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Hydrological processes in major types of Chinese forest

X. Wei,[1]* S. Liu,[2] G. Zhou[3] and C. Wang[4]

[1] *Endowed Watershed Management Chair, Earth and Environmental Science, Okanagan University College, Kelowna, BC V1V 1V7, Canada*
[2] *Research Institute of Forest Ecology, Environment and Protection, Chinese Academy of Forestry, Beijing 100091, People's Republic of China*
[3] *South China Institute of Botany, Chinese Academy of Sciences, Guangzhou, People's Republic of China*
[4] *College of Forestry, Northeast Forestry University, Harbin, 150040, People's Republic of China*

Abstract:

Overexploitation of forest resources in China has caused serious concerns over its negative impacts on water resources, biodiversity, soil erosion, wildlife habitat and community stability. One key concern is the impact of forestry practices on hydrological processes, particularly the effect of forest harvest on water quality and quantity. Since the mid 1980s, a series of scientific studies on forest hydrology have been initiated in major types of forest across the country, including Korean pine (*Pinus koraiensis*), Chinese fir (*Cunninghamia lanceolata*), oak (*Quercus mongolica*), larch (*Larix gmelinii*), faber fir (*Abies fabri*), Chinese pine (*Pinus tabulaeformis*), armand pine (*Pinus arandi*), birch (*Betula platyphylla*) and some tropical forests. These studies measured rainfall interception, streamflow, evapotranspiration and impacts of forest management (clearcutting and reforestation). This paper reviews key findings from these forest hydrological studies conducted over the past 20 years in China.

Forest canopy interception rates varied from 15 to 30% of total rainfall, depending on forest canopy and rainfall characteristics. Stemflow is generally a small percentage (<5%) of total rainfall, but it accounts for 15% in the oak forest in northeast China. The high amounts of stemflow, as well as higher amounts of nutrients contained in stemflow, may allow oak trees to adapt to a dry and nutrient-poor environment. Evapotranspiration was a significant component of the water budget in these Chinese forests studied, ranging from 80–90% of total rainfall in the northern temperate forests to 40–50% in the southern tropical forests. Forests substantially reduced surface runoff and erosion. However, no consistent response on total streamflows was observed. The reason for the inconsistency may be due to complexities of streamflow processes and the utilization of different methodologies applied at the various spatial scales. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS forest hydrology; forest management; interception; stemflow; evapotranspiration; runoff

INTRODUCTION

The water cycle is a key ecosystem function that links other processes in forest ecosystems. Meanwhile, hydrological processes are difficult to study because they are influenced by a myriad of biophysical factors. Forest hydrology, an important science addressing the relationship between forests and hydrology, has received significant attention globally.

China occupies a large geographic territory with a variety of climatic and topographic conditions, which sustain various forest ecosystems ranging from boreal forests in the north to tropical rain forests in the south. These forests play a crucial role in environmental protection, and in social and economic development in the country (Wang, 1980). However, overexploitation of forest resources in past decades has caused serious concerns regarding negative impacts on water resources, biodiversity, soil erosion, wildlife habitat and community stability, especially the effect of forest harvesting on water quality and quantity (Zhou X, *et al.*, 1994). In the early 1980s, a nationwide debate over the relationship between forest conservation and

* Correspondence to: X. Wei, Earth & Environmental Science, Okanagan University College, Kelowna, BC V1V 1V7, Canada.
E-mail: awei@ouc.bc.ca

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water resources took place (Zhou X, *et al.*, 1994). Scientists from forestry and environmental disciplines emphasized the significance of forests in regulating streamflow and controlling soil erosion. Other scientists, mainly from the fields of geography, climatology and agriculture, considered forests to play a limited role on water budgets. The debate was fruitless because of the lack of convincing data on forest hydrology, and was criticized as 'fighting civil war with foreign weapons' (Zhou X, *et al.*, 1994). However, the debate did launch an important research program. More than 15 long-term ecological stations, covering the major vegetation types in various climatic and geographic zones, have been established since the middle of the 1980s. The research projects have been focused on structures and functions of various vegetation types and their responses to forest management (e.g. harvesting or reforestation). In this paper we summarize the results on forest hydrology from the seven selected stations that represented the major forest types in China.

