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A comparative analysis of forest cover and catchment water yield relationships in northern China

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ABSTRACT

During the past few decades, China has implemented several large-scale forestation programs that have increased forest cover from 16.0% in the 1980s to 20.4% in 2009. In northern China, water is the most sensitive and limiting ecological factor. Understanding the dynamic interactions between forest ecosystems and water in different regions is essential for maximizing forest ecosystem services. We examined forest cover and runoff relationships in northern China using published data from a variety of sources. In the Loess Plateau region, forest cover is not correlated with annual precipitation ($r = 0.08$, $p > 0.05$) at micro (<50 km^2) and meso scales (50–1000 km^2), while they are positively correlated at macro (>1000 km^2) scale ($r = 0.77$, $p < 0.05$). Moreover, forest cover is negatively correlated with the runoff coefficient ($r = -0.64$, $p < 0.05$). In Northwest China, natural forest distribution is highly correlated with annual precipitation ($r = 0.48$, $p < 0.05$) but not with the runoff coefficient ($r = -0.09$, $p > 0.05$). In Northeast China, we found a positive relationship between forest cover and the runoff coefficient ($r = 0.77$, $p < 0.05$), but the correlation between forest cover and precipitation was not significant ($r = 0.28$, $p > 0.05$). The multiple stepwise regression analysis indicated that runoff was influenced by altitude, annual precipitation, forest cover, and PET (potential evapotranspiration) in Northeast China. We concluded that geographic differences could mask the true role of forests in the partitioning of rainfall into runoff and evapotranspiration (ET) in a catchment. In determining the forest–water relationship, one must consider climatic controls on ET in addition to forest cover. Forests could potentially enhance the complementary relationship between ET and PET. Therefore, a greater amount of ET in forested areas may decrease the PET on a regional scale.

1. Introduction

Forests provide important ecosystem services and have long been recognized as playing an important role in environmental rehabilitation, biodiversity maintenance, carbon sequestration, bio-fuel, timber production, amenities, and social benefits (Calder, 2007). However, forests cannot usually simultaneously produce multiple, positive ecosystem services because of the trade-offs among different or competing functions. Maximizing one service may cause substantial declines of other services (Bennett et al., 2009). As the demand for reliable provisions from almost all ecosystems including forests is increasing globally (Millennium Ecosystem Assessment, 2005), it is essential to understand the dynamic relationships among all forest ecosystem services. Water is the most sensitive and limiting ecological factor in forest systems. Forests and water supplies are closely linked, and trade-off between water and biological carbon sequestration has been recognized (Jackson et al., 2005; Sun et al., 2006, 2007). Therefore, maximizing the production of forest ecosystem services must essentially understand the interactions between forests and water at the regional scale.

In China, forests have long been recognized for their role in environmental protection and the development of human societies (Sun et al., 2008). During the past few decades, in addition to changes in forest management principles and strategies, China has implemented several large-scale forestation programs that have increased forest cover (the proportion of forest to total land area) from 16.0% in the 1980s to 20.4% in 2009 (State Forestry Administration, 2009). Forestation programs include reforestation (forest regenerations from original forest land) and afforestation (forest establishment in non-forest land) practices. The earliest large scale forestation program in China is the Three-North Forest Shelterbelt Program, which began in 1978 and will end in 2050. The program is underway in Northeast, North Central, and Northwest China, together referred to as the Three-North Plains. The program, covering a total of 590 counties in 17 arid and semiarid provinces and autonomous regions, was designed to improve forest cover in arid and semiarid China from 5% in the 1980s to 15% by 2050 to combat desertification and

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control dust storms. This project is being implemented in three stages (1978–2000, 2001–2020, and 2021–2050) and follows eight engineering plans (2002–2010) (Wang et al., 2010). Following the severe flood in 1998 in the Yangtze River Basin, another forestation program, the Natural Forest Protection Program (NFPP) was conducted in late 1998 in 17 provinces and autonomous regions along the upper reaches of the Yangtze River and the upper and middle reaches of the Yellow River. The program area contains 73 million ha of natural forests, which amount to 69% of the total natural forests area in China (Zhang et al., 2000). A third program, "Sloping Land Conversion Program" or "Grain for Green" was launched in 1999 to return cultivated land with slopes of 25° or more to perennial vegetation across China. The target of this conversion was 32 million ha by 2010, and the goal of the program is to reduce water and soil erosion by increasing forest cover. The program has been implemented in more than 2000 counties across 25 provinces and autonomous regions (Wei et al., 2008). Implementation of above three large-scale forest restoration programs has generated a significant growth in forest resources. The forest cover increased by 20.5 million ha since 2003, and the extent of China's total forest plantations is approximately 54 million ha, which accounts for one fourth of the world's total forested area (Raloff, 2009).

Forests can strongly influence the partitioning of precipitation into ET (evapotranspiration, which includes evaporation and transpiration) and runoff in a catchment (Schymanski et al., 2009; Wang et al., 2011). The change in soil water and groundwater storage is assumed to be negligible over years at catchment scale (Wang et al., 2011). The water balance equation can be written as:

$$P = \mathrm{ET} + R$$

where P is precipitation or the water input for a catchment, ET is evapotranspiration or the amount of water lost to the atmosphere from a catchment, and R is surface runoff measured as stream flow, often referred to as the water yield of a catchment. The runoff coefficient, which equals R/P, indicates the proportion of a catchment's water yield from precipitation. Forests may influence precipitation patterns at local to regional scales by changing surface–atmosphere transfers of heat and moisture. However, it is proven that this effect is very small (van Dijk and Keenan, 2007). Therefore, the effect of forests on catchment water yield can be attributed mainly to the changes in ET throughout the year (Farley et al., 2005; Jackson et al., 2005; Wang et al., 2011).

