JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 44, No. 5 AMERICAN WATER RESOURCES ASSOCIATION October 2008

# THE FOREST-STREAMFLOW RELATIONSHIP IN CHINA: A 40-YEAR RETROSPECT[1]

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ABSTRACT: The relationship between forests and streamflows has long been an important research interest in China. The purpose of this paper is to summarize progress and lessons learned from the forest-streamflow studies over the past four decades in China. To better measure the research gaps between China and other parts of the world, a brief global review on the findings from paired watershed studies over the past 100 years was also provided. In China, forest management shifted in the later 1990s from timber harvesting to forest restoration. Forest-streamflow research was accordingly changed from assessing harvesting impacts to evaluating both harvesting and forestation effects. Over the past four decades, Chinese forest hydrology research has grown substantially. Significant progress has been made on measuring individual processes, but little solid, long-term data were available to assess the relationship between forest changes and streamflows because of an absence of standard paired watersheds. In addition, misuse of statistical analyses was often found in the literature. A unique opportunity exists in China to study the forestation effects on streamflow as several large-scale forestation programs are being implemented. Such an opportunity should include a robust paired watershed design under an integrated watershed ecosystem framework to avoid repeating the lessons already learned. Recommendations on future forest-streamflow research directions in China are provided.

(KEY TERMS: forestation; harvesting; streamflow; hydrology; paired watersheds; China.)

Wei, Xiaohua, Ge Sun, Shirong Liu, Hong Jiang, Guoyi Zhou, and Limin Dai, 2008. The Forest-Streamflow Relationship in China: A 40-Year Retrospect. *Journal of the American Water Resources Association* (JAWRA) 44(5):1076-1085. DOI: 10.1111/j.1752-1688.2008.00237.x

## INTRODUCTION

Since the founding of the Peoples Republic of China in 1949, forestry practices have gone through significant changes. Different management objectives during this period can be distinguished by their effects on the resources: damage, development, and rehabilitation. Three distinct phases or periods are recognized (Forestry Strategic Research Group of China Sustainable Development, 2002). Phase 1 (from the 1950s to the end of the 1970s) was characterized by timber utilization and resultant deforestation. Phase 2 (from the end of the 1970s to the late 1990s)

[1]Paper No. JAWRA-07-0094-P of the *Journal of the American Water Resources Association* (JAWRA). Received July 26, 2007; accepted January 2, 2008.  **Discussions are open until April 1, 2009**.

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placed equal emphasis on both timber production and ecological improvement. The ecological improvement was mainly an implementation of the large-scale Three-North Shelterbelt Development Program. Phase 3 (from the late 1990s to the present) was characterized by an implementation of sustainable forest management principles and strategies to protect and restore various ecological functions. Although promotion of ecological, economic, and social development is a general guide, more emphasis has been placed on forest restoration and protection. As a result, several more large-scale forestation programs were initiated in the late 1990s.

The large-scale flood occurring in the Yangtze River basin in 1998 was perhaps the most important turning point between Phases 2 and 3. The flood killed more than 2,000 people and caused direct loss of more than U.S. $20 billion) (Yin and Li, 2001). The tragedy acted as a wake-up call to China to recognize the importance of forest protection. Since then, China has initiated a series of large-scale forest protection and reforestation programs. For example, forest harvesting was banned starting in 1998 in the upper reaches of the Yangtze River and Yellow River basins; a program called "Sloping Land Conversion" or "Grain for Green" was launched in 1999 to return cultivated land with slopes of 25° or more to perennial vegetation (the target of this conversion is 32 million ha by 2010); and the large-scale Natural Forest Protection Program has also been implemented since 1998 (with full implementation in 2000) to protect or restore natural forest ecosystems. Implementation of these large-scale forest restoration programs has generated a growth in forest resources in China. Forest cover rates were changed from 16.00% in the 1980s to 18.21% in 2006 (State Forestry Administration, 2006).

