Journal of Hydrology (2006) **328**, 548–558

available at www.sciencedirect.com

SCIENCE DIRECT®

journal homepage: www.elsevier.com/locate/jhydrol

Potential water yield reduction due to forestation across China

Ge Sun [a,*], Guoyi Zhou [b], Zhiqiang Zhang [c], Xiaohua Wei [d], Steven G. McNulty [a], James M. Vose [e]

[a] *Southern Global Change Program, USDA Forest Service, 920 Main Campus Dr., Venture II, Suite 300, Raleigh, NC 27606, USA*
[b] *Southern China Botanical Garden, Chinese Academy of Sciences, Guangzhou, PR China*
[c] *College of Soil and Water Conservation, Beijing Forestry University, Beijing, PR China*
[d] *University of British Columbia-Okanagan, 3333 University Way, Kelowna, BC, Canada V1V 1V7*
[e] *Coweeta Hydrologic Laboratory, USDA Forest Service, Otto, NC 27606, USA*

Received 25 April 2005; received in revised form 5 August 2005; accepted 27 December 2005

KEYWORDS
Forest hydrology;
Forestation;
Hydrologic impact;
Water yield;
China

Summary It is widely recognized that vegetation restoration will have positive effects on watershed health by reducing soil erosion and non-point source pollution, enhancing terrestrial and aquatic habitat, and increasing ecosystem carbon sequestration. However, the hydrologic consequences of forestation on degraded lands are not well studied in the forest hydrology community as a whole. China has the largest area of forest plantations in the world now, and the hydrologic consequences of massive forestation are unknown. We applied a simplified hydrological model across the diverse physiographic region to estimate the potential magnitude of annual water yield response to forestation. Our study suggests that the average water yield reduction may vary from about 50 mm/yr (50%) in the semi-arid Loess Plateau region in northern China to about 300 mm/yr (30%) in the tropical southern region. We conclude that forestation in China that often involves a combination of tree planting and engineering (e.g., terracing) may have even a higher potential to greatly reduce annual water yield in headwater watersheds, especially in the semi-arid Loess Plateau region. However, the forestation area is relatively small for most large basins with mixed landuses in China, thus the regional effects of forestation on water resource management may not be of major concern. Comprehensive science-based evaluation of roles of forests on regulating regional water resources is critical to the current forestation endeavors in China.

* Corresponding author. Tel.: +1 919 515 9498; fax: +1 919 513 2978.
E-mail address: Ge_Sun@ncsu.edu (G. Sun).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2005.12.013

Introduction

Much progress has been made in understanding forest and water relations during the past century around the globe. There have been several comprehensive reviews on forest–water issues including the classic paper by Bosch and Hewlett (1982). Andreassian (2004) synthesized experimental results from 137 paired watersheds located in various geographic regions around the world. A review by Robinson et al. (2003) focuses on Europe, and Scott et al. (1998) on forestation in South Africa, and Bruijnzeel (1996, 2004) and Scott et al. (2004) for the tropics, and Ice and Stednick (2004) on North America. Although there is a large variability due to differences in climate, soils, and vegetations, these studies concur that deforestation generally increases water yield and baseflow, and forestation reduces the two variables for most watersheds. There is more uncertainty on the effect of forestation on peakflows than that on annual water yield and baseflows (Jones and Grant, 1996; Thomas and Megahan, 1998; Bruijnzeel, 2004; Andreassian, 2004). Water yield response to forest removal across diverse geographic regions has been well studied in North America (Stednick, 1996; Ice and Stednick, 2004; Sun et al., 2005a), and these studies generally support the above conclusions. For example, clear-cutting forests in the US may result in up to 540 mm increase in annual water yield, and it may take up to 30 years to return to pre-harvesting water yield conditions with natural forest regeneration (Stednick, 1996; Ice and Stednick, 2004).

Chinese people have long recognized the importance of forest and water on the environment and societal development. Popular sayings, such as 'beautiful clear waters drain from green mountains', 'those who rule the waters rule the nation', 'forests and reservoirs are alike', reflect the basic understanding of the close relationships between water and forests. Forest resources in China suffered greatly in the past century, but forest areas have been increasing. China has the world's largest amount of forest plantations, approximately 45 million ha or one fourth of world total (FAO, 2001). The total forest coverage in China has recovered from about 11% of land area in the 1980s to the current 16.7% or about 163.5 million ha in the year 2000 (FAO, 2001). China's natural forests and plantation forests increased 5% between 1990 and 2000 (FAO, 2001). It was not until the 1980's that science-based studies on the forest–water relations began to emerge in China (Ffolliott and Guertin, 1987; Yu, 1991; Liu et al., 1996). Most of the existing forest hydrologic studies focused on the benefits of forests in retaining water for discharge during non-rainfall seasons (water redistribution), in reducing soil erosion (Zhou et al., 2002) and large floods, or single processes such as evapotranspiration (Zhou et al., 2004) and infiltration processes. The majority of the forest hydrology studies did not follow the rigorous classic paired watershed approach in detecting hydrologic changes as a consequence of forest cover change, mostly due to lack of funding and long-term commitment of hydrologic research. Large, devastating floods such as those occurred in 1981 and 1998 in the Yangze River and water use concerns of exotic tree species in the Yellow River basins and southern China greatly motivated forest hydrologic research in the headwaters of big rivers and areas under massive forestation.

Plot-scale studies in the hilly regions that are often vulnerable to water and wind erosion in China have documented that forestation can reduce soil erosion and sediment transport (Wei et al., 2003, 2005), enhance carbon sequestration (Fang et al., 2001), and thus improve stream water quality in small watersheds (Ma, 1993). However, few rigorous long-term studies have examined the relations between water quantity and quality and forestation activities at the watershed and regional scales. Flooding and drought events cause huge economic losses each year in this heavily populated country. Empirical observations and data on the positive environmental influence of forests on flooding and drought are limited, often inconclusive, and even contradictory due to the large geographic and climatic variability in China (Wei et al., 2005). Scientific debates among ecologist, hydraulic engineers, and geographers on the role of forests to alleviate droughts and floods since early 1980's have promoted several major national ecological monitoring and land management initiatives (Zhou et al., 2001). National ecological networks, such as China Ecological Research Network (CERN), and the China Forestry Ecological Network (CFEN), were recently established to monitor the ecological effects of landuse and landcover changes. Unfortunately, few of research stations conducted hydrologic experiments using a paired watershed ecosystem approach. The majority of the ecosystem studies were manipulation experiments at the stand and plot-scale (Wei et al., 2005). Watershed-scale studies were rare (Zhou et al., 2002).