Over the past century, significant progress has been made in understanding the relationship between forests and water, especially in North America, Europe, and Australia (Andréassian, 2004). Paired catchment studies have provided a basis for assessing relationships between catchment vegetation, ET and runoff (Peel, 2009). Hibbert (1967) reviewed results from 39 paired catchment experiments and concluded that a reduction in forest cover increased the water yield, while the establishment of forest cover on sparsely vegetated land decreased the water yield. Bosch and Hewlett (1982) reviewed 94 paired experiments, and reported a diminished uncertainty and quantified trends for different vegetation manipulations. Brown et al. (2005) analyzed 72 additional paired catchment studies with respect to the study of Bosch and Hewlett (1982), increasing the total datasets of the paired catchment experiment to 166. The authors grouped the experiments into four broad categories: afforestation (conversion of short vegetation to forest), deforestation (conversion of forest to short vegetation), regrowth (forest removal and regrowth), and forest conversion (replacement of one forest type with another). Their review also considered long-term annual changes, adjustment time scales, the seasonal pattern of flows, and changes in both annual and seasonal flow duration curves. These reviews indicated that harvesting forests generally increased annual water yield and low flows, and had a great impact on small peak flows but a minor impact on large peak flows. In general, forestation practices decreased annual water yields and low flows due to increases in ET, but it had minimal or no effect on floods, particularly for large floods (Hornbeck et al., 1993; Stednick, 1996; Sahin and Hall, 1996; Andréassian, 2004). However, the hydrologic recovery processes after forestation are not simply the reversal of those of deforestation. Deforestation experiments generally reach a new equilibrium faster than forestation experiments (Brown et al., 2005). Zhao et al. (2009a) also illustrated that water yields changed following vegetation changes and this process occurred not only in small catchments but also in larger ones. Wei et al. (2008) stated that forestation campaigns were not likely to lead to large scale changes in annual water yield, low flow, or flood peaks before the hydrologic properties of degraded soils were fully improved.

China is characterized by diverse climatic and topographic conditions that sustain various forest ecosystems ranging from boreal forests in the North to tropical rain forests in the South. Many hydrologic studies in China's forests have focused on a single process, including forest canopy interception, stemflow, throughfall, and ET at the field level (Zhang and Yu, 1988; Zhou et al., 1994; Zhang et al., 2001, 2004; Liu et al., 1996, 2003). Surprisingly, there are few established standard paired catchment experiments (Wei et al., 2008). Hence, empirical observations and the limited data available on the environmental influences of forests are often inconclusive and even contradictory, especially concerning hydrologic cycles (Wei et al., 2003, 2005). This situation can likely be attributed to the relatively late inception of studies on the forest–water relationship in the 1980s and the highly diverse hydrologic processes that exist within a wide range of geographic and climatic regions in China (Sun et al., 2008). Sun et al. (2006) suggested that the large spatial and temporal variability of hydrologic responses to reforestation will follow gradients in climate, topography, soil, and disturbances in China. The different responses will depend on several key factors including climate, soil conditions, and stage of vegetation recovery.

Understanding of the hydrologic effects of forestation is especially critical in the semi-arid Loess Plateau and other areas of northern China that have been experiencing chronic water shortages. The trade-offs between reforestation and water resources are likely most significant in northern China (Sun et al., 2006). Although numerous studies have been conducted in individual regions, a comparative cross-region synthesis on forest–water relationships is still needed. The objectives of this study are as follows. First is to review studies on forest and water interactions. Second is to discuss the relationships between forest cover and runoff coefficients in the Loess Plateau region, Northwest China, and Northeast China. Third is to characterize the regional differences in forest–water patterns.

2. Methods

2.1. Data compilation

We compiled catchment datasets from published in peer-reviewed Chinese and international journals. We examined data from catchments where forest cover and runoff were measured. The final datasets used for this analysis contained 70 catchments for Loess Plateau, 26 ones for Northwest, and 22 ones for Northeast China. The Qingshui catchment of Loess Plateau underwent three distinguished forest cover stages (1960–1969, 1970–1979, and 1980–1989). Each stage was considered as a different catchment in this study. Therefore, the total actual datasets for Loess Plateau is 72. The detailed description of the complied catchments datasets is shown in Table 1. We analyzed the datasets for two main variables, forest cover and runoff coefficients.

Table 1
Descriptions of the compiled catchments.