STUDY AREAS

China has the most abundant forest types in the world. The forests, covering 16·55% of the total area, include boreal forest and mixed coniferous broad-leaved forest in the north, temperate deciduous broad-leaved forest and coniferous forest in the central region, and subtropical evergreen broad-leaved forest, warm temperate coniferous forest, tropical rain forest and seasonal forest in the south. These varieties of forest are associated with diversities of climate and topography, and offer us a unique opportunity to compare hydrological processes between major types of world forest ecosystem. Average precipitation is about 600 mm $year^{-1}$, with vast spatial variation and seasonal distribution. As a result of monsoon precipitation systems and increase in elevation from east to west, the southeastern region receives the most precipitation (>2000 mm) and the northwestern region has the lowest (<100 mm), exhibiting a clear climatologic gradient. Because of this gradient, stream peak flows are associated with heavy rainfalls in summer or early fall in the southeastern river systems, whereas snow-dominated processes operate in north and west China.

Based on the representativeness of forest types and availability of hydrological data, we selected seven long-term ecological stations for this review (Figure 1). They represent key Chinese forest ecosystems, including Korean pine (*Pinus koraiensis*), Chinese fir (*Cunninghamia lanceolata*), oak (*Quercus mongolica*), larch (*Larix gmelinii*), faber fir (*Abies fabri*), Chinese pine (*Pinus tabulaeformis*), armand pine (*Pinus arandi*), birch (*Betula platyphylla*), sub-tropical monsoon evergreen and tropical forests. Some details of these seven sites are presented in Table I.

METHODS

In order to facilitate comparison among all ecological stations, consistent research methodologies were proposed (Ma, 1994) (Figure 2). However, variations to the proposed methodologies have also been applied to suit to specific forests and local conditions better.

Rainfall interception

Throughfall T was collected by various devices, such as troughs or plates of different shapes placed underneath forest canopies (Figure 2c). For example, Wei and Zhou (1991) used five $4 \times 0{\cdot}2 \times 0{\cdot}2$ m^3 plastic troughs randomly located underneath the canopy of each selected forest type (oak, birch, pine and larch) in the Mao-er-shan ecological station (number 2 in Table I). Rainfall R was measured using standard rain gauges in adjacent openings in all selected stations. Stemflow S was normally collected using an open PVC tube mounted around each of the selected stems and collected in a container (Figure 2d). Sufficient trees of various diameter classes in each of the forests studied were selected to collect stemflow, and total stemflow, expressed as millimeters per hectare, was calculated from those measured stemflows and forest stand information. The canopy rainfall interception I was then calculated as follows:

$$I = R - T - S \tag{1}$$

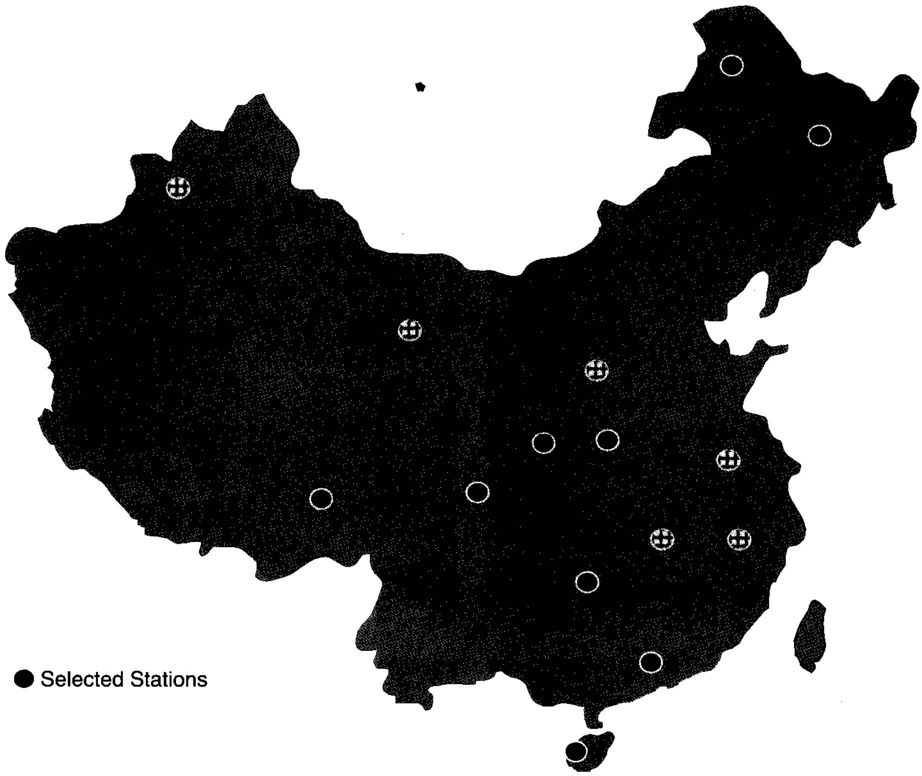

Figure 1. The key Chinese long-term ecological research network and the stations selected for this study (see Table I for details of the stations selected)

Evapotranspiration

Several methods, including energy balance, water balance or direct measurement of evaporation and transpiration, were used to quantify evapotranspiration (ET) in the forests studied. Among them, the energy balance method was the most popular applied in Chinese ET studies (He and Liu, 1980). In order to apply the energy balance method, a wooden or metal-framed tower (at least 5 m above the forest canopy) must be installed in a forest (Figure 2a). The tower is evenly divided into five layers, with the highest layer situated above the canopy and the lowest layer situated at the ground surface. Data collected at each layer included radiation, humidity, temperature, wind and evaporation at an hourly interval for the selected dates of the seasons studied.

