictory conclusions might be due to data interpretation (Wang *et al.* 2011b).

Why these different conclusions about the relationship between forests and runoff levels? Wei *et al.* (2008) argue that the effects of afforestation on stream flow may not be decisive because there are few established standard paired catchment experiments in China. Empirical observations and limited data on the environmental influences of forests are often inconclusive and even contradictory. Vertessy *et al.* (2001) showed that this relationship varied over time with changes in watershed conditions and ecosystem structure. Hibbert (1967) concluded that the response of stream flow to altered land use was "highly variable and for the most part unpredictable". Sun *et al.* (2006) suggested that large spatial and temporal variability of hydrologic responses to afforestation will follow gradients in climate, topography, soil conditions and stage of vegetation.

This study is focused on the uncertainty of the effects of forests on runoff at different scales through an analysis of the relationships between a) precipitation and catchment forest cover, b) precipitation and catchment runoff/runoff coefficients, and c) catchment cover and annual runoff coefficient. The objective is to clarify relationships between forest cover and water yields in order to provide a sound eco-hydrological basis for improving future forestry development strategies on the Loess Plateau and in other arid regions in China.

Methods

Study area

The Loess Plateau is along the upper and middle reaches of the Yellow River (Fig.1) with a total area of 632 520 km^2, approximately 6.3% of the land area of China, and lies mostly on the transitional border between the monsoon and the continental arid climate zones. Mean annual precipitation ranges from 110 mm to 800 mm and average yearly temperatures from 5°C to 12.5°C from NW to SE. There are four climatic sub-zones over the Plateau: (i) arid temperate; (ii) semi-arid temperate; (iii) semi-arid warm temperate; and, (iv) sub-humid warm temperate. The area is characterized by thick layers of loess[1], often 100 m to 200 m in depth. Soil texture ranges from sand, sandy loam, light loam, medium loam to heavy loam. Common tree species are black locust (*Robinia pseudoacia* L.), Chinese pine (*Pinus tabulaeformis* Carr.), apple (*Malus domestica* Borkh.), Little-leaf peashrub (*Caragana microphylla* Lam.) and Seabuckthorn shrub (*Hippophae rhamnoides* L.) in plantations. However, due to water limitations, these planted trees grow quite slowly, appearing "small but old" (McVicar *et al.* 2007).

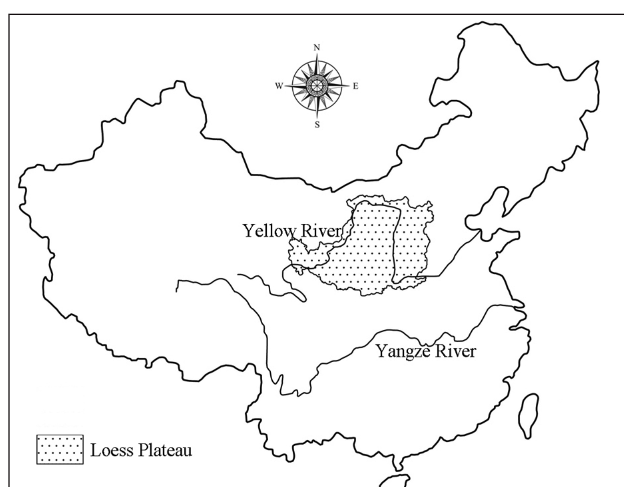

Fig 1. Location of the Loess Plateau.

[1]Loess is wind-blown deposits of fine-grained, calcareous silt or clay, buff to grey in colour.

Data compilation

Catchment datasets were collected from published, peer-reviewed Chinese and international journals where annual precipitation, annual runoff, annual evapotranspiration and forest cover percent were recorded. The final datasets used for this analysis covered 67 catchments (Table 1). Detailed description of complied catchments datasets is shown in Table 1, in which runoff coefficient is the percentage of annual runoff and annual precipitation.