Name	Site	Data period	Catchment area (km^2)	Altitude (m)	River slope (‰)	Forest cover (%)	Average annual temperature (°C)	July average temperature (°C)	Average annual precipitation (mm)	Average annual PET (mm)	Average annual runoff (mm)	Runoff coefficient	Source
Northeast China													
Ashen river	Maoershan	1971–1987	183	450	7.1	50	3.03	22.27	638	1195	205.6	0.32	(1)
Ashen river	Acheng	1971–1987	2313	190	1.2	35	3.25	22.38	626	1296	148.2	0.24	(1)
Douzuizi	Binxian	1971–1987	99	400	9.1	70	3.65	22.7	536	1003	167.8	0.31	(1)
Mayi river	Lianhua	1971–1987	8664	310	1.5	66	2.4	21.8	633	1159	191.8	0.3	(1)
Woken river	Woken	1971–1987	4164	200	0.5	59	3.23	21.87	510	1240	118.5	0.23	(1)
Hengdao	Hengdaohe	1971–1987	145	750	15.4	80	3.3	22.03	719	898	371.5	0.52	(1)
Anbang river	Fulitun	1971–1987	579	90	5.3	71	3.45	22.1	535	1284	168.1	0.31	(1)
Naoli river	Caizuizi	1971–1987	20796	100	0.3	44	2.5	21.45	509	1169	92.8	0.18	(1)
Nianzi river	Boli	1971–1987	142	350	12	70	3.5	22	541	1099	113.2	0.21	(1)
Nenjiang	Kumotun	1971–1987	31693	410	1.4	52	−2.18	19.03	487	1045	169.5	0.35	(1)
Namoer	Dedu	1971–1987	7200	350	7.3	34	1.45	21.02	520	1088	69.2	0.13	(1)
Wuyuerhe	Beian	1971–1987	2592	300	0.7	40	0.2	20.7	547	1132	145.1	0.27	(1)
Wuyuerhe	Yian	1971–1987	7423	220	0.6	22	1	21.23	495	1229	85.1	0.17	(1)
Nenjiang	Fulaerji	1971–1987	123190	350	0.1	49	0.42	20.76	466	1203	140.8	0.3	(1)
Neijiang	Jiangqiao	1971–1987	177253	260	0	33	1.9	21.84	459	1221	115.4	0.25	(1)
Ni river	Nihe	>10 years	617	180	1.6	0	2.25	22.25	521	1537	65.4	0.13	(2)
Hulan river	Lanxi	>10 years	27305	190	0.6	35	1.79	21.89	559	1185	135.4	0.24	(3)
Tangwang	Chenming	>10 years	18857	420	1	94	−0.4	20.47	599	989	264.7	0.44	(3)
Yongcui	Dailing	>10 years	169	580	19.7	90	−0.05	20.25	588	1000	260.4	0.44	(2)
Wutong river	Baoquanling	>10 years	2750	350	4.2	50	1.6	21	564	1000	193.9	0.34	(2)
Emuer river		>10 years	15523			63.7			418		150.3	0.36	(4)
Pangu river		>10 years	4369			68.7			433		212.5	0.49	(4)
Northwest China													
Yili river	Yamadu	1960–1973	44516	2050		4.7	9.5	24	269	985	240.4	0.89	(5)
Piliqing	Piliqing	1960–1973	794	1820		5.7	9.9	24.1	432	1440	224.7	0.52	(5)
Boertala	Wenquan	1960–1973	2206	2938		5.6	3.5	19.9	205	852	147.5	0.72	(5)
Manasi river	Kensiwate	1960–1973	4637	3260		3	6.3	24.4	349	1003	251.3	0.72	(5)
Taxi river	Shimenzi	1960–1973	664	3170		7.2	4.4	20.6	433	868	348.6	0.81	(5)
Hutubi river	Shimen	1960–1973	1840	3250		6	5.6	21	389	918.7	230.2	0.59	(5)
Santun river	Nianpanzhuang	1960–1973	1636	2791		7.2	6.1	23	253	879	220.1	0.87	(5)
Toutun river	Zhicaichang	1960–1973	840	3024		19.3	4.8	19.8	396	825	273.8	0.69	(5)
Wulumuqi	Yingxiongqiao	1960–1973	924	3310		4.7	1.7	15.1	477	661	263.5	0.55	(5)
Kaiken river	Kaikenhe	1960–1973	371	3500		7.5	3.2	17.6	608	894	259.8	0.43	(5)
Mulei river	Yuejin shuiku	1960–1973	467	3150		14.3	4.3	20.6	434	1071	85.2	0.2	(5)
Yiwu river	Weizixia	1960–1973	1057	2590		2.7	7.5	25.4	60	1509	51.8	0.86	(5)
Sidelong		1973–1980	110		0.1	32			560		413.6	0.74	(6)
Tianlaochi		1973–1980	13		0.1	65.9			599		380.8	0.64	(6)
Upper heihe		1973–1980	2557			5.9			37		15.9	0.43	(6)
Kukesu		1957–1962	5379	1210		4.6			450	944	410.1	0.91	(7)
Gongnaisi		1957–1962	4123	900		13.3			466	873	351	0.75	(7)
Qiedeke		1957–1962	291	940		11.7			459	942	436.4	0.95	(7)
Jiagesitai		1985–1989	231	1410		21.7			341	983	251.1	0.74	(7)
Wuertakeleisi		1985–1989	938	1330		6.8			233	778	154.6	0.66	(7)
Kusumuqieke		1985–1989	1103	1400		16.3			240	800	91.5	0.38	(7)
Bayingou		1985–1989	1579	850		3.3			244	923	193.8	0.8	(7)
Jingou river		1985–1989	1273	810		6.2			237	1278	246.7	1.04	(7)
Hongnigou		1985–1989	3902	1100		2.5			348	1107	251.4	0.72	(7)
Baiyang river		1985–1989	252	1100		8			252	897	242.1	0.96	(7)
Xidalongkou		1985–1989	255	1200		13.4			284	915	172.5	0.61	(7)
Loess Plateau													
Beipo		2001–2005	2			92.5			357		1.8	0.01	(8)
Liugou		2001–2005	2			83.4			360		5.4	0.02	(8)
Nanbeiyao		2001–2005	1			0			358		27.5	0.08	(8)
Liujiaao		2002–2005	4			82.7			369		5.9	0.02	(8)
Jingou		2002–2005	3			15.2			367		16.9	0.05	(8)
Chashang		2002–2005	32			70			375		4.5	0.01	(9)
Diantou		2001–2005	34			56			560		11.2	0.02	(9)
Wannianbao		2001–2005	286			80			333		1	0	(9)
Beizhangdian		>5 years	270			17			438		3.5	0.01	(9)
Siping		>5 years	192			9			407		5.7	0.01	(9)
Nanguan		>5 years	257			52			455		5	0.01	(9)
Gedonggou		>5 years	73			63			350		2.8	0.01	(9)
Lengkou		>5 years	76			90			580		11.6	0.02	(9)
Xiaodian	Gansu	>10 years	272			15			531		47	0.09	(10)
Caijiaomiao	Gansu	>10 years	270			15			530		32	0.06	(10)
Yaofenggou	Gansu	>10 years	219			20			511		40	0.08	(10)
Hejiapo	Gansu	>10 years	100			20			489		30	0.06	(10)
Nanxiao	Gansu	1959–1962	28			0			500		12	0.02	(11)
Wangjia	Gansu	1959–1962	48			90			639		10	0.02	(11)

(*continued on next page*)

Table 1 (*continued*)