In addition, Zhou and Pan (1988) estimated ET for a Chinese fir plantation in southern China using the following equation:

$$E_t = E_p \left\{ 1 + \frac{s}{E_p} - \left[1 + \left(\frac{s}{E_p} \right)^{\frac{nh}{h^2 - h - 1} + h + 1} \right]^{\frac{1}{\frac{nh}{h^2 - h - 1} + n + 1}} \right\} \quad (2)$$

where E_t (mm) is the total actual ET of the ecosystem; E_p (mm) represents the potential ET for the ecosystem, which is determined by radiation energy that enters the ecosystem and climatic environment; s (mm) is the water storage of the ecosystem; h is the relative humidity as a decimal fraction; and n is a dimensionless constant (0–∞), representing the capacity of the ecosystem to prevent liquid water from flowing outside.

Table I. Brief description of the selected long-term ecological stations in China

Selected station[a]	Location (lat., long., elevation)	Vegetation–climate type	Forest type	Mean annual temperature (°C)	Precipitation (mm $year^{-1}$)
1. Inner Mongolian–Genhe	50°49′N, 121°31′E, 784–1142 m	Cold temperate coniferous	Larch	−5·4	450–550
2. Heilongjiang Mao-Er-Shan	47°7–14′N, 128°48′E, 707 m	Temperate coniferous–broadleaf	Korean pine, oak, birch	0·0	676
3. Shichuan–Miyaluo (now Wolong)	31°31–39′N, 102°39′E, >2000 m	Temperate coniferous	Subalpine fir–spruce	3·0	700–1000
4. Sha'anxi–Qinling	33°14–44′N, 99°31′E, 1420–2474 m	Warm temperate coniferous	Chinese pine, Armand pine, oak	12·0	1023
5. Hunan–Huitong	26°50′N, 109°45′E, 270–400 m	Subtropical evergreen broadleaf	Chinese fir plantation	15·4	1550
6. Guangdong–Dinghushan	23°10′N, 112°34′E, 100–700 m	Subtropical monsoon evergreen	Evergreen broadleaf, eucalyptus	21·0	1900
7. Hainan–Jianfengling	18°40′N, 108°49′E, 0–1421 m	Tropical forests	Semi-deciduous monsoon forest	19·7–24·5	1650–2650

[a] Numbers refer to the selected stations shown in Figure 1.