Table 1. Description of catchments

Catchment name	Location	Data period	Catchment area (km^2)	Forest cover (%)	Average annual precipitation (mm)	Average annual runoff (mm)	Runoff coefficient (%)	Annual evapo-transpiration (mm)	Data sources
Chashang	Chashang, Shaanxi Province	2002–2005	32	70	375	4.5	1.20	–	Wang *et al.* 2011a
Diantou	Diantou, Shaanxi Province	2001–2005	34	56	560	11.2	2.00	–	
Wannianbao	Wannianbao, Shaanxi Province	2001–2005	286	80	333	1	0.30	–	
Beizhangdian	Beizhangdian, Shaanxi Province	>5years	270	17	438	3.5	0.80	–	
Siping	Siping, Shaanxi Province	>5years	192	9	407	5.7	1.40	–	
Nanguan	Nanguan, Shaanxi Province	>5years	257	52	455	5	1.10	–	
Gedonggou	Gedonggou, Shaanxi Province	>5years	73	63	350	2.8	0.80	–	
Lengkou	Lengkou, Shaanxi Province	>5years	76	90	580	11.6	2.00	–	
Xiaodian	Xiaodian, Gansu Province	>10 years	272	15	531	47	8.85	484	Hu, 2000
Caijiaomiao	Caijiaomiao, Gansu Province	>10 years	270	15	530	32	6.04	498	
Yaofenggou	Yaofenggou, Gansu Province	>10 years	219	20	511	40	7.83	471	
Hejiapo	Hejiapo, Gansu Province	>10 years	100	20	489	30	6.13	459	
Nanxiao	Nanxiao, Gansu Province	1959–1962	28	0	500	12	2.40	488	Li and Xu 2006
Wangjia	Wangjia, Gansu Province	1959–1962	48	90	639	10	1.56	629	
Qingjian	Qingjian, Shaanxi Province	1951–1963	916	0	509	34	6.68	475	
Xianguhe	Anmingou Shaanxi Province	1951–1963	24	0	624	37	5.93	587	Liu and Chung 1978
Beiluo	Liujiahe Shaanxi Province	1951–1963	7315	18.3	475	29	6.11	446	
Fenchuan	Linzhen Shaanxi Province	1951–1963	1121	94.4	555	18	3.24	537	
Beiluo	Zahngcunyi Shaanxi Province	1951–1963	5400	97	568	19	3.35	549	
Xianguhe	Hongmiaogou Shaanxi Province	1951–1963	42	98.5	636	29	4.56	607	
West branch of Qingshui	Qingshui, Hebei Province	1963–1981	706	4.1	439	36	8.20	403	Min and Yuan 2001
East branch of Qingshui	Qingshui, Hebei Province	1963–1982	775	39.8	500	44	8.80	456	
Qingshui	Qingshui, Shanxi Province	1960–1969	435	25.3	589	55	9.34	534	Wang and Zhang 2001
Qingshui	Qingshui, Shanxi Province	1970–1979	435	55.3	551	46	8.35	505	
Qingshui	Qingshui, Shanxi Province	1980–1989	435	57.9	516	23	4.46	493	