Name	Site	Data period	Catchment area (km^2)	Altitude (m)	River slope (‰)	Forest cover (%)	Average annual temperature (°C)	July average temperature (°C)	Average annual precipitation (mm)	Average annual PET (mm)	Average annual runoff (mm)	Runoff coefficient	Source
Qingjian	Zichang	1951–1963	916			0			509		34	0.07	(11)
Xiangu	Anminggou	1951–1963	24			0			624		37	0.06	(12)
Beiluo	Liujiahe	1951–1963	7315			18.3			475		29	0.06	(12)
Fengchuan	Linzhen	1951–1963	1121			94.4			555		18	0.03	(12)
Beiluo	Zahngcunyi	1951–1963	5400			97			568		19	0.03	(12)
Xiangu	Hongmiaogou	1951–1963	42			98.5			636		29	0.05	(12)
Xi Qingshui		1963–1981	706			4.1			439		36	0.08	(13)
Dong Qingshui		1963–1982	775			39.8			500		44	0.09	(13)
Qingshui	Shanxi	1960–1969	435			25.3			589		55	0.09	(14)
Qingshui	Shanxi	1970–1979	435			55.3			551		46	0.08	(14)
Qingshui	Shanxi	1980–1989	435			57.9			516		23	0.05	(14)
Yan	Ganguyi	1959–1970	5981			8			536		42	0.08	(15)
Liujia	Beiluohe	1959–1970	7325			9			462		38	0.08	(15)
Xinshui	Daning	1959–1970	3992			10			527		50	0.1	(15)
Zhouchuan	Jiaxian	1959–1970	436			10			436		53	0.12	(15)
Hulu	Zhangcunji	1959–1970	4715			100			569		29	0.05	(15)
Fengchun	Linzhen	1959–1970	1121			100			539		23	0.04	(15)
Wudinghe	Dingshi	1980–2000	327			0			375		36	0.1	(15)
Wudinghe	Hanjiamao	1980–2000	2452			0			317		31	0.1	(15)
Huangpuchuan	Huangpuchuan	1980–2000	3175			0			366		33	0.09	(15)
Wudinghe	Hengshan	1980–2000	2415			0			378		21	0.06	(15)
Wudinghe	Lijiahe	1980–2000	8.7			0.1			392		31	0.08	(15)
Wudinghe	Caoping	1980–2000	187			0.1			403		38	0.09	(15)
Wudinghe	Mahuyu	1980–2000	371			0.1			391		38	0.1	(15)
Kuyehe	Wangdaohengta	1980–2000	3839			0.2			346		40	0.12	(15)
Jialuhe	Shenjiawan	1980–2000	1121			0.6			386		38	0.1	(15)
Wudinghe	Qingyangcha	1980–2000	662			0.6			413		34	0.08	(15)
Kuyehe	Xinmiao	1980–2000	1527			0.8			357		53	0.15	(15)
Kuyehe	Shenmu	1980–2000	7298			0.9			356		55	0.15	(15)
Kuyehe	Weijiachuan	1980–2000	8645			0.9			361		56	0.16	(15)
Gushanchuan	Gaoshiya	1980–2000	1263			1			385		41	0.11	(15)
Wudinghe	Dingjiagou	1980–2000	23422			1			348		33	0.1	(15)
Wudinghe	Baijiachuan	1980–2000	29662			1.1			362		33	0.09	(15)
Wudinghe	Zhaoshiku	1980–2000	15325			1.3			342		29	0.09	(15)
Yanhe	Ansai	1980–2000	1334			3.8			446		40	0.09	(15)
Qingjianhe	Zichang	1980–2000	913			4			444		41	0.09	(15)
Yanhe	Yanan	1980–2000	3208			4.2			456		39	0.09	(15)
Qingliangshigou	Yangjiapo	1980–2000	283			4.3			431		32	0.07	(15)
Xianchuanhe	Jiuxian	1980–2000	1562			4.4			412		11	0.03	(15)
Qingjianhe	Yanchuan	1980–2000	3468			5			455		39	0.09	(15)
Quchanhe	Peigou	1980–2000	1023			6.4			478		26	0.05	(15)
Yanhe	Xinghe	1980–2000	479			7.7			439		37	0.08	(15)
Yanhe	Ganguyi	1980–2000	5891			9.7			470		34	0.07	(15)
Zhujiachuan	Xialiuji	1980–2000	2881			10.3			424		11	0.03	(15)
Qiushuihe	Linjiaping	1980–2000	1873			11			448		25	0.06	(15)
Sanchuanhe	Houdacheng	1980–2000	4102			21.1			471		43	0.09	(15)
Yanhe	Zaoyuan	1980–2000	719			24.8			488		35	0.07	(15)
Xinshuihe	Daning	1980–2000	3992			28.2			484		23	0.05	(15)
Weifenhe	Xinxian	1980–2000	650			34			446		28	0.06	(15)
Zhouchuanhe	Jixian	1980–2000	436			37.9			493		21	0.04	(15)
Yunyanhe	Xinshihe	1980–2000	1662			48			507		20	0.04	(15)
Yunyanhe	Linzhen	1980–2000	1121			65.3			508		16	0.03	(15)
Shiwanghe	Dacun	1980–2000	2141			72.7			528		28	0.05	(15)

Sources: (1) Cao et al., 1991; (2) Zhang et al., 1994; (3) Zhang and Zhou, 1999; (4) Cai et al., 1995; (5) Gao et al., 2000; (6) Wang et al., 1999; (7) Wang and Che, 1998; (8) Liu et al., 2004; (9) Jing, 2002; (10) Hu, 2000; (11) Li and Xu, 2006; (12) Liu and Zhong, 1978; (13) Min and Yuan, 2001; (14) Wang and Zhang, 2001; (15) Zhang et al., 2007b.

2.2. Comparative analysis

Our goal was to determine the relationship between forest cover and catchment water yields and to compare regional differences of this relationship. First, we correlated forest cover and precipitation and then performed a correlation and regression analysis between forest cover and the runoff coefficient to remove the impact of precipitation on water yields. Subsequently, we conducted a multiple stepwise regression analysis on runoff, runoff coefficient and PET, with respect to forest cover, annual precipitation, altitude and annual temperature variables using SPSS for Windows 13.0.

3. Study areas

The catchments used in this study are located in northern China, including the Loess Plateau, Northwest and Northeast China (Fig. 1). Each region is described below.