Nevertheless, several influential studies have demonstrated the uncertainty and variability of forestation on potential hydrologic responses across China due to the large differences in climate and soil conditions. Liu and Zhong (1978) reported that forested watersheds on loess soils had lower water yield (25 mm/yr) and lower water yield/precipitation ratios than adjacent basins with lower forest coverage in the upper reaches of the Yellow River, northwestern China. They concluded that forests in the Loess Plateau region may reduce streamflow by 37%. The Mao-er-shan Ecological Station represents a rare paired watershed experiment in a hardwood forest site in northeastern China. The area has a temperate climate with averaged annual precipitation of 600–700 mm and averaged pan evaporation less than 500 mm/yr. Experiments on the watersheds concluded that a 50% thinning increased runoff by 26–31 mm/yr (Ma, 1993; Wei et al., 2005). However, contradictory reports on the impact of forest on water yield also exist. For example, Ma (1987) compared watershed hydrology of an old-growth fir forest watershed with a clear-cut watershed. Both watersheds were located in a cool, humid, mountainous region of southwestern China, upper reach of the Yangtze River basin with average annual precipitation approximately 1010 mm. This study found that water yield from the 331 ha forested watershed was 709 mm/yr and the runoff ratio was 0.70. The annual water yield from the 291 ha clear-cut watershed was only 276 mm and the runoff ratio was 0.27 during 1965–1967 (Liu et al., 1996). Re-cutting 60% the forested watershed in 1969 resulted in a water yield decrease of about 380 mm/yr comparing to the forested control watershed. A comparison of streamflow from 10 large basins (674–5322 km^2) in the Yangze River basin suggested that basins with higher forest coverage generally had higher runoff/rainfall ratios (>0.9) (Ma, 1993). Similar positive correlations between forests and water yield for large basins (>100 km^2) were reported for northern China (Wei et al., 2003). These findings were corroborated with Russian literature, that suggests streamflow is generally higher for large forested basins (Wei et al., 2003). One unsubstantiated hypothesis was that forest increased 'fog drip' precipitation and forests have lower evapotranspiration, thus increasing streamflow. Russian studies on the forest–water relations had a large impact in China before the 1980's when access to western literature was not readily available. Wei et al. (2003) attributed several reasons for the inconsistence findings that include: (1) heterogeneous large basins have large buffering capacity and may mask the forest cover effects, (2) inconsistent methods and measurement errors and (3) differences in climate and watershed characteristics among the contrasting basins that could have obscured the forest cover effect.

Scientists in China have started questioning the traditional published literature and hypotheses described above as better quality forest hydrologic data becoming increasingly available (Zhou et al., 2001). Land managers are calling for more process-based hydrologic research, and rigorous applications of the forest ecological principles in watershed management (Zhou et al., 2001). There is an urgent need to examine how the current large scale forestation efforts throughout China affect water resources at watershed to regional scales (Zhou et al., 2001; Li, 2001).

The objective of this study was, to apply a simple watershed water balance model to project water yield reductions due to forestation across the diverse geographic regions (topography, precipitation, and heat gradients) of continental China. We intend to develop hypotheses that describe the hydrologic recovery processes of lands under large scale forestation, and develop a method to evaluate the hypotheses. Our ultimate goal was to provide scientific, quantitative information on the potential hydrologic consequences of vegetation management in different regions. This information will offer guidance on policy making in forestation efforts in China.

Methods

Empirical data clearly show that the effects of forest vegetation on watershed hydrology vary greatly among the experimental watersheds as affected by climate, geology (soils), vegetation characteristics and management practices such as deforestation or forestation (Andreassian, 2004). However, it remains challenging to separate the contribution of each individual factor to the overall hydrologic response. Mathematical models probably are the best tools in analyzing the complex non-linear relations between forest water yield response and major environmental factors. For a continental scale analysis in this study, we used a simplified approach although more sophisticated hydrologic models are available that can address hydrologic responses to multiple ecosystem disturbances.

Water yield response model

Annual averaged stream flow for a watershed during pre- and post-forestation periods can be described as:

For pre-forestation condition

$$Q_1 = P_1 - \mathrm{ET}_1 \pm \Delta S_1$$

For forested condition

$$Q_2 = P_2 - \mathrm{ET}_2 \pm \Delta S_2$$

where, Q, P, ET, and ΔS are annual streamflow, precipitation, evapotranspiration, and change in water storage, respectively. The subscript 1 and 2 denotes pre- and post-forestation period, respectively.

Then, the effects of forestation can be expressed as:

$$Q_2 - Q_1 = P_2 - P_1 + \mathrm{ET}_1 - \mathrm{ET}_2 \pm (\Delta S_2 - \Delta S_1)$$

Assuming the amount of precipitation is constant and that the change in soil water storage during the two periods is similar, then, the change of Q due to forestation is essentially the change of evapotranspiration between the two periods:

$$\Delta Q = \mathrm{ET}_1 - \mathrm{ET}_2 \tag{1}$$

We adopted the annual ET model (Eq. (2)) developed by Zhang et al. (2001). Using hydrologic data from over 250 watersheds worldwide across a wide range of climatic zones and biomes, Zhang et al. (2001) correlated mean annual actual evapotranspiration (ET), annual precipitation (P), and Priestley–Taylor potential evapotranspiration (PET):

$$ET = \left(\frac{1 + w\frac{\mathrm{PET}}{P}}{1 + w\frac{\mathrm{PET}}{P} + \frac{P}{\mathrm{PET}}}\right) \times P \tag{2}$$

where, w is the plant-available water coefficient and represents the relative differences of water use for transpiration among plant communities. The w parameter was reported as 0.5 for short grass and crops and 2.0 for forests. For a watershed with mixed land uses:

$$\text{Watershed ET with mixed landcover} = \sum(\mathrm{ET}_i^* f_i) \tag{3}$$

where, f_i is the percentage of each land use such as grass land, cropland, and forests. Sun et al. (2005a) applied this model for southern US and suggested the model adequately explained the spatial variability of ET at the regional scale. The model does not differentiate vegetation community types (conifer vs. deciduous). Methods were developed to overcome this deficiency in a southern US model application when high-resolution landcover data were available (Sun et al., 2005a).