Catchment name	Location	Data period	Catchment area (km^2)	Forest cover (%)	Average annual precipitation (mm)	Average annual runoff (mm)	Runoff coefficient (%)	Annual evapo-transpiration (mm)	Data sources
Yanhe	Ganguyi, Shaanxi Province	1959–1970	5981	8	536	42	7.84	494	Zhang *et al.* 2007
Liujia	Beiluohe, Shaanxi Province	1959–1970	7325	9	462	38	8.23	424	
Xinshui	Daning, Shanxi Province	1959–1970	3992	10	527	50	9.49	477	
Zhouchuan	Jixian, Shanxi Province	1959–1970	436	10	436	53	12.16	383	
Hulu	Zhangcunji, Shaanxi Province	1959–1970	4715	100	569	29	5.10	540	
Fenchuan	Linzhen, Shaanxi Province	1959–1970	1121	100	539	23	4.27	516	
Wudinghe	Dingshi, Shaanxi Province	1980–2000	327	0	375	36	9.60	339	
Wudinghe	Hanjiamao, Shaanxi Province	1980–2000	2452	0	317	31	9.78	286	
Huangpuchuan	Huangpuchuan, Inner Mongolia Province	1980–2000	3175	0	366	33	9.02	333	
Wudinghe	Hengshan, Shaanxi Province	1980–2000	2415	0	378	21	5.56	357	
Wudinghe	Lijiahe, Shaanxi Province	1980–2000	8.7	0.1	392	31	7.91	361	
Wudinghe	Caoping, Shaanxi Province	1980–2000	187	0.1	403	38	9.43	365	
Wudinghe	Mahuyu, Shaanxi Province	1980–2000	371	0.1	391	38	9.72	353	
Kuyehe	Wangdaohengta, Shaanxi Province	1980–2000	3839	0.2	346	40	11.56	306	
Jialuhe	Shenjiawan, Shaanxi Province	1980–2000	1121	0.6	386	38	9.84	348	
Wudinghe	Qingyangcha, Shaanxi Province	1980–2000	662	0.6	413	34	8.23	379	
Kuyehe	Xinmiao, Shaanxi Province	1980–2000	1527	0.8	357	53	14.85	304	
Kuyehe	Shenmu, Shaanxi Province	1980–2000	7298	0.9	356	55	15.45	301	
Kuyehe	Weijiachuan, Shaanxi Province	1980–2000	8645	0.9	361	56	15.51	305	
Gushanchuan	Gaoshiya, Shaanxi Province	1980–2000	1263	1	385	41	10.65	344	
Wudinghe	Dingjiagou, Shaanxi Province	1980–2000	23422	1	348	33	9.48	315	
Wudinghe	Baijiachuan, Shaanxi Province	1980–2000	29662	1.1	362	33	9.12	329	
Wudinghe	Zhaoshiku, Shaanxi Province	1980–2000	15325	1.3	342	29	8.48	313	
Yanhe	Ansai, Shaanxi Province	1980–2000	1334	3.8	446	40	8.97	406	
Qingjianhe	Zichang, Shaanxi	1980–2000	913	4	444	41	9.23	403	
Yanhe	Yanan, Shaanxi Province	1980–2000	3208	4.2	456	39	8.55	417	
Qingliangsigou	Yangjiapo, Shanxi Province	1980–2000	283	4.3	431	32	7.42	399	
Xianchuanhe	Jiuxian, Shanxi Province	1980–2000	1562	4.4	412	11	2.67	401	
Qingjianhe	Yanchuan,Shaanxi Province	1980–2000	3468	5	455	39	8.57	416	
Quchanhe	Peigou, Shanxi Province	1980–2000	1023	6.4	478	26	5.44	452	
Yanhe	Xinghe Shaanxi Province	1980–2000	479	7.7	439	37	8.43	402	
Yanhe	Ganguyi, Shaanxi Province	1980–2000	5891	9.7	470	34	7.23	436	
Zhujiachuan	Xialiuji, Shanxi Province	1980–2000	2881	10.3	424	11	2.59	413	
Qiushuihe	Linjiaping, Shanxi Province	1980–2000	1873	11	448	25	5.58	423	
Sanchuanhe	Houdacheng, Shanxi Province	1980–2000	4102	21.1	471	43	9.13	428	
Yanhe	Zaoyuan, Shaanxi Province	1980–2000	719	24.8	488	35	7.17	453	
Xinshuihe	Daning, Shanxi Province	1980–2000	3992	28.2	484	23	4.75	461	
Weifenhe	Xinxian, Shanxi Province	1980–2000	650	34	446	28	6.28	418	
Zhouchuanhe	Jixian, Shanxi Province	1980–2000	436	37.9	493	21	4.26	472	
Yunyanhe	Xinshihe, Shaanxi Province	1980–2000	1662	48	507	20	3.94	487	
Yunyanhe	Linzhen, Shaanxi Province	1980–2000	1121	65.3	508	16	3.15	492	
Shiwanghe	Dacun, Shaanxi Province	1980–2000	2141	72.7	528	28	5.30	500	