3.1. The Loess Plateau

The Loess Plateau of China is located in the upper and middle reaches of the Yellow River between the western Taihang

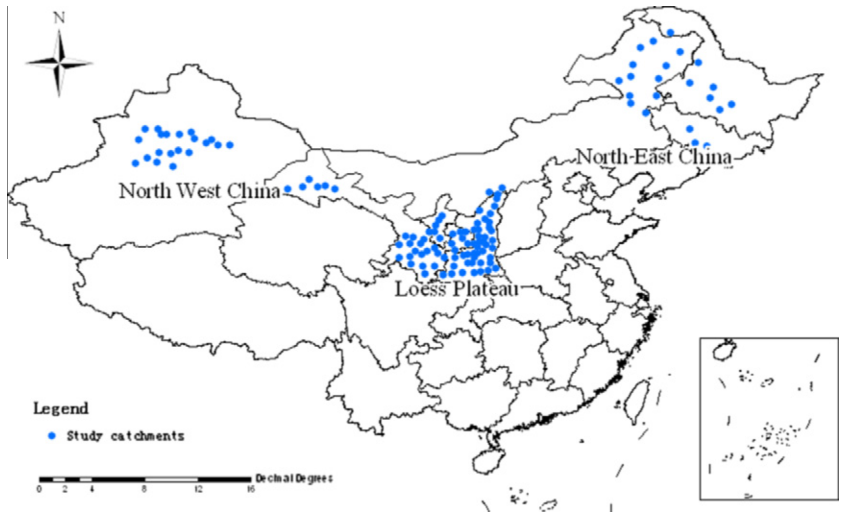

Fig. 1. The study catchments in the Loess Plateau, Northwest China and Northeast China.

Mountains, eastern Riyue–Helan Mountains, northern Qinling Mountains, and southern Yinshan Mountains. The primary implementation area of the "Sloping Land Conversion Program" stretches across a southern semi-humid forest zone, a middle semi-arid forest-steppe zone, and a northern semi-arid drought-prone typical steppe zone. Common forest species include black locust (*Robinia pseudoacia*), Chinese pine (*Pinus tabulaeformis Carr.*), apple (*Malus domestica Borkh*), Littleleaf peashrub (*Caragana microphylla*) and Seabuckthorn shrub (*Hippophae rhammoides*) in agricultural forest plantations. However, due to water shortage, these trees grow quite slowly, appearing "small but old" (Li et al., 2008; McVicar et al., 2007).

3.2. Northwest China

Northwest China is characterized by little precipitation and high potential evapotranspiration (PET). We chose the Qilian and Tianshan Mountains as study areas. Both of these areas contain complex ecosystems consisting of forests, grasslands and glaciers. These areas are typical arid ecosystems with typical continental climates (Zhao et al., 2009b).

3.3. Northeast China

The northeast region extends over ten degree latitudes from south to north and includes territories of Liaoning, Jilin, Heilongjiang and the eastern part of the Inner Mongolia Autonomous Region. The region is characterized by a temperate climate and has one of the lowest ET rates in China (Ni and Zhang, 2000). Forest types in this area include cold-temperate conifer mixed forests, temperate conifer and broadleaf mixed forests, and warm–temperate deciduous broadleaf mixed forests. Plantation and secondary forests account for a large proportion of the total forested area (Liu et al., 1996). Much of the catchment forest and runoff data used in this paper were from the Songhuajiang and Heilongjiang basins.

4. Results

4.1. The Loess Plateau

In the Loess Plateau region, the correlation analysis revealed that there was no statistically significant relationship between forest cover and precipitation ($r = 0.08$, $p > 0.05$) at micro (<50 km^2) and meso scales (50–1000 km^2), while they were positively correlated at macro (>1000 km^2) scale ($r = 0.77$, $p < 0.05$) (Fig. 2). The analysis of 72 average annual catchment values of forest cover and runoff coefficient in the Loess Plateau indicated that there was a significant negative relationship between these two variables ($r = -0.64$, $p < 0.05$, Fig. 2).

4.2. Northwest China

In Northwest China, forests are generally not planted, and natural forests are distributed within areas with higher precipitation. We analyzed data from published articles, including 26 average annual catchment values of forest cover and precipitation in the northern Tianshan Mountains and Qilian Mountains. The results showed that forest cover and precipitation are significantly correlated ($r = 0.48$, $p < 0.05$, Fig. 3). Forest cover and runoff coefficients in the two regions also exhibited a negative, but not statistically significant trend ($r = -0.09$, $p > 0.05$, Fig. 3).

4.3. Northeast China

In Northeast China, analysis of 22 average annual catchment values of forest cover and runoff coefficient showed that there was a positive relationship between the two ($r = 0.77$, $p < 0.05$, Fig. 4). However, the correlation between forest cover and precipitation was not significant ($r = 0.28$, $p > 0.05$, Fig. 4). Because the datasets from Northeast China were more complete, we also conducted a stepwise regression analysis to examine key influences on runoff.

$$R = -203.8 + 1.17\mathrm{FC} + 0.45P + 0.17A \ (r^2 = 0.86, \ p < 0.05)$$

where R is runoff, A is altitude, P is precipitation, FC is forest cover.

Forest cover, precipitation, and altitude explain 10%, 15%, and 62% of the variability of R, respectively.

$$\mathrm{PET} = 1432.4 - 0.45A - 2.69\mathrm{FC} \ (r^2 = 0.68, \ p < 0.05)$$

where PET is potential evapotranspiration calculated by standard Pan evaporation at the nearby weather stations.

Altitude and forest cover explain 55% and 11% of the variations of PET, respectively.

Linear stepwise regression analyses suggested that runoff was dependent on altitude, precipitation, and forest cover, while PET was dependent on altitude and forest cover in Northeast China.