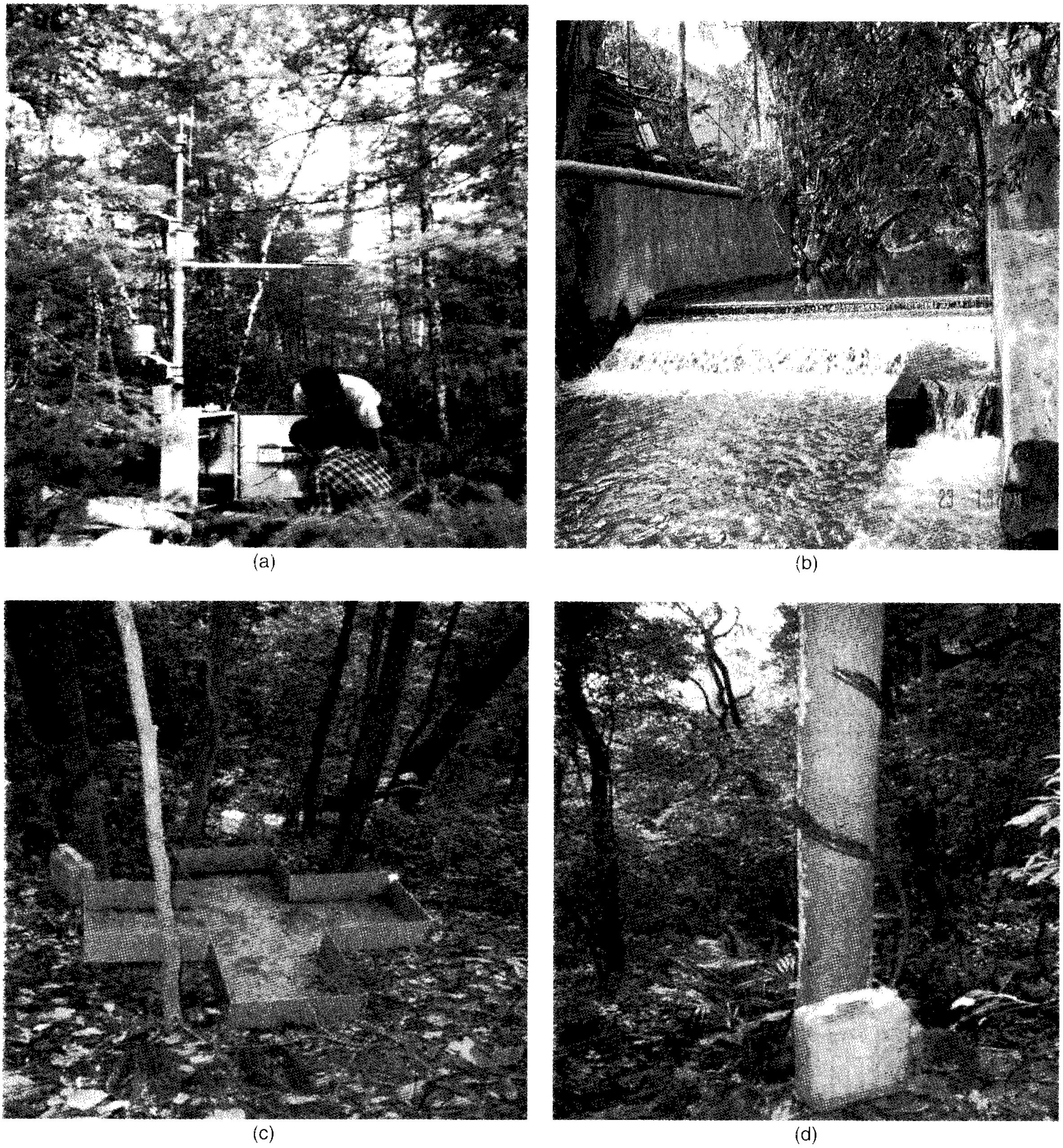

Figure 2. Examples of devices used to measure hydrological processes: (a) metal tower for applying energy balance method for quantification of evaportranpiration; (b) streamflow discharge measurement; (c) collection of throughfall; (d) stemflow collection

Runoff and streamflow

Three methods were used to quantify runoff and streamflow at various watershed scales.

1. Small, closed experimental plots (2–100 m^2). A typical small, closed runoff plot is the one used to measure the runoff generation process (Wei and Zhou, 1991). Because of easy control and fewer confounding factors,

Table II. Canopy rainfall interception and stemflow for the major Chinese forests

Station	Forest type	Interception (% of total rainfall)	Stemflow (% of total rainfall)	Data Source
1	Larch	17·5	3·3	Zhou (2003)
2	Mongolian oak	20	15·5	Wei and Zhou (1991)
	Birch	25·9	4·6	Wei and Zhou (1991)
	Korean pine	25·3	3·8	Zhou X, *et al.* (1994)
3	Chinese pine	20	2·6	Lei *et al.* (1994a,b)
	Armand pine	19	5	Lei *et al.* (1994a,b)
	Oak	17·9	2·3	Lei *et al.* (1994a,b)
4	Faber fir–spruce	24	Not measured	Liu *et al.* (2001)
5	Chinese fir plantation	25·8	0·2	Tian *et al.* (1994)
6	Monsoon evergreen broadleaf	31·8	8·3	Yan *et al.* (2003)
	Mixed pine broadleaf	25·2	6·5	Yan *et al.* (2003)
	Monsoon pine forest	14·7	1·9	Yan *et al.* (2003)
7	Semi-deciduous monsoon forests	29·1	3	Zeng (1994)

the small, closed plot offered particular merit in examining runoff processes and generation (Wei and Zhou, 1991). However, owing to local soil conditions, small experimental plots were of different sizes and shapes with various runoff variables collected at the different forests studied. For examples, two small, closed plots (2 m^2 in size; one with a tree inside and one without) were paired to examine the impacts of harvesting on hydrological processes at the Mao-er-shan ecological station. The variables measured included surface runoff, interflow and assumed deep seepage along the bedrock surface (Wei and Zhou, 1991). At the Dinghushan ecological station, three 5 m × 10 m experimental plots were set up in the subtropical monsoon forest to examine surface runoff processes and soil erosion only.