Thus, the effects of forestation on annual water yield can be approximated mathematically as:

$$\Delta Q = \mathrm{ET}_1 - \mathrm{ET}_2 = -\left(\frac{1 + 2.0\frac{\mathrm{PET}}{P}}{1 + 2.0\frac{\mathrm{PET}}{P} + \frac{P}{\mathrm{PET}}} - \frac{1 + 0.5\frac{\mathrm{PET}}{P}}{1 + 0.5\frac{\mathrm{PET}}{P} + \frac{P}{\mathrm{PET}}}\right) \times P \tag{4}$$

Eq. (4) indicates that the water yield effect of forestation follows a non-linear function of both potential ET and precipitation. A hypothetical example is given in Fig. 1 to illustrate the potential curve of annual water yield response to forestation. This simple theoretical analysis suggested that a dry region such as the Loess Plateau in northwestern

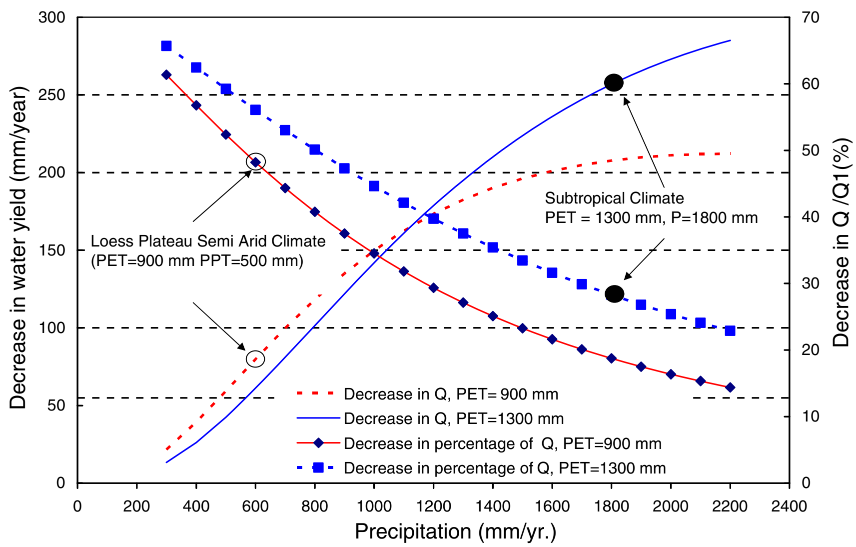

Figure 1 Theoretical analysis of the potential hydrologic response to vegetation changes using Zhang et al. (2001) model (Eq. (2)) under two contrasting climatic regimes in China.

China (PET = 900 mm, P = 600 mm) would have a much lower water yield response (~80 mm) than a subtropical region in southern China (PET = 1300 mm, P = 1800 mm). However, when these absolute response values were expressed as a percentage change term ($-\Delta Q/Q_1$), the response in the dry region would be much higher (48%) than for a warm and wet region (28%) in southern China (Fig. 1).

Regional databases

Topographic data (Digital Elevation Model) that were acquired from the Global Land 1-km Base Elevation (GLOBE) project (http://www.ngdc.noaa.gov/mgg/topo/globe.html) were used to classify China into two broad land surface categories including hilly and plain regions for water yield model validation purposes (Fig. 2). Similarly, global 1-km resolution landcover data (Loveland et al., 2000) developed by the International Geosphere–Biosphere Programme Data and Information System (IGBP-DIS) were used to represent 1992 land cover conditions. The IGBP-DIS landcover had 17 classes dominated by shrublands–savanna–grasslands ecosystem and croplands (46% and 29% of total land area, respectively; Fig. 3). To derive the potential change in water yield due to conversion from grasslands to forests at the continental scale by Eq. (4), regional climate databases including monthly precipitation and monthly air temperature at an approximately

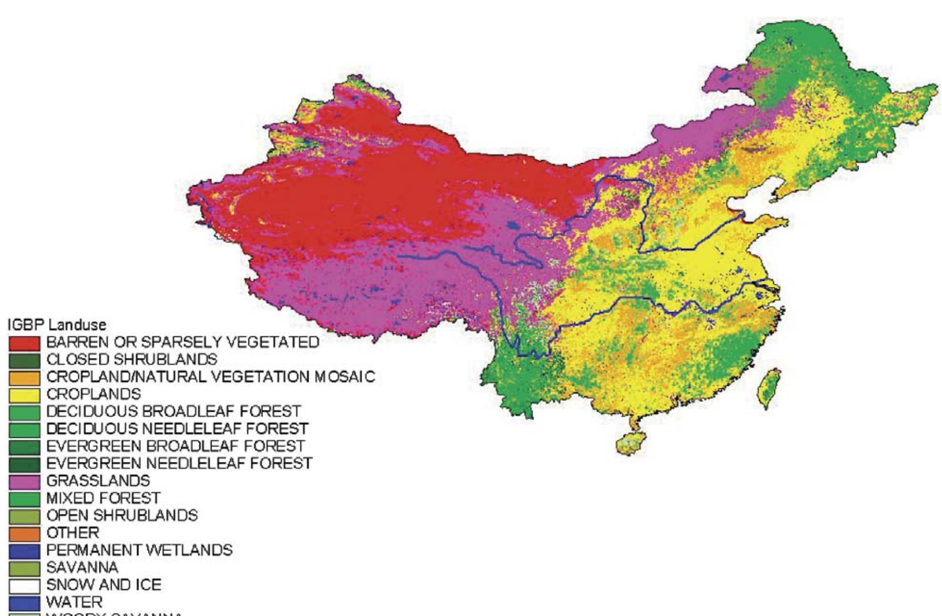

Figure 2 Landcover of China as classified by the IGBP system. Majority of the forestlands are located in the hilly remote mountains in the southwestern and northeastern regions.

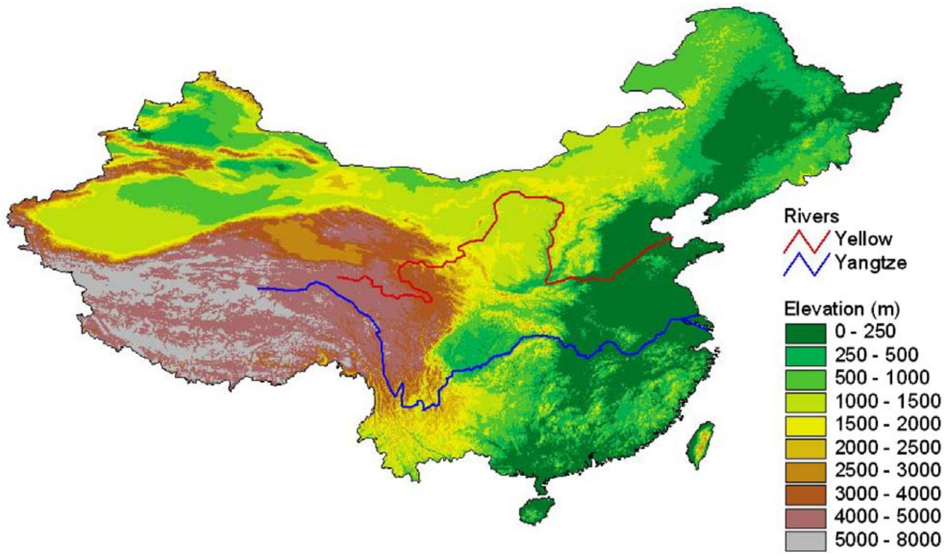

Figure 3 The large topographic gradients control the precipitation and heat redistribution, and land use patterns. Over 70% of the lands in China are in the mountains or desert, not suitable for crop production and vulnerable to water and wind erosion.