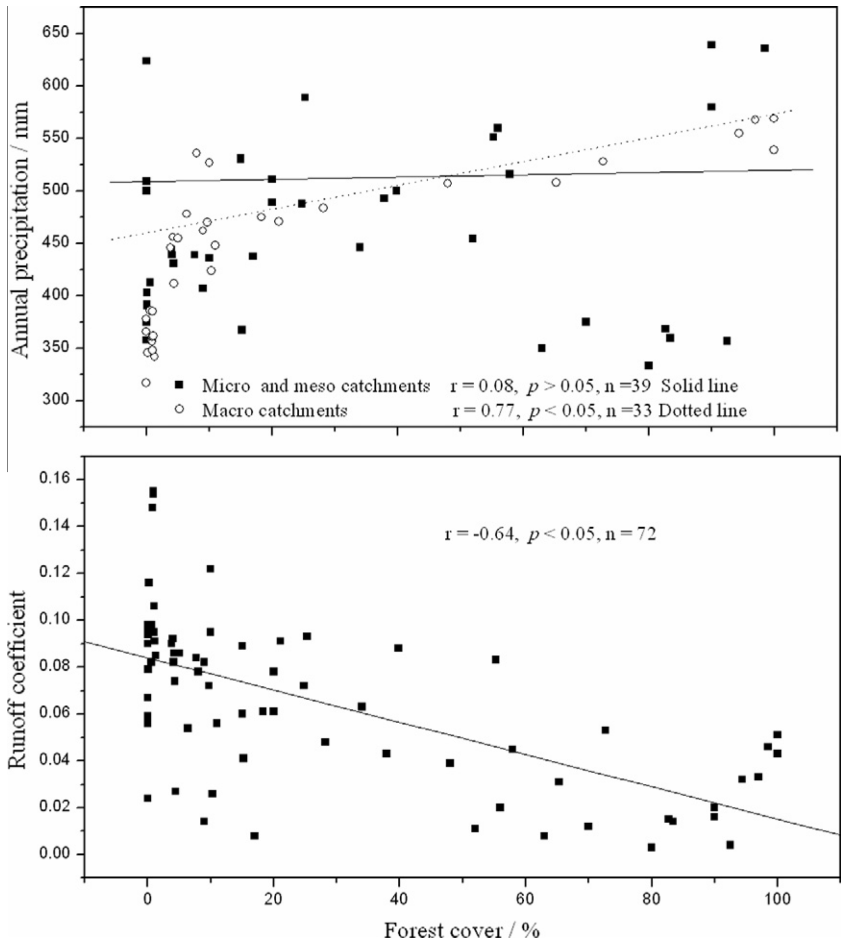

Fig. 2. The relationship between forest cover, annual precipitation and runoff coefficients in the Loess Plateau.

5. Discussion

5.1. Relationships between forest cover and catchment water yield

The results indicated that the correlations between forest cover and precipitation was geographically variable and dependent on the scale (Wang et al., 2011). For example, at Loess Plateau, they showed no significant correlation at micro and meso scales. However, at macro scale they showed a significant positive correlation. This fact that inequalities exist between levels of forest cover and precipitation is likely related to decisions about how to manage forestation programs and not dependent upon precipitation. These inequalities may also contribute to geographical variations in the relationship between forest cover and runoff coefficients. Chang and Wang (2005) calculated the average of annual overland flow reduction after forestation was 7.7 mm at the plot scale. Huang et al. (2003) reported that this reduction was 4.6 mm at the paired catchments about 1 km^2. However, about 50 mm reduction was determined mainly based on climatic conditions by Sun et al. (2006). The main processes and influence factors changed with scales. Although the magnitudes of the effects of forests are different, the trends are consistent at both small and large scales. With the increase of catchment area, runoff coefficient also increased ($r = 0.32$, $p < 0.05$, Table 1) in the Loess Plateau (the figure not shown here), but no obvious trend was found in the other two regions because their samples are not enough.

The stage of forests development also affected water yield (Farley et al., 2005). Zhang et al. (2006) reported an increasing annual ET of plantations with increasing tree age. We deliberately used the average values of the records of longer duration (range of 3–21 years) in an attempt to minimize these errors. This approach has already been shown to be a simple and effective one which can assess the hydrological effects of forestation (Wang et al., 2011). If the forests coverage showed dramatically change, we analyzed separately. For example, we distinguished Qingshui basin at Loess Plateau as three stages: 1960–1969, 1970–1979, 1980–1989. Large scale afforestation in China began in the 1980s. It seems that the forests in these catchments have not yet attained their climatic effects so far.

The results for the Loess Plateau were consistent with the general conclusions of the global paired catchment studies. Studies conducted in the Loess Plateau by Liu and Zhong (1978) more than 30 years ago also found that forested catchments on loess soils had lower water yield amounts (25 mm/yr.) and that the runoff coefficient was less than that of adjacent non-forested areas. The authors also estimated that forests in the Loess Plateau region may reduce the annual water yield by 37%. Based on continental-scale simulations using a generalized ET model, Sun et al. (2006) concluded that an average water yield reduction may vary from about 50 mm/yr (50%) in the semi-arid Loess Plateau region to about 300 mm/yr (30%) in the tropical southern region. Other studies (Lu et al., 2009; Liu et al., 2005; Zhang et al., 2006; Li, 2001; Huang and Liu, 2002) have shown that there was an obvious decline in water yield as forest cover increased. However, many of these studies observed increased flow in low flow seasons, indicating that forested catchments produced greater base flows and more natural springs.

In Northwest China, the Tianshan Mountain north hill and the Qilian Mountains are complex ecosystems consisting of forests, grassland and glaciers. The relationships between forest cover