2. Paired watersheds (0·1–10 km^2). The paired watershed approach was used to examine the effect of forest harvesting on streamflow yield and nutrient output in small watersheds (Figure 2b). For example, three gauged watersheds were established at the Mao-er-shan ecological station in 1984, namely the control (1·47 km^2), watershed 1 (0·16 km^2), and watershed 2 (0·24 km^2) (Wang and Zhou, 1994). After 4 years of calibration measurements, about 50% of the watersheds (1 and 2) were harvested, and hydrological variables were continuously monitored afterwards.
3. Multivariate regression analysis. For large-sized catchments (> 10 km^2) it is very difficult to find comparable paired watersheds. An alternative is to apply multivariate regression modelling to examine relationships between streamflow and vegetation and environment factors (Cao *et al.*, 1991).

It should be noted that not all of the above three methods were conducted in each of the seven research forests or areas selected. The first and second methods are often implemented in most of the forests studied, and the third depends mainly on data availability in large-scale watersheds. This makes it difficult to examine hydrological processes across various watershed scales in the forests studied.

RESULTS AND DISCUSSION

Rainfall interception

Canopy rainfall interception varied from 14·7 to 31·8% of total rainfall depending upon stand characteristics (Table II). These values agree well with other studies in the world, such as *Pinus pseudostrobus* Lindl. (19·2%), *Quercus* sp. (13·6%) and pine–oak natural forests (23%) in northeastern Mexico (Silva and Rodriguez, 2001), and others (Spittlehouse, 1998). Reducing the coverage of the Mongolian oak stands from 95% to 60% via thinning caused the interception to decrease from 20% to 15·2% of total rainfall (Wei and Zhou, 1991).

Forest canopy interception was also affected by rainfall properties. The interception rate was greater (>50%) when rainfall was less than 5 mm and rainfall intensity was less than 10 mm hr^{-1}; it generally decreased with rainfall amount and intensity (Wei and Zhou, 1991; Liu *et al.*, 2001), probably because of the limited water-holding capacity of the canopy when it is wet. Figure 3 shows the geographic pattern of rainfall interception by forest ecosystems in China, which is consistent with rainfall distribution. A greater rainfall amount leads to a greater rainfall interception. Rainfall interception in northwestern forests is the lowest because of its lower rainfall and forest biomass.

The ecological role of canopy interception should be noted. The intercepted water evaporates during and after rainfall events. Canopy interception may reduce the kinetic energy of rainfall drops, which reduces surface impact and consequently soil erosion, particularly when understory vegetations exist (Zhou *et al.*, 2002a,b). However, canopy interception can also increase kinetic energy due to increasing of drop sizes, and consequently may accelerate soil erosion when there is limited or no understory vegetation (Lei, 1994; Zhou *et al.*, 2002a,b). This clearly highlights the importance of protection of multilayer structures (tree canopy, understory vegetation and litter) for controlling soil erosion.

Stemflow

The standard protocol for measuring stemflow in all forests studied in China allows a sound comparison. Table II shows that stemflow as a percentage of total rainfall varied tremendously with forest type. The oak forests had the highest amount of stemflow (15·5%) and Chinese fir forests had the lowest (<1%). These findings are consistent with many stemflow studies in the world is forests, as summarized by Levia and Frost (2003) (Table III). In a comprehensive review of stemflow hydrology and its chemistry in forested and agricultural ecosystems, Levia and Frost (2003) concluded that stemflow quantities are highly variable between and within types of vegetation cover characteristic of tropical, temperate, and semi-arid and arid eco-regions (Table III).

Stemflow production may be related to differences in climatic pattern, meteorological conditions, species composition, canopy structure and morphological characteristics of tree leaves, branches and bark (Levia

Figure 3. Geographic pattern of integrated rainfall interception by forest ecosystems (reproduced from Liu *et al.* (1996))

Table III. Range of selected stemflow production values under diverse vegetation cover in tropical, temperate, semi-arid and arid ecoregions (after Levia and Frost (2003))