Analysis

Simple comparative analysis using SPSS 20.0 for Windows shows relations between precipitation and forest cover percent, precipitation and runoff or runoff coefficient, runoff coefficient and forest cover percent, runoff coefficient and catchment area.

Results

Annual precipitation and forest cover percent

Average annual precipitation in selected catchments ranges between 300 mm and 650 mm. Forest cover is low (less than 20%; Fig. 2), especially where annual precipitation is less than 400 mm. However, forest cover may reach as high as 100% when precipitation is more than 500 mm.

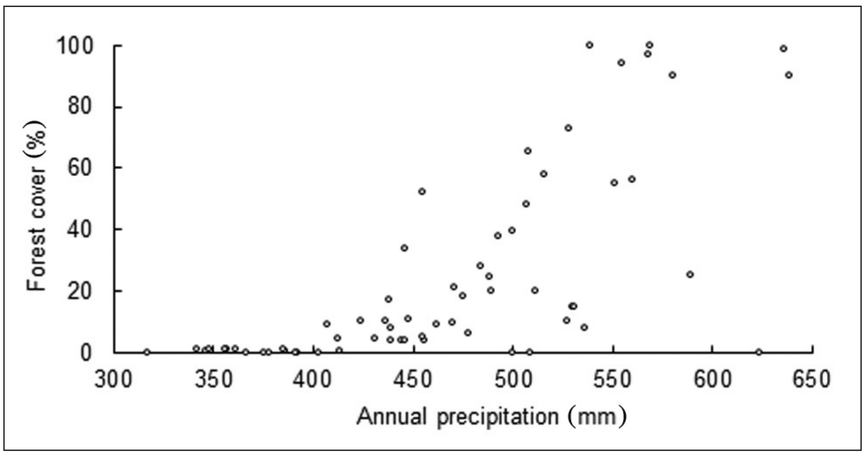

Fig. 2. Relationship between annual precipitation and forest cover.

Annual precipitation and runoff

The scatter plots of annual precipitation and runoff (Fig. 3a) indicate that the relationship is complex and not a good linear relationship. Statistical results show that the Pearson correlation is 0.05, significant at the 0.35 level. However, there is a significant negative relationship at the 0.001 level and Pearson correlation is 0.36 (Fig. 3b). This is because runoff is generally low in the semi-arid regions of the Plateau. The reasons for this complicated relationship may be: 1) differences in annual precipitation and other factors such as topography, climate and soils types; and, 2) when annual precipitation is similar, rainfall intensities are very different in different years and over different catchments. On the Loess Plateau, the depth of runoff is determined more by rainfall intensity than amount.