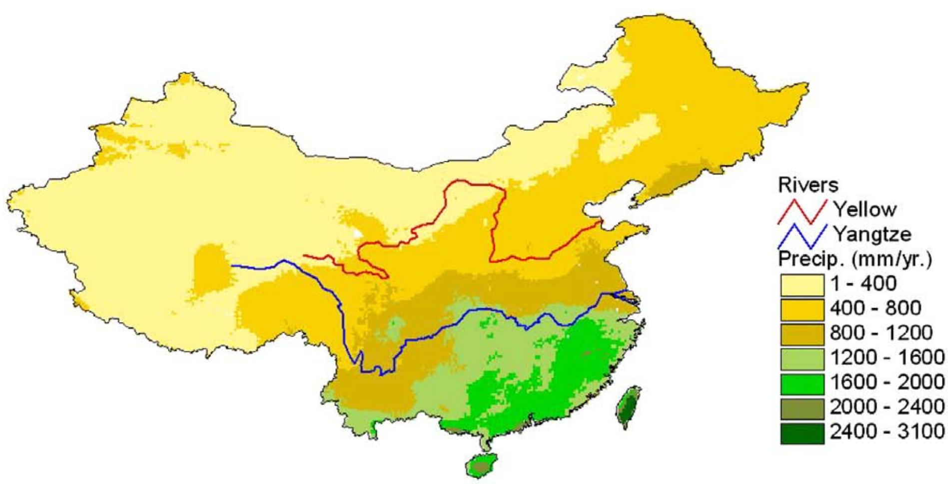

Figure 4 Averaged annual precipitation distribution patterns show a strong decreasing gradient from the southeast to the northwest characteristic of strong influence of a monsoon climate.

$18 \times 18\ \text{km}^2$ spatial resolution were acquired (Figs. 4 and 5) (Ni et al., 2000). These gridded climate databases represent spatial long-term averages from over 160 weather stations across China. Monthly precipitation was summed up as the annual average. Annual PET was calculated as the sum of monthly PET that was derived from air temperature and day time length using the Hamon PET method (Federer and Lash, 1978; Lu et al., 2005). The Hamon PET method was a simpler but comparable method (Federer et al., 1996) that requires fewer climatic parameters compared to the standard Priestley—Taylor method used in Zhang et al. (2001).

Results

Model comparisons

Eq. (2) was evaluated by comparing annual water yield (P − ET) to those predicted by the simpler empirical formula derived using measured regional streamflow data from over 100 basins throughout China (Liu, 1986):

$$Q = P - C[1 - e^{(-P/C)}] \tag{5}$$

C is an empirical parameter that varies from 800 mm for mountainous regions to 1100 mm for plains regions. The disadvantage of this empirical model is that it does not reflect the effects of landuse/landcover and potential ET on streamflow. Overall Eq. (2) predicted water yield lower than Eq. (5) did, but predictions by the two methods correlated well as suggested by a linear regression model with the intercept set as zero ($n = 32{,}911$, $R^2 = 0.89$, $p < 0.001$, slope = 0.74). Both models suggested that the average annual runoff ratio (Q/P) across China was about 25% (Fig. 6) and there was a large spatial variability of runoff across China. As expected, the runoff—precipitation relations described by Eq. (2) was more complex than the function described by Eq. (5) (Fig. 6) since, the former formula con-

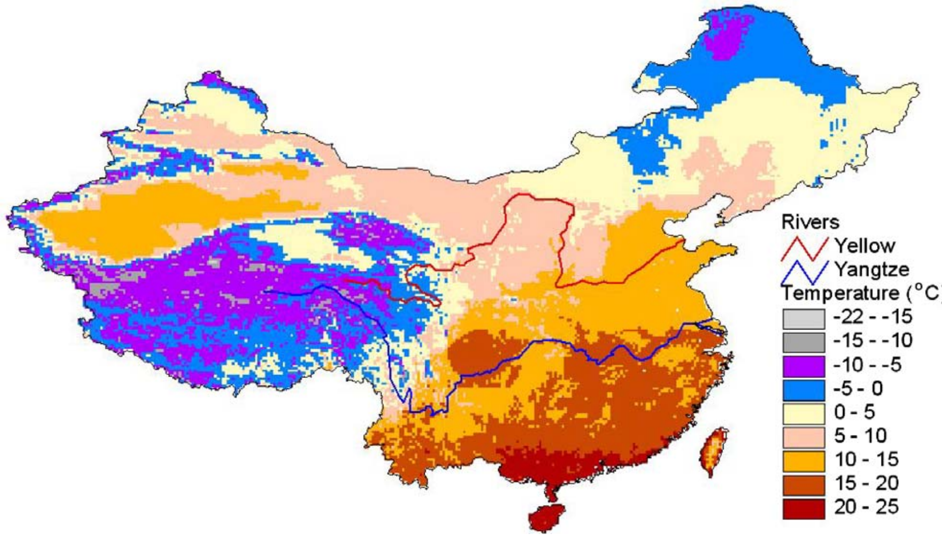

Figure 5 Annual averaged air temperature distribution patterns show a strong decreasing gradient from the south to the north and from low elevation to high elevations.

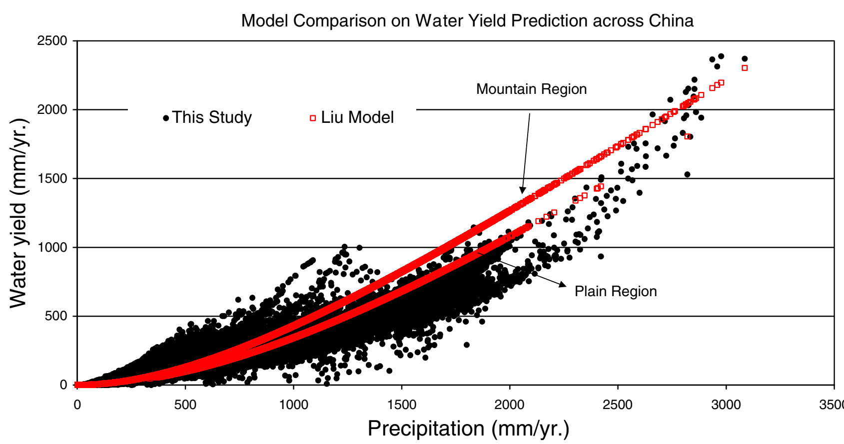

Figure 6 A comparison of predicted water yield by the precipitation-driven model by Liu (1986) (Eq. (5)) and the climate and landcover driven model by Zhang et al. (2001) (Eq. (2)).

siders the influences of both potential evapotranspiration and landcover on actual evapotranspiration. Sun et al. (2002) reported details on model validation and climate change study applications of Eq. (2).