Vegetation type	Stemflow (% of incident precipitation)
Tropical montane rainforest	13·6
Tropical rainforest	1·8
Cacao plantation	1·99
Tropical dry forest	0·6–0·9
Tropical motane rainforests	<1 · 0
Tropical rainforests	0·9–1·5
Pine–hemlock–beech plots	1·2–9·6
Pinus radiata plantation	3·1–3·9
Dry sclerophyll forest	4·8
Subalpine balsam fir forest	3–8
Northern red oak plantation	4
Pinus radiata plantation	11·2
Evergreen-broadleaf forest	14–20
Slash pine forest	0·94–10·4
Japanese pine forest	6·6–15·7
Chihuahuan desert shrubs	4·0–45
Semi-arid shrubs	0·76–5·14
Chihuahuan desert shrubs	2·0–27·0
Creosote bushes	5·9–26·9
Thornscrub community	3·0
Laurel forest	1·2–13·6
Mediterranean holm oak forest	2·6–12·1

and Frost, 2003). At the Mao-er-shan ecological station, northeast China, oak forest delivered much higher amounts of stemflow than birch forests did (Table II). Because of the same rainfall characteristics in both forests, we believe that higher amounts of stemflow quantity in oak forests are mainly due to their large thick leather-like leaves, rigid petioles and steep branch inclination angles that allow more interception and stemflow formation. This suggests that tree leaf morphology and canopy structure arrangement can be an important factor influencing stemflow production.

The importance of stemflow is commonly neglected in most forest ecosystem studies, largely because of its relatively small amount (Wei, 1984; Wei and Zhou, 1989). However, stemflow may be crucial for Mongolian oak to grow in the harsh microenvironment of this region. Oak forests normally occur on hilltops, where other species rarely survive due to dry and nutrient-poor soils. Wei and Zhou (1991) reported that the nutrient contents (N, P, K) in stemflow were significantly greater than in rainfall and throughfall. Because of stemflow, oak forests can, therefore, access more nutrients and moisture. These results also suggest that the stemflow of oak might be one of the mechanisms for Mongolian oak to adapt to nutrient-poor and dry soils.

ET

ET, including physical evaporation and biological transpiration, was a significant component of forest water budgets, ranging from 80–90% of total rainfall in the northern temperate forests to 40–50% in the southern tropical forests in China (Table IV). As expected, the actual amount of ET is greatest in the low-latitude tropical forests due to the high temperature and rainfall, whereas the amount of ET is relatively low in the dry high-latitude northern temperate forests (Table IV). However, ET as a percentage of total rainfall decreases with decreasing latitude (Figure 4). The relatively high ET percentages in the northern temperate forests (stations 1 and 2) may be attributed to the coincidence of high temperature with high rainfall (water availability) during the growing season in northeast China, while the relatively low ET percentages in the tropical forests may be due to the fact that more rainfall becomes streamflow as a result of higher intensity rainstorms. Atmospheric demand can also be an important factor. Relatively dry air in the north makes potential evaporation fully realized, whereas the opposite occurs in the south as the result of very humid air.

Unexpectedly, the ET percentage in the faber fir forests in the upper reaches of the Yangtze River (station 4) is the lowest of the forests studied. This may have important implications for forest and water management in the Yangtze River watershed. The low ET rates in the faber fir forests may be attributed to high-elevation mountains, high atmospheric humidity and low annual temperature.

The Chinese studies clearly demonstrated large variances in ET percentage (40 to 90%) between various types of forest. These results are consistent with the studies in other world forests (Rutter, 1968). In spite of these differences, ET from a forest is generally greater than from pasture or bare land. This, together with evidence from many experimental studies, has led to the long-standing belief in both research and resource management communities that conversion of forests to bare land or agricultural land (pasture) can increase water yield or streamflow because of less ET associated with the latter types of land use. A recent review by Scott *et al.* (2004) also shows that reforestation can cause decreased water yield. However, the belief is based

Table IV. Rainfall R and ET in the major forest types in China

Station	Forest type	R (mm)	ET (mm)	ET/R (%)	Source
1	Larch	n·a	n·a	n.a.	
2	Mongolian oak	700	504	77	Wei *et al.* (2003)
	Birch	700	554	89	Ren and Zhang (1991)
	Korean pine	716	602	84	Zhu (1982)
3	Chinese pine	740	528·8	72	Lei *et al.* (1994a,b)
	Armand pine	762·6	477·2	63	Lei *et al.* (1994a,b)
	Oak	764·9	476·3	62	Lei *et al.* (1994a,b)
4	Faber fir	700–900	210–360	30–40	Liu *et al.* (2003)
5	Chinese fir plantation	1158	896	77	Tian *et al.* (1994)
6	Monsoon evergreen broadleaf	1910	1008·5	53	Yan *et al.* (2001)
	Mixed pine broadleaf	1910	979·8	51	Yan *et al.* (2001)
	Monsoon pine	1910	872·9	46	Yan *et al.* (2001)
7	Semi-deciduous monsoon	1826	915·5	50	Zeng (1994)

[a] n.a.: data not available.