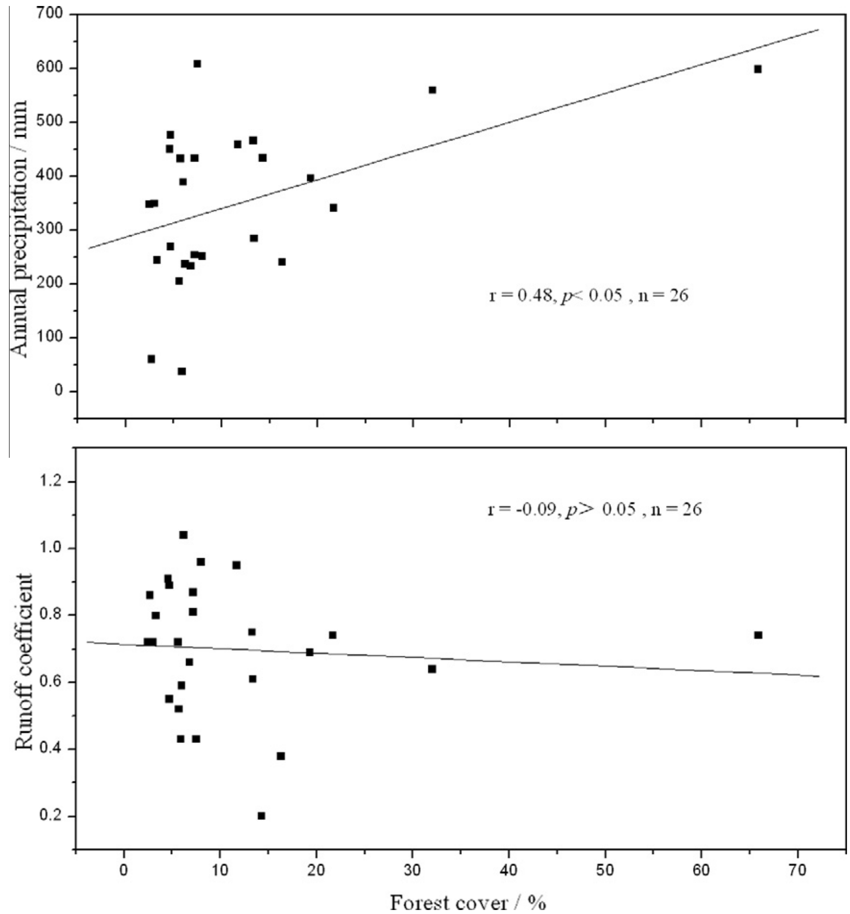

Fig. 3. The relationship between forest cover, annual precipitation and runoff coefficients in Northwest China.

and water yield are equally as complex. Many of these catchments occur in less than 30% forest cover, and few occur in areas with more than 60% cover. The results showed a negative but not statistically significant relationship between forest cover and runoff coefficient for Northwest China. In the Tianshan Mountain north hill region, if forest cover percentage was 0–10%, the water yield increased with forest cover percentage, but when forest cover percentage was greater than 10%, the runoff coefficient decreased as forest cover percentage increased (Gao et al., 2000). Long-term observations by the local research station on Qilian Mountain indicated that forest vegetation might reduce surface runoff, postpone runoff period, and minimize flooding (Wang and Che, 1998; Wang et al., 1999).

Although our studies found results similar to an earlier study by Cao et al. (1991), specifically a positive relationship between forest cover and water yield for northeastern China, we believe that ET is significantly influenced by PET and elevation in addition to precipitation. In contrast, in the arid Loess Plateau region, ET is largely controlled by precipitation and vegetation. Previous studies in northern China on the relationships between forest cover and water yield have been conflicting (Chen and Li, 2001). In fact, we observed that forests tend to be distributed at higher altitudes ($r = 0.56$, $p < 0.05$), with steeper slopes ($r = 0.71$, $p < 0.05$), more precipitation ($r = 0.55$, $p < 0.05$) and lower PET values ($r = -0.74$, $p < 0.05$) (Table 1). Therefore, these regions partition more precipitation into runoff, making the runoff coefficient higher.

Observed relationships between forest cover and water yield in different regions are complex and can be inconsistent. Wei et al. (2003) attributed the inconsistencies to several factors: (1) large, heterogeneous basins have a large buffering capacity and may mask the effects of forest cover; (2) different measurement methods are used with varying biases and errors; and (3) differences in climate and watershed characteristics among the contrasting basins may obscure the effects of forest cover. While differences exist among the three regions, in Northeast China, forest cover positively correlated with catchment water yield, but in the Loess Plateau and Northwest China a negative correlation was observed, while the correlation were not significant for Northwest China.

5.2. Regional differences

ET has a large impact on the balance of water within an ecosystem. The water yield from a catchment is altered through changes in transpiration, interception, and evaporation. Zhang (2001) postulated that the long-term average annual ET of a catchment depends upon the minimum value of potential evaporation (PET) and the available water (AW) for evapotranspiration within the catchment. Forestation may affect these two values. Forestation increases the value of AW through transpiration, or by removing water from soil and intercepting precipitation. Contrarily, forestation reduces the value of PET for several possible reasons. First, forestation increased near infrared reflectance but caused no significant differences in visible radiation reflectance compared with other land cover, resulting in a reduced absorption of net radiation (Cheng and Chen, 2004). Second, accumulated ET resulted in low temperature and high humidity, further reducing PET (Qiu et al., 1999). Lastly, fog intercepted by the forest canopy constituted a significant portion of total precipitation, but this water was not recorded as precipitation and ultimately evaporates (Clus et al., 2008). Throughout this process, it will consume a great deal