Spatial waters yield responses to forestation

We mapped the potential water yield impact of forestation across China to show its sensitivity to climatic variability. The water yield reduction was computed as the difference between water yield distribution for grasslands and forested lands (Fig. 7). Areas with annual precipitation less than 400 mm were eliminated from the map since they do not support forests and forestation is not feasible. The amount of water yield reduction due to forestation was projected to increase from dry regions in the northwest to the wet regions in the southeast. However, the relatively reduction of water yield, as defined as the change of water yield following forestation divided by the water yield under background conditions (grasslands), shows an opposite trend compared to the trend of absolute amount of water yield reduction (Fig. 8). For example, streamflows are generally low in northern China due to low precipitation but high potential ET, thus small changes in water yield amount will result in a large relative change in the region. These modeled results suggest that forestation in China may cause long-term stream flow decreases in the range of 50–300 mm/yr or 10–50% of average pre-forestation flow rates. These values represent the maximum potential response of converting complete a grassland or cropland to a mature forest.

Frequency distributions of the six water yield reduction categories show that almost half the study region that can support forests may see a potential reduction in water yield with a narrow range of 50–100 mm/yr. The other half of the region has a wider range of 100–250 mm/yr of potential water yield reduction (Fig. 9). On a relative basis, about 70% of the land mass may experience water yield reduction

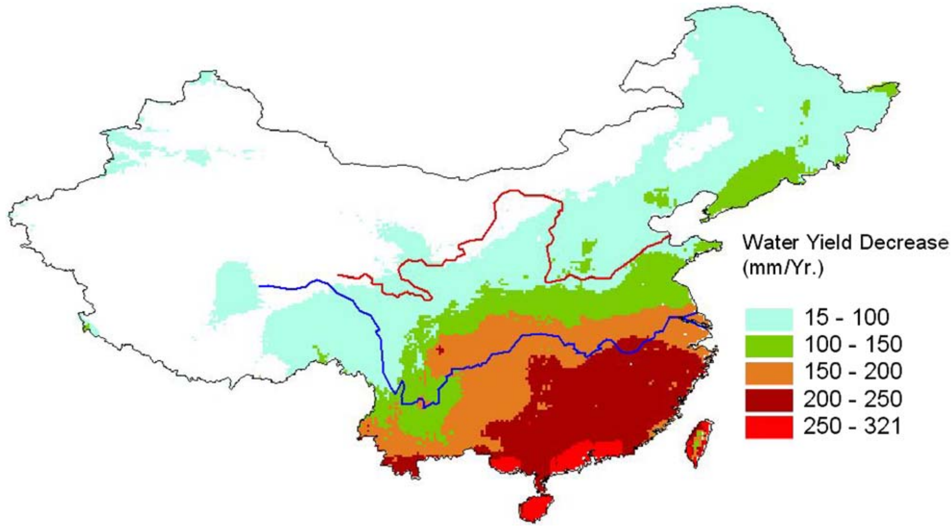

Figure 7 Predicted potential annual water yield reduction (mm/yr) due to converting grasslands to forest lands, showing a strong increasing gradient from the dry and cold northwest to the warm and wet southeast.

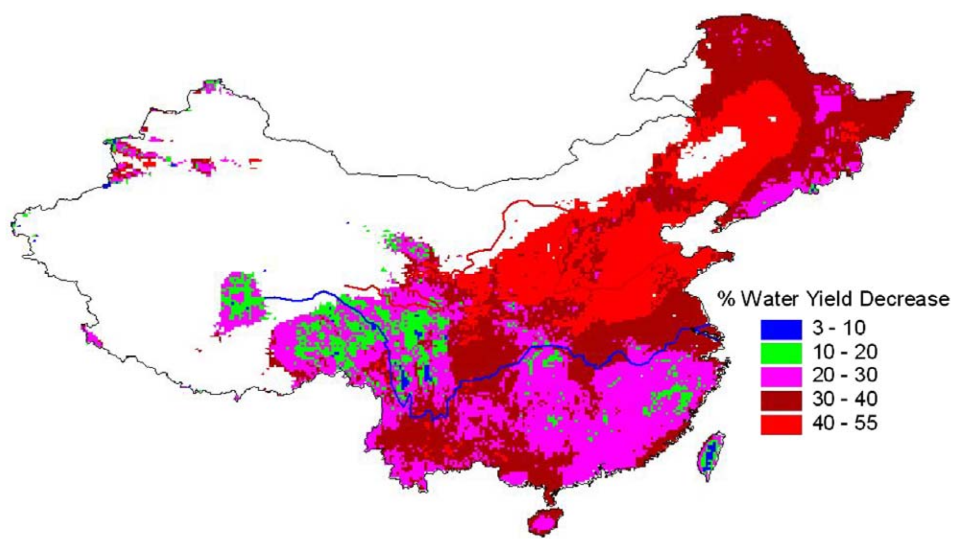

Figure 8 The potential water yield reduction as percentage of water yield of grasslands from forestation showing a strong decreasing gradient from the dry and cold northwest to the warm and wet southeast. Forestation in the Yellow River basins will have more pronounced impact than in the Yangtze River basins.

between 20% and 40% (Fig. 10). Severe water yield reductions of 40–50% may occur in about 23% of area subject to forestation. These values represent the potential spatial scale and magnitude of water yield impacts due to forestation, and they should not be intemperate as the reality since it is unlikely that the entire study area will be forested.

A conceptual model describing hydrologic recovery

To summarize our view points on the potential effects of forestation in China over time and space, we developed a simple conceptual model that may help to illustrate the combined watershed physical and biological controls on hydrologic responses (Fig. 11). In addition to climate as discussed in previous paragraphs, we also included the potential effects of two key factors: soil thickness and the recovery stage of the vegetation. As suggested by Andreassian (2004), we contend that soil thickness is an important watershed physical parameter that determines how soil water use by different vegetation covers will vary due to distinct plant rooting depths. We also hypothesize that it takes about 30–50 years for plantations to reestablish, mature, and fully function as natural forests in each of the five major regions. For example, compared to other regions, forestation in rainy, warm southern China will have the highest impact on water yield, and that these impact will occur most quickly. However, because the background water yield is generally large (runoff/precipitation ratio about 50%), the relative impact is expected to be lower than the dry, cool regions in Northern China, such as in the semi-arid Loess Plateau with deep soils, and low runoff amount and runoff/precipitation ratios (<15%). The hypothetical curves