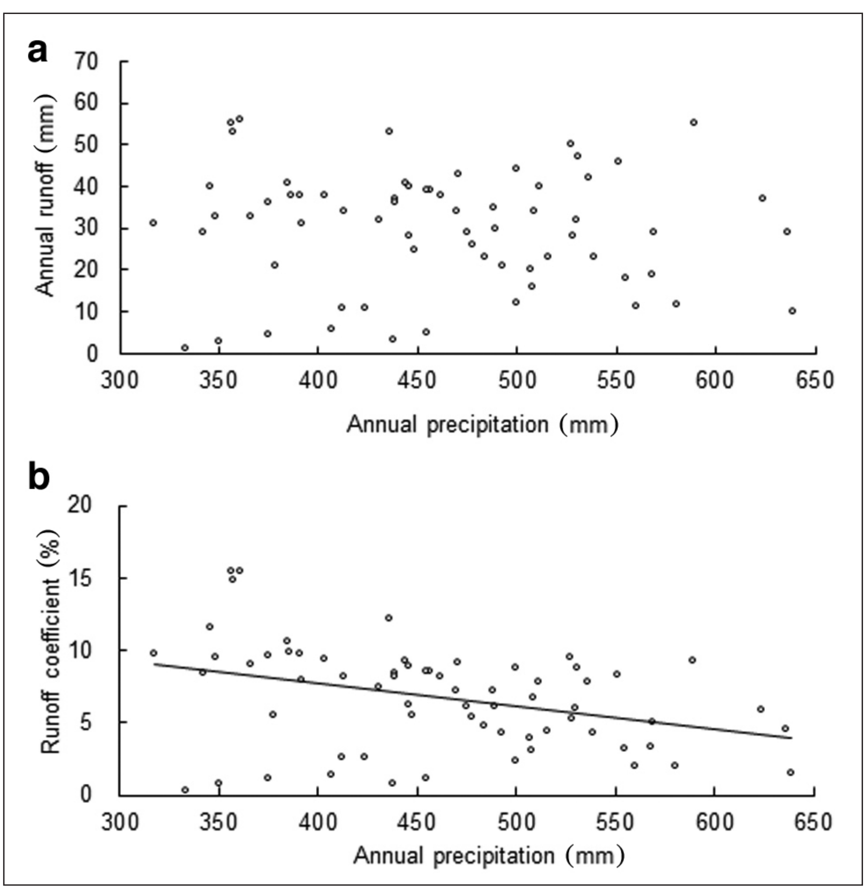

Fig. 3. Relationship between annual precipitation and runoff depth (A) or runoff coefficient (B).

Forests cover percent and annual runoff coefficients

The percent of forest cover and annual runoff coefficient (Fig.4) illustrates that afforestation reduces runoff. However, this effect decreased as forest cover increased, until the annual runoff coefficient fluctuated around a fixed value.

Catchment area (spatial scale) and annual runoff coefficients

Fig. 5a illustrates that the relationship between catchment area and annual runoff coefficient is irregular when catchments are less than 50 km^2, but gradually becomes stable with increasing size. Runoff coefficients vary considerably for different catchments even if the areas are similar. The relation between precipitation and runoff is complicated with several factors affecting this relationship. If the logarithm value of the catchment area is used, there is a positive linear relation (Fig. 5b).

The 67 catchments were separated into three groups by plotting forest cover percentages and runoff coefficients. These groups illustrate three different catchment spatial scales. Less than 50 km^2 is a micro catchment or small watershed and is the basic unit for erosion control; 50 km^2 to 3000 km^2 is a meso catchment; greater than 3000 km^2 is a macro-scale catchment. Relationships between forest cover and runoff coefficient in different scales are different (Fig. 6). For catchments less than 50 km^2, the relationship is insignificant (R^2 = 0.29; correlation significant at the 0.21 level). This relationship on small watersheds may be due to local topography, rainfall

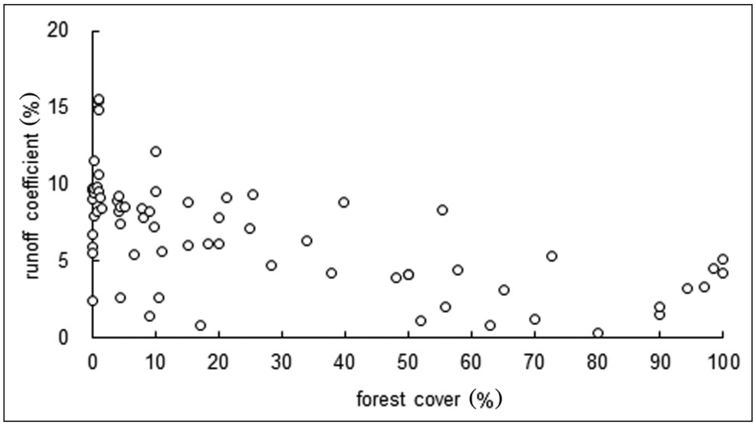

Fig. 4. Relationship between forest cover and runoff coefficient.