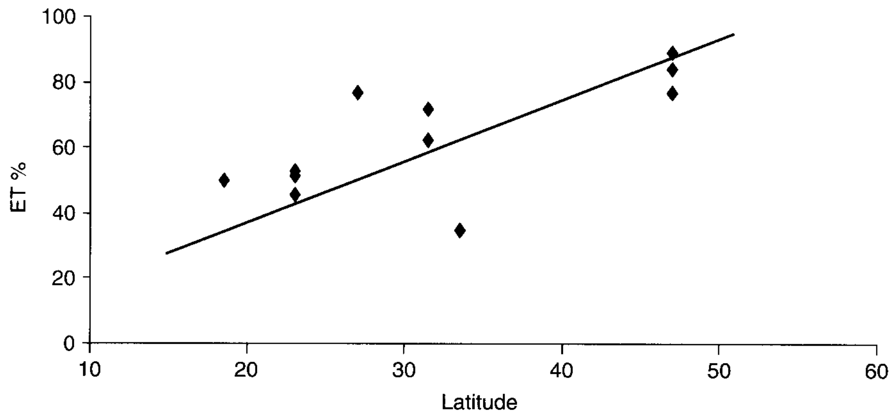

Figure 4. The relationship between forest ET percentage and latitude ($n = 11$, $P < 0.05$)

on the assumption of a constant relationship between precipitation and ET, so a reduced ET can logically lead to a gain of water yield. However, when this assumption is not true or when the relationship between precipitation and ET varies in time and space, then the simple logic may not apply. Therefore, using ET information to infer water yield may not always correct.

Runoff and streamflow

Hydrological variables, such as annual mean discharge, maximum flow and surface or overland flows, have different implications for water and water-related resource management. Maximum and overland flows are important information for managing floods and controlling soil erosion, and annual flows are highly relevant to water supply, water allocation and aquatic habitat protection.

Research to date in China has shown that forests effectively reduce maximum discharge and surface runoff, which leads to less chance of flooding and soil erosion (Table V). In other words, forest harvesting increases maximum flow and surface runoff and, consequently, soil erosion and flooding. The importance of understanding the relationship between forests and maximum flows has made the subject one of the most important research topics in forest hydrology. Although there is no intent to provide a through review on the maximum flow subject in this paper, a few important studies deserve mention here. Jones and Grant (1996) quantified long-term changes in streamflow with clearcutting and road construction in the Cascades Range, western Oregon, USA. They examined differences in paired peak changes for 150 to 370 storm events for five basin pairs, and found that forest harvesting has increased peak discharges by as much as 50% in small basins and 100% in large basins over the past 50 years. However, using the same datasets, Thomas and Megahan (1998) showed that peak flow was increased significantly for the smallest peak flows on both clearcut and the patch and roaded watersheds, but these effects decreased as flow event size increased and were not detectable for flows with 2 year return intervals or greater. Although the above studies placed more focus on small peak flow events, Beschta *et al.* (2000) provided further analysis on streamflow associated with large peak flow events of the same watersheds studied as in Jones and Grant (1996) and Thomas and Megahan (1998). They concluded that peak flow increases averaged approximately 13–16% after treatment for 1 year recurrence interval events, and 6–9% for 5 year recurrence interval events in small basins, and even smaller changes (1–7%) in harvesting-induced peak flows in large basins.

The above-mentioned hydrological studies in the western cascades of Oregon clearly demonstrated that results are dependent upon the periods of the data records reported, on the methods of analysis and on targeted peak flow magnitudes (Beschta *et al.*, 2000). Because of this, interpretation of published results is necessary. The results from seven ecological stations in China all show increased maximum flow after

Table V. Impacts of temperate forests on hydrological variables estimated from different approaches at various scales

Station	Approach	Impacts of forests[a]			Data source
		Annual mean flow	Peak flow	Overland flow	
2	Small runoff plots (2 m^2)	↓	↓	↓	Wei and Zhou (1991)
	Paired watersheds (0·2–2 km^2)	↓	↓	↓	Wang and Zhou (1994)
	Regression analysis (2–100 km^2)	↓	↓	—[b]	Zhou X, *et al.* (1994)
1	Regression analysis (>100 km^2)	↑	↓	—[b]	Cao *et al.* (1991)
4	Small runoff plots (100 m^2)	↓	↓	↓	Lei *et al.* (1994)
3	Paired watersheds (3–4 km^2)	↑	↓	↓	Liu *et al.* (2001)
5	Small runoff plots (142–356 m^2)	↓	↓	—	Tian *et al.* (1994)
7	Single watershed (300 m^2)	↓	↓	↓	Zhou Guangyi, *et al.* (1994)

[a] decrease; ↑ increase
[b] Not measured. ↓.

harvesting, but because of lack of differentiation of peak flow magnitudes and various analytical methods used from study to study, it may be difficult to compare those results across different forests and to draw a specific conclusion on peak flow changes related to various peak flow events caused by harvesting. Further work is necessary to examine the impacts of forests or forest removal on streamflow with various peak flow events or return intervals.