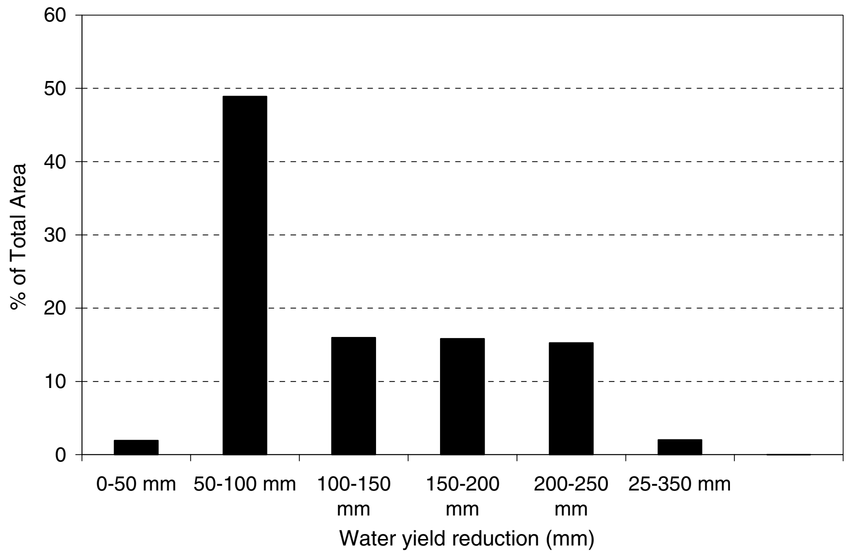

Figure 9 Frequency distribution of potential water yield reduction in the forestation region where average annual precipitation is above 400 mm/yr. Simulation results show that forestation would have 50—150 mm/yr water yield reduction across most of the study region.

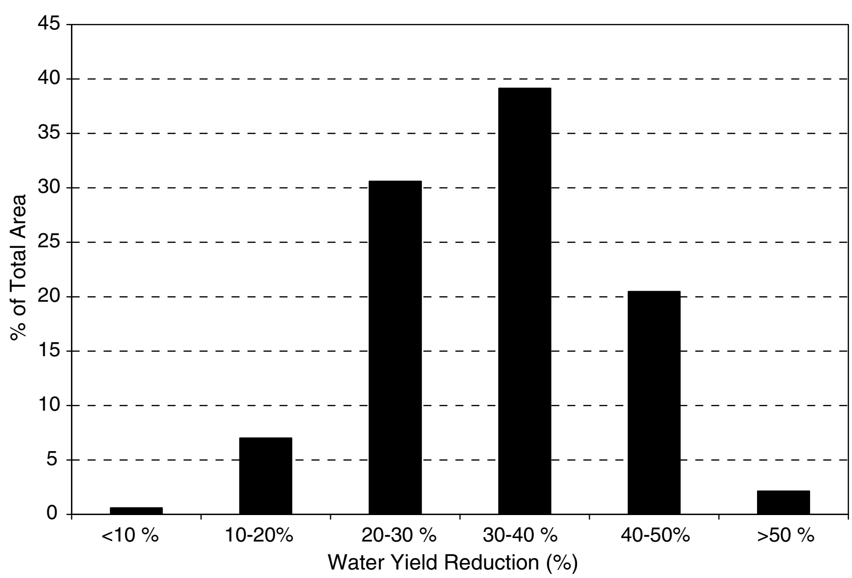

Figure 10 Frequency distribution of potential water yield reduction percentage in the forestation region where average annual precipitation is above 400 mm/yr. Simulation results show that forestation would have 20—40% water yield reduction across most of the study region.

presented in Fig. 11 should be quantified with empirical data and mathematical simulation models. For example, Scott et al. (2004) presented a set of similar hydrologic recovery curves with field data, suggesting a much faster recovery rate for water yield. They argued that maximum effects of vegetation reestablishment occurred in year 25—30 with declining tree vigor afterwards. However, Chen et al. (2004) found that an old growth Douglas-fir stand (age 450 years) in the pacific northwestern US transpired 12% and 70% more water than 40-year- and 20-year-old stands, respectively. The 40-year-old stand had the highest water use efficiency and had the largest net ecosystem exchange rate. We expect this critical threshold will vary across the complex and large physiographic regions in China.

Discussion

Massive forestation activities are expected in the next decades in China (Lei, 2002). Programs such as cropland conversion 'Grain for Green' that aims to increase forested areas by 440,000 km^2 or 5% of China's landmass in the next 10 years (Lei, 2002) have potential effects on watershed hydrology. These large scale vegetation-based watershed

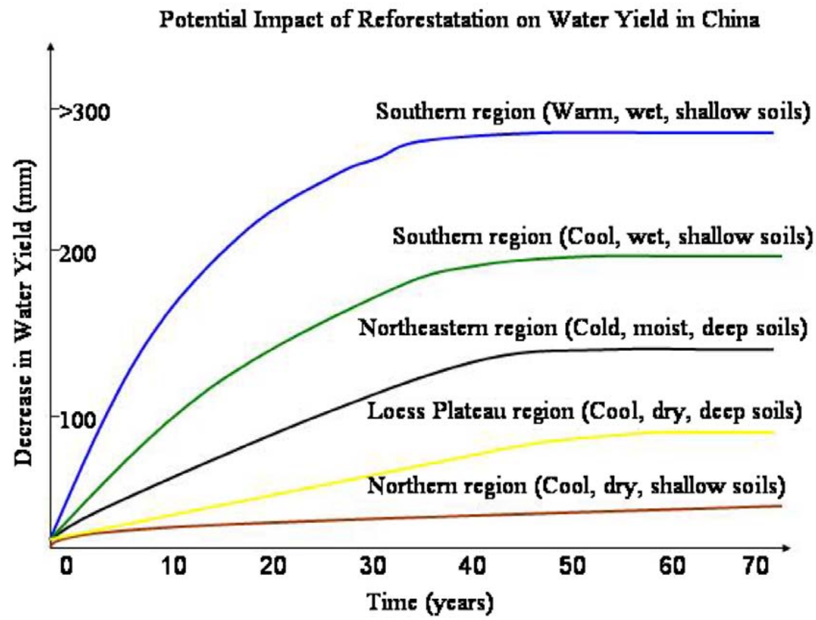

Figure 11 A conceptual model that illustrates the potential reduction in annual water yield due to forestation as a function of climate and soil characteristics over time across major geographic regions in China.

restoration efforts may have many implications to the water cycles and extreme hydrology such as droughts and floods (Robinson et al., 2003). However, the consequences are not well known in the academic community. Our current understanding of forest and water relations is largely based on small watershed experiments on deforestation, rather than on forestation (Hibbert, 1967; Bosch and Hewlett, 1982; Trimble et al., 1987; Whitehead and Robinson, 1993; Stednick, 1996; Vertessy et al., 2001; Andreassian, 2004; Bruijnzeel, 2004). Many practical questions, such as 'Can forestation alleviate flooding?', and 'Can forestation elevate base flow and spring recurrences?', are still open for debate (Burt and Swank, 2002; Andreassian, 2004).