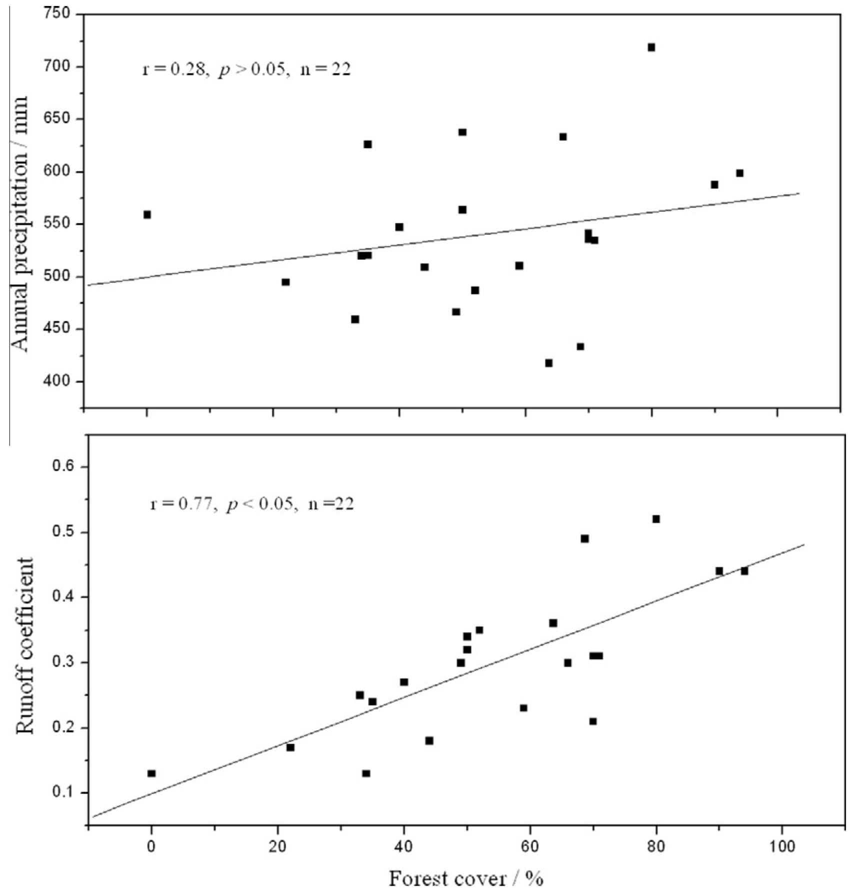

Fig. 4. The relationship between forest cover, annual precipitation and runoff coefficients in Northeast China.

of the PET (Kalthoff et al., 2006). Therefore, the "fog drip" precipitation in forests will greatly reduce PET (Beysens et al., 2007). These findings agree with the complementary relationship between ET and PET (Xu and Singh, 2005). The influence of forestation on water yield can be illustrated in two extreme cases. In humid conditions, the value of AW is greater than PET and actual ET depends on the value of PET. Therefore, when a forestation program is implemented, the value of PET will decrease and the loss of water will be smaller, which resulting the increase of water yield of the catchment. In arid conditions where the value of AW is less than the PET value, actual ET depends on the value of AW, and forestation alteration will therefore increase the value of AW and actual ET, reducing the amount of water yield.

Forestation activities may prompt land conversion in one of these two extreme cases, but the ultimate result depends on changes in AW and PET, which are determined by local geographic conditions. The Loess Plateau area experiences an arid to semi-arid climate, and the PET is far greater than available water, so the actual ET is controlled by AW. When forestation was implemented in this extremely arid region, AW increased while PET decreased, and actual ET increased correspondingly. Subsequently, water yield decreased in the Loess Plateau area. In dry Northwest China, the situation is similar, but water is available in the form of glacier runoff. Therefore, the mechanism is more complex and a change in the proportion of forest cover has little impact on water yield in dry Northwest China. However, in the low-temperature, high-humidity environments of the Northeast, "fog drip," or "horizontal precipitation" occurs. Fog is not recorded as precipitation, but the cumulative amount increased by forest cover may be greater than the amount of increased ET, so larger forested areas result in increased water yields. This analysis is consistent with other low-temperature and high-humidity areas such as the upper reaches of Yangtze River and Russia (Sun et al., 2007; Liu et al., 2007; Zhang et al., 2007a; Ma and Zhang, 1998). This has also been confirmed by a recent study by Zhou et al. (2010), which illustrated that large-scale forest recovery did result in a water yield increase over the past 50 years in the humid Guangdong Province.

Catchments are integrated systems, and impacts on water yield should be considered collectively rather than focusing on specific processes such as interception, stem flow, and infiltration. The main water input into ecosystems is precipitation, including vertical precipitation (the most commonly recognized and measured form of precipitation) and horizontal precipitation (not recorded as precipitation). The key outputs are ET and runoff (water yield). Influence of forests on global precipitation patterns is complex and at local to regional scales it is evidenced to be very small (van Dijk and Keenan, 2007). Therefore, the change in water yield is mainly determined by the difference between the increase in horizontal precipitation and actual ET. However, "fog drip" is difficult to quantify and is therefore rarely reported. Many studies have focused on calculating ET, but the accuracy of their results is still difficult to determine. Some models estimate variations in ET based on vegetation changes to compare the impacts of vegetation changes on ET, thus lacking well-thought out field verifications. Therefore, the precise calculation of ET is still a priority for forest hydrology.

5.3. Potential limitations

Various sources of uncertainty were consistently flagged in the compiled datasets and throughout the analyses. Few causal correlations exist between confounding variables, a fact likely related to the heterogeneity of the datasets. In addition, the stage of forest development could not be precisely included in the analysis because these data were not reported in many studies. Average values of the longer duration records were used in an attempt to minimize these errors. The analysis also includes catchments with very different spatial scales, scale effects on precipitation and runoff coefficient were discussed. Finally, the pattern of rainfall may relate to the species of trees, which may influence the relationship between forest cover and runoff. Because of dataset limitations, these issues were necessarily overlooked. Despite these limitations, this comparative analysis of forest–water relations is useful and can potentially contribute to the understanding of forest hydrology in different regions of northern China.

6. Conclusions

Water shortages are common in northern China, and large-scale forestation efforts must consider the impact of increased forest cover on hydrological processes. ET is the major source of consumption in a catchment, and changes in water yield depend on variations in ET caused by increased or decreased forest cover. This study concluded that geographic differences could mask the true role of forests in partitioning rainfall into runoff and ET in a catchment. Future studies must consider climatic controls on ET in addition to forest cover when determining the forest–water relationship. Our hypothesis is that trees can increase the water available for ET and enhance the complementary relationship between actual ET and PET such that more actual ET will lower the PET. In arid conditions, the principal control on evaporation is the availability of plant-water, while under wet conditions, the main control is atmospheric demand, which is determined by PET. Under intermediate conditions, the control depends upon the relative importance of each of these factors. In northern China, the Loess Plateau is relatively dry, Northeast China is relatively wet, and Northwest China presents a complex system based on glacier runoff. An analysis of these ecosystems may not be able to pinpoint a cause–effect relationship but can confirm that there is a relationship between them. However, the data used in this study are incomplete and cover a short period of time. Long-term observations are needed to gain a better understanding of the forest–water interactions in these three regions.

Acknowledgments

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