Table V shows contradictory conclusions with respect to the impacts of forest vegetation on annual mean discharge. Bosch and Hewlett (1982) summarized the results from 94 catchment experiments and concluded that almost all studies reviewed show reductions of water yield with increases in forest cover, with the exception of perhaps one. Although the majority of forest hydrology studies in China (in addition to the studies shown in Table IV) support the conclusion by Bosch and Hewlett (1982), there are a few studies indicating the opposite results. Studies from the Shichuan Miyaluo station (station 3), located in the upper reaches of the Yangtze River, indicated that harvesting tends to reduce water yield based on paired watershed comparisons (Ma, 1987; Wang, 1989). Cao *et al.* (1991) analysed the relationship between forest vegetation cover and streamflow based on data from 20 large-sized watersheds (from 100 to 177 000 km^2) and concluded that there is a significant positive relationship between cover and streamflow, and that annual discharge increased 1·46 mm with every 1% increase in cover. This conclusion is also supported by two Russian studies in the far-east region (Cao *et al.*, 1991).

We speculate that for the above contradiction is for the following reasons: (1) As watershed scales increase, landscape heterogeneity (wetlands, ponds, etc.) increases, which could act as a buffer to streamflow changes in response to forest changes. A quicker response of streamflow is generally expected from forest cover change in smaller watersheds. (2) Inconsistent methods employed in the studies summarized make direct comparisons difficult. (3) Specific characteristics of watersheds (climate, geology, soil, vegetation, and land uses) may obscure the effect of forest coverage on streamflow. This suggests that impacts of forests on hydrology are site specific and scale specific. The paucity of data impedes our understanding of the uncertainties in these studies. More research is needed to study scale issues of forest hydrology and other important topics, such as groundwater, snow hydrology and climate-change impacts in China.

In spite of some inconsistent results from these forest hydrological studies across China, these long-term hydrological stations continue to allow us to build a solid foundation in understanding the interactions between forests and hydrological processes. However, most of the studies have focused on understanding whether forests or harvesting are important in the aspects of water protection and soil erosion, and almost none of them aim at determining what percentage of forested land in a watershed or a landscape must be protected in order to minimize negative impacts of harvesting on water resources. The latter question is important and must be answered in order that we may design and implement sustainable forest practices.

Summary and future study

Forest hydrology is an important topic for China. Recently, the Chinese government has initiated a series of programmes (such as a national natural forest conservation project and conversion of farmland back to forests) to address forest management and water resource protection issues. However, the country suffers greatly from frequent floods and droughts due to a loss of watershed functions as a result of large-scale deforestation, urbanization and land-use competition. Hydrological studies are important for supporting environment protection and economic development in China. These studies provide strategic information for determining what percentage of forest land in a region is required in order to protect water resources and support economic development. These studies also provide important information that supports operational practices, such as forest regeneration programmes, watershed restoration and best forest management practices.

In spite of some inconsistent results, all studies have demonstrated that forests play an important, positive role in reducing surface runoff and peak streamflows. Soil erosion and flood frequency in forested ecosystems would be expected to be less than in harvested ecosystems because of reduced surface and peak flows. Forest impacts on hydrology are site specific and scale specific, and caution must be exercised when extrapolating results from one scale to others.

Hydrological studies conducted over the past 20 years have significantly improved our knowledge of the relationships between forests and hydrology. However, further studies are needed to address some critical knowledge gaps for supporting sustainable resource management in China. These gaps are briefly described as follows:

1. Snow hydrology. Snow hydrology is often ignored. This topic is particularly relevant in the temperate and boreal forests in China. Information on snow hydrology (accumulation, melting and land-use impacts) will greatly help fully understand hydrological processes.
2. Impacts of forest practices or 'treatments' on hydrology. As indicated earlier, most of the studies have focused on understanding whether forests or harvesting are important in the aspects of water protection and soil erosion. Almost none of them aim at evaluating impacts of specific forest management questions, such as selection of harvesting levels or percentages in a watershed, riparian management strategies, selection of various forest structures, silvicultural practices, etc. A robust statistical design must be applied to achieve this objective for evaluating the effects of various forest practices or 'treatments' on hydrology.
3. Application of hydrological models. Where there are sufficient data or understanding in forest hydrology, application of hydrological models can be beneficial to sustainable forest management because they can allow us, within a short time, to evaluate the impacts of different forest management scenarios on hydrology.

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