Our modeling study did not address forestation effects on droughts, baseflow, or floods. We focused on testing the annual water yield sensitivity to climatic variability in response to forestation from grasslands across a large climatic gradient. The results clearly show that forestation practices may reduce water yield up to 50%, which is especially significant in the temperate zones of northern China. Andreassian (2004) suggests that the watershed water yield responses to deforestation (or forestation) are affected by pedological conditions (i.e., soil depth), climate (e.g., wet year vs. dry year; timing of precipitation), and plant physiologic characteristics (e.g., leaf area, sapwood area, succession stages). Therefore, our study further suggests that the Loess Plateau region of Northern China with deep loess soils (i.e., 10–100 m) will likely to have a large reduction of water yield from forestation. One should also expect soil and water conservation practices such as bioengineering techniques (e.g., 'fish scale pits') that are commonly used on eroded hillslopes to help seedling establishment during forestation will also increase surface roughness, reduce overland flow, increase soil water storage. These conditions will increase ET and reduce annual total water yield at the watershed-scale. Another emerging issue in Northern China is observed climate change (Liu and Fu, 1996). Increased potential evapotranspiration and reduction of precipitation will further aggravate the water yield reduction concerns in the region.

Our modeling study and discussion have focused on the long-term effect of forestation (assuming mature forests). However, it takes many years for forested land to develop into well-functioning forests in the temperate and boreal regions. On another hand, in the warm and humid regions, it often takes less than 5 years, for a deforested site to regenerate or plantation to fully recover in leaf area to its pre-disturbed conditions (Brown and Lugo, 1990; Gholz and Clark, 2002). Hydrologic response depends on the vegetation species, age, and climate, and plant physiological properties that affect evapotranspiration processes such as leaf area and hydraulic architecture (Bruijnzeel, 2004). We expect that a newly forested site will not have large changes in watershed hydrology in the short-term unless significant mechanical site preparation activities (i.e., terracing, plowing) have altered the soil hydrologic properties and infiltration capacity. This is especially true for degraded soils that have a history of chronic soil erosion and their soil depth and physical properties are difficult to recover. Bruijnzeel (2004) questioned the positive roles of low flow augmentation of newly established forests on lands with reduced soil water storage due to historical soil erosion problems in the southeastern Asia region. A recent review on the impacts of mechanical disturbance on soil properties suggests that natural soil recovery from compaction may take several decades (NCASI, 2004). A thorough discussion on the hydrologic effects of forestation on degraded lands in the tropics is found in Scott et al. (2004) and Bruijnzeel (2004).

Our discussion on forestation has been focused on the impact potential for basins subjected to complete cover change from bare lands or grasses/crops. This type of change is very unlikely to happen for large basins in China even under the current massive forestation campaign given the fact that large areas of croplands are needed to meet the food demands in the rural areas. Bosch and Hewlett (1982); Bruijnzeel (1996); Andreassian (2004), and Eq. (4) (this study) show that forestation effects on water yield closely correlate with the percentage of forested area over the entire watershed. For example, a 30% forestation in a grassed watershed will result in a decrease in water yield at a rate of 30% of that projected by Eq. (4). The theoretical projection represents the maximum potential water yield response for a full grass-to-forest conversion scenario. The water yield reduction is not imminent, and it takes years to reach the minimum potential for many regions. Therefore, we argue that forestation campaigns may have noticeable local effects on water yield reduction in watersheds with full land conversions, but regional impacts on large basin water resources are of less concern since the areas subject to forestation vary greatly as determined by eco-environmental conditions and socioeconomics (Sun et al., 2005b).

Conclusions

Watershed hydrologic effects of forestation have not been well studied in the international forest hydrology community as a whole. We hypothesized that the hydrologic recovery processes from forestation should be different from those of deforestation where most of the existing watershed experiments have been conducted. There is an urgent need to study the effects of forestation on watershed hydrologic processes to fully understand the magnitude of water quantity and quality responses at multiple spatial and temporal scales across China. Such eco-hydrological studies are essential to guide the recent massive forestation and ecological restoration campaigns.

Our modeling study suggested that forestation practices under the averaged historical climatic conditions of China would have the potential to reduce streamflow by 50–150 mm/yr or 20–40% across most of the nation. Problems associated with local water yield reduction due to large scale forestation can occur in Northern China, a temperate zone that has experienced global warming and other water shortage challenges in recent decades. Assessing long-term potential impacts on water resource availability is important for the success of forestation campaigns and vegetation-based watershed restoration in the region. Quantifying the hydrologic responses that should include not only total yield but also baseflow and stormflow components at the regional to continental scale remains challenging, and the models developed in this study need further validation and improvement.

Acknowledgments

We thank Dr. L.A. Bruijnzeel at Vrije University, the Netherlands for his insight and input that improved the earlier draft of this paper. This study was supported by the Southern Global Change Program, USDA Forest Service and a collaboration program with the Southern China Botany Garden, Chinese Academy of Sciences. Partial support was also from China Key Basic Research Program (973 Program) 'Influence and Control of Forest Vegetation Covers on Agricultural Ecological Environments in Western China' (2002CB111502).

References

Andreassian, V., 2004. Waters and forests: from historical controversy to scientific debate. Journal of Hydrology 291, 1–27.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55, 3–23.

Brown, S., Lugo, A.E., 1990. Tropical secondary forests. Journal of Tropical Ecology 6, 1–32.

Bruijnzeel, L.A., 1996. Predicting the hydrologic effects of land cover transformation in humid tropics: the need for integrated research. In: Gash, J.H., Nobre, C.A., Roberts, J.M., Victoria, R.L. (Eds.), Amazonian Deforestation and Climatem. Wiley, Chichester, pp. 15–55.

Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soils for the trees. Agriculture Ecosystems and Environment 104, 185–228.

Burt, T., Swank, W.T., 2002. Forest and floods? Geography Review 15, 37–41.

Chen, J., Paw U, K.T., Ustin, S., Suchanek, T., Bond, B.J., Brosofske, K.D., Falk, M., 2004. Net ecosystem exchanges of carbon, water, and energy in young and old-growth Douglas-Fir forests. Ecosystems 7 (5), 534–544.

Fang, J., Chen, A., Peng, C., Zhao, S., Ci, L., 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. Science 292, 2320–2322.

FAO, 2001. Global Forest Resources Assessment 2000 Main report. FAO Forestry Paper 140, Rome.

Federer, C.A., Lash, D., 1978. BROOK: a hydrologic simulation model for eastern forested. Research Report 19. Water Resources Research Center, University of New Hampshire, Durham, NH, pp. 84.

Federer, C.A., Vörösmarty, C., Fekete, B., 1996. Inter-comparison of methods for calculating potential evaporation in regional and global water balance models. Water Resources Research 32, 2315–2321.

In: Ffolliott, P., Guertin, D.P. (eds), 1987. Proceedings of a Workshop Forest Hydrologic Resources in China: an Analytical Assessment. Harbin, China, 18–23 August 1987, United States Man and Biosphere Program, pp. 143.

Gholz, H.L., Clark, K.L., 2002. Energy exchange across a chronosequence of slash pine forests in Florida. Agricultural and Forest Meteorology 112, 87–102.