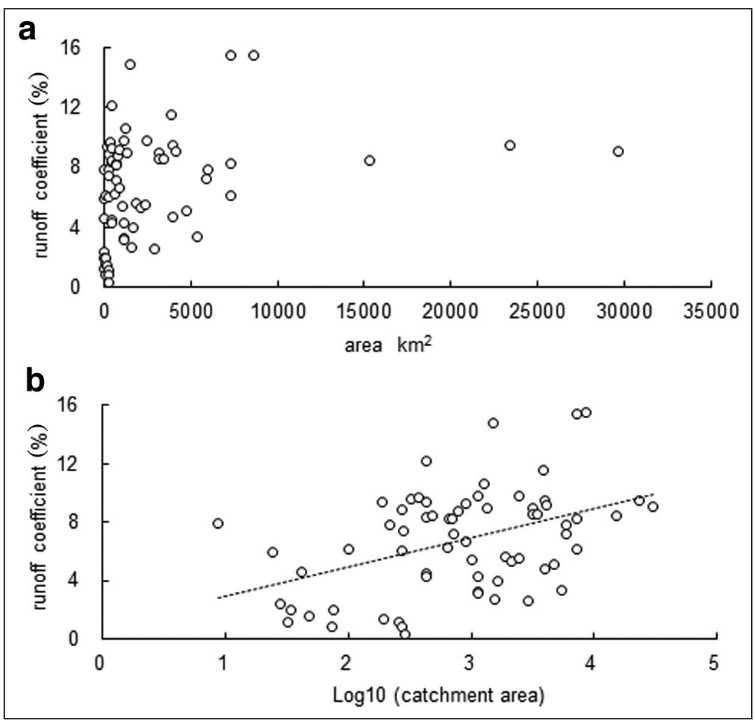

Fig. 5. Scatter diagram of catchment area and runoff coefficient.

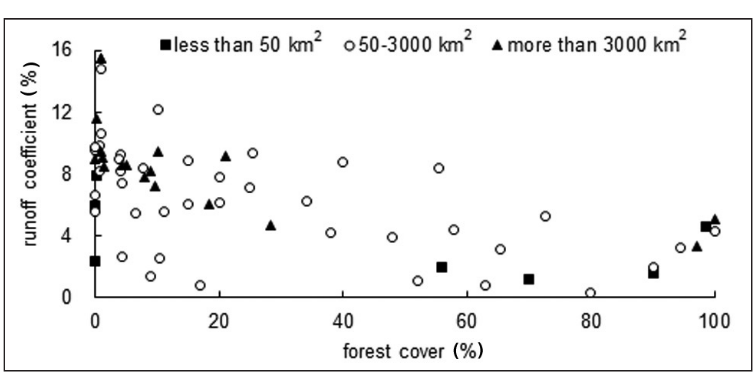

Fig. 6. Relationship between forest cover and runoff coefficient at different spatial scales. Note: squares denote catchments less than 50 km², circles catchments from 50 km² to 3000 km², and triangles catchments larger than 3000 km².

intensity, soil types and forest structure but not forest cover. The relationship between forest cover and runoff first decreases and then stabilizes as cover increases with meso level catchments. The relationship with macro-scale catchments is not clear because the samples were limited. With large catchments, forest cover may be less than 30%. It seems that the larger the watershed, the more complicated the relations between forest cover and runoff. Large watersheds have relatively high buffering capacities that may mask the forest cover effects on runoff.