Hibbert, A.R., 1967. Forest treatment effects on water yield. In: Sopper, W.E., Lull, H.W. (Eds.), Forest Hydrology, Proceedings of a National Science Foundation Advanced Science Seminar, Pergamon Press, Oxford, pp. 527–543.

Ice, G.G., Stednick, J.D., 2004. A Century of Forest and Wildland Watershed Lessons. Society of American Foresters, Bethesda, MD, pp. 287.

Jones, J.A., Grant, G.E., 1996. Peak flow response to clear-cutting and roads in small and large basin, western Cascade, Oregon. Water Resource Research 32 (4), 959–974.

Lei, J., 2002. China's Implementation of Six Key Forestry Programs. Available from: <http://www.newscientist.com/article.ns?id=dn2291>. Accessed January 10, 2005.

Li, W., 2001. A summary of perspective of forest vegetation impacts on water yield. Journal of Natural Resources 16, 398–405 (in Chinese).

Liu, C., 1986. Analysis of water balance and water resources in China. In: Proceedings of the Third Hydrological Session of the Geography Society of China. Science Press, pp. 113–118.

Liu, C., Fu, G., 1996. The impacts of climate warming on hydrological regimes in China: an overview. In: Jones, J.A.A. (Ed.), Regional Hydrological Response to Climate Change. Kluwer Academic Publishers, pp. 133—151.

Liu, C-M., Zhong, J., 1978. Effects of forests on annual streamflow in the Loess Plateau region. Acta Geographica Sinica 33, 112—126 (in Chinese).

Liu, S., Wen, Y., Wang, B., Zhou, G., 1996. Ecohydrologic Characteristics of Forest Ecosystems in China. China Forestry Publication House, Beijing, pp. 346 (in Chinese).

Loveland, T.R., Reed, B.C., Brown, J.F., Ohlen, D.O., Zhu, J., Yang, L., Merchant, J.W., 2000. Development of a global land cover characteristics database and IGBP DISCover from 1-km AVHRR data. International Journal of Remote Sensing 21, 1303—1330.

Lu, J., Sun, G., Amatya, D.M., McNulty, S.G., 2005. A Comparison of six potential evapotranspiration methods for regional use in the southeastern United States. Journal of American Water Resources Association 41, 621—633.

Ma, X., 1987. Hydrologic processes of a conifer forest in the subalpine region in Sichuan, China. Scientia Silvae Sinicae 23, 253—265 (in Chinese).

Ma, X., 1993. Forest Hydrology. China Forestry Publication House, Beijing, pp. 398 (in Chinese).

NCASI, 2004. Effects of heavy equipment on physical properties of soils and long-term productivity: a review of literature and current research. Technical Bulletin No. 887. Research Triangle Park, N.C.: National Council for Air and Stream Improvement, Inc.

Ni, J., Sykes, M.T., Prentice, I.C., Carmer, W., 2000. Modeling the vegetation of China using the process-based equilibrium terrestrial biosphere model BIOME3. Global Ecology and Biogeography 9, 463—479.

Robinson, M., Cognard-Plancq, A.L., Cosandey, C., David, J., Durand, P., Fuhrer, H.-W., Hall, R., Hendriques, M.O., Marc, V., McCarthy, R., McDonnell, M., Martin, C., Nisbet, T., O'Dea, P., Rodgers, M., Zollner, 2003. Studies of the impact of forests on peak flows and baseflows: a European perspective. Forest Ecology and Management 186, 85—97.

Scott, D.F., Le Maitre, D.C., Fairbanks, D.H.K., 1998. Forestry and streamflow reductions in South Africa: a reference system for assessing extent and distribution. Water SA 24, 187—199.

Scott, D.F., Bruijnzeel, L.A., Mackensen, J., 2004. The hydrologic and soil impacts of forestation. In: Bonell, M., Bruijnzeel, L.A. (Eds.), Forests, Water and People in the Humid Tropics. Cambridge University Press, Cambridge, pp. 622—651.

Stednick, J.D., 1996. Monitoring the effects of timber harvest on annual water yield. Journal of Hydrology 176, 79—95.

Sun, G., McNulty, S.G., Moore, J., Bunch, C., Ni, J., 2002. Potential impacts of climate change on rainfall erosivity and water availability in China in the next 100 years. In: Proceedings of the Twelfth International Soil Conservation Conference. Beijing, China, May 2002.

Sun, G., McNulty, S.G., Lu, J., Amatya, D.M., Liang, Y., Kolka, R.K., 2005a. Regional annual water yield from forest lands and its response to potential deforestation across the southeastern United States. Journal of Hydrology 308, 258—268.

Sun, G., McNulty, S.G., Cohen, E., Moore-Myers, J., Wear, D., 2005b. Modeling the impacts of climate change, landuse change, and human population dynamics on water availability and demands in the Southeastern US ASAE Paper No. 052219. St. Joseph, Mich.: ASAE.

Thomas, R.B., Megahan, W.F., 1998. Peak flow response to clear-cutting and roads in small and large basin, western Cascade, Oregon: a second opinion. Water Resources Research 34 (12), 3393—3403.

Trimble, S.W., Weirich, F.H., Hoag, B.L., 1987. Forestation and reduction of water yield on the southeastern Piedmont since circa 1940. Water Resources research 23, 425—437.

Vertessy, R.A., Watson, F.G.R., O'Sullivan, S.K., 2001. Factors determining relations between stand age and catchment water balance in mountain ash forests. Forest Ecology and Management 143, 13—26.

Wei, X., Zhou, X., Wang, C., 2003. The influence of mountain temperate forest on the hydrology in northern China. The Forestry Chronicle 79, 297—300.

Wei, X., Liu, S., Zhou, G.-Y., Wang, C., 2005. Hydrological processes of key Chinese forests. Hydrological Process 19 (1), 63—75.

Whitehead, P.G., Robinson, M., 1993. Experimental basin studies-an international and historical perspective of forest impacts. Journal of Hydrology 145, 217—230.

Yu, X., 1991. Forest hydrologic research in China. Journal of Hydrology 122, 23—31.

Zhang, L., Dawes, W.R., Walker, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research 37, 701—708.

Zhou, X., Zhao, H., Sun, H., 2001. Proper assessment of the hydrologic effects of forests. Natural Resources 16 (5), 420—426 (in Chinese).

Zhou, G.-Y., Morris, J.D., Yan, J.H., Yu, Z.Y., Peng, S.L., 2002. Hydrological impacts of forestation with eucalyptus and indigenous species: a case study in southern China. Forest Ecology and Management 167, 209—222.

Zhou, G.-Y., Yin, G., Morris, J., Bai, J., Chen, S., Chu, G., Zhang, N., 2004. Measured sap flow and estimated evapotranspiration of tropical *Eucalyptus urophylla* plantations in China. Acta Botanica Sinica 46, 202—210 (in Chinese).