Discussion

Results indicate a complex, non-linear relation between forest cover and runoff. Runoff does not always decrease with increased forest cover. This does not agree with previous studies based on the water balance equation—runoff equals precipitation less evapotranspiration. In the equation, evapotranspiration is a key factor. Although the existing "curve-type" models (Zhang *et al.* 2001) are generally easy to use for continental-scale studies, they are difficult to apply on a regional scale. The equation did not explicitly account for vegetation characteristics and seasonal dynamics of key controls on actual evapotranspiration (Feng *et al.* 2012). However, when applied at a regional scale, it is difficult to determine numerical values for heterogeneous watersheds affected by land cover, soil, geology and topography (Zhang *et al.* 2008). In addition, large basins generally have complex cover compositions beyond forest and grass lands.

Regional annual water yields on the Loess Plateau, like any terrestrial ecosystem, are controlled mostly by precipitation and evapotranspiration (Potter *et al.* 2005). Changes in land use/land cover and climate can directly impact the regional hydrological cycle by altering evapotranspiration processes (Zhang *et al.* 2004, Sun *et al.* 2011). Therefore, many studies use the water balance equation to analyze the effects of afforestation on stream flow yields, and conclude that forests decrease runoff based on the changes of evapotranspiration using Zhang's model (Ma *et al.* 2008, Zhang *et al.* 2008). The results indicate that evapotranspiration from forested land is larger than from other land uses. Annual evapotranspiration in Zhang's model depends upon the minimum value of potential evapotranspiration and available water for evapotranspiration. It considers two major cover types, forest and grasslands, using an empirical *coefficient w* to represent the relative differences of water use for transpiration among plant communities. The *w* parameter is reported as 0.5 for short grasses and crops and 2.0 for forests. Sun *et al.* (2006) applied this model to analyze potential water yield reductions due to afforestation across China. This simple analysis suggested that a dry region such as the Loess Plateau will have a much higher decrease in runoff due to forest cover. However, according to long-term studies of evapotranspiration during the growing season from different land uses (Yin *et al.*

Table 2. Evapotranspiration by different land uses

Land use	Evapotranspiration (mm) April	May	June	July	August	September	October	Total	Relative ratio of evapotranspiration
Bare land	35.7	53.4	64.8	62.7	51.3	46.5	21.9	336.3	1.00
Grassland	36.0	53.7	71.1	78.3	65.1	52.2	21.6	378.0	1.12
Forest land *(Pinus tabulaeformis)*	63.3	69.9	77.4	85.2	74.4	72.6	52.2	495.0	1.47
Forest land *(Robinia pseudoacacia)*	59.4	66.0	73.5	112.8	82.5	62.4	37.5	494.1	1.47

2005), if the evapotranspiration of bare land is 1, then the ratio of evapotranspiration of the main species for afforestation, black locust and Chinese pine, is 1.5 (Table 2).

Conclusions

Watershed hydrological effects of afforestation have not been well studied by the international forest hydrology community as a whole. This study has provided a simplified analysis of the water balance of catchment basins on the Loess Plateau using literature published over the past 50 years. The results show that the relationships between forest cover and runoff is uncertain because forest hydrological processes are complex. There are numerous interacting factors that need to be studied further. The following should be addressed in future studies: 1) relations between water yield and forest cover, and other factors such as the heterogeneity of catchments, watershed scale features, and forest features (structure, species, age); 2) long-term observations to better understand forest–water interactions to minimize uncertainties.

With China's afforestation program, there is a strong desire to increase forest cover but little consideration of the effects on local precipitation. These results may help local forest managers to make more informed decisions on the optimum forest cover on a catchment. A rigidly uniform cover percent should not be applied to every catchment when planning afforestation. Trade-offs between afforestation for erosion control and the maintenance of sufficient water supplies must be carefully balanced. An integrated management of water and forest/vegetation should be an important aspect of forestry policy in dry regions like the Loess Plateau.

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