Interestingly, Chinese forest hydrology research has also gone through significant changes along with forest resource management. Significant deforestation as a result of "big leap forward" fever in the 1960s, increasing demands on timber and conversion of forest lands to agriculture and other uses, caused many environmental problems such as widespread soil erosion and loss of fertility and biodiversity. In the early 1980s this resulted in a nationwide debate over the relationship between forests and water resources (Huang, 1981, 1982; Zhou *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, argued that forests had only a limited effect on water budgets and flood control. The debate was fruitless because there was no convincing field data from research on forest hydrology in China, and was criticized as "fighting civil war with foreign weapons" (Zhou *et al.*, 1994). However, the debate did help launch an important forest research program. About 20 long-term forest 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 focused on structures and functions of vegetation types and their role in watershed processes. Forest hydrology has been one of the key research areas in those ecological stations.

With the launching of several large-scale reforestation programs in the late 1990s, Chinese forest hydrology research shifted emphasis from harvesting impact assessments to including both harvesting and forestation hydrology. Numerous research projects are now targeting the effects of reforestation strategies on hydrological processes and water resources as many regions in China are short of water. Concern has been expressed over possible reduction in available water as a result of large-scale reforestation activities in relatively dry regions (Sun *et al.*, 2006; Wei *et al.*, 2005a; Zhang *et al.,* this issue).

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 both environmental protection, and social and economic development (State Forestry Administration, 2004). Whether the focus was on extraction in Phases 1 and 2 or reforestation in Phase 3, the essence is the same: the relationship between forest changes and water. In this paper, reforestation (forest regenerations from original forest land) and afforestation (forest establishment on non-forest land) practices are generally referred to forestation as a concise term for communication purposes.

The objectives of this paper were: (1) to briefly summarize key findings from forest-streamflow research conducted around the world in the past 100 years, and the studies in China in the past 40 years; (2) to summarize key lessons learned in China; and (3) to offer recommendations for future research directions.

## KEY RESULTS OF GLOBAL LONG-TERM PAIRED WATERSHED STUDIES

A brief summary on what we have learned in the past 100 years in the world is useful for two counts. First, abundant forest types in China indicate that the results from the forest-streamflow studies in different world forest ecosystems may potentially be applied to the similar forests in China, and vice versa. Second, the review can help measure the gaps in forest-streamflow research between China and outside of China. However, conducting such a review is a daunting task because it involves comparisons of research methods, spatial and temporal scales, forest types and hydrological variables, and many other related factors. Here, we only drew the key findings from the paired watershed studies mainly from outside of China (i.e., North American and Europe) as they provided the most reliable results in quantifying the relationship between forests and streamflow. We summarized the results on both harvesting (deforestation) hydrology and forestation hydrology.

### *Harvesting Impacts*

Since the first paired watersheds were established in 1910 at the Wagon Wheel Gap in the USA, this design has gained popularity in forest hydrology research in many countries. Various reviews have summarized what we have learned. For examples, Hibbert (1967) reviewed 39 paired watersheds from various countries, while Bosch and Hewlett (1982) summarized the results from 94 paired watersheds. A recent review by Andreassian (2004) used data from 137 paired watersheds. Other review papers by MacDonald and Stednick (2003), Bruijnzeel (2004), Calder (2004, 2007), and Hubbart *et al.* (2007) were also the sources of this summary.

**Effects on Annual Water Yield.** Forest harvesting increased annual water yield, but the magnitude of the increase depended on various factors such as types of forests, watershed characteristics, and dominant hydrological processes (snow *vs.* rain). An exception to this was where fogs intercepted by the forest canopy constituted a significant portion of total precipitation. Forest harvesting could reduce this "fog drip" precipitation and consequently decrease water yield.

**Effects on Peak Flows.** Forest harvesting generally increased peak flows, but such increases largely depended on the definition of peak flows. In general, harvesting had large impacts on small peak flows (or peak flows with high exceedence probability), while its impact on large peak flows (or peak flows with low exceedence probability) were limited. Although not common, some research showed opposite results. For example, Austin (1999) reviewed 82 peak flow related reports, and in five of them harvesting decreased peak flows. Long-term research on the Upper Penticton watershed in British Columbia, Canada showed that forest harvesting in lower elevations in the watershed can have desynchronization effects on streamflow and consequently lead to reduction of peak flows in this watershed dominated by snowmelt events (Dr. Rita Winkler, Ministry of Forests and Range, British Columbia, Canada, August 10, 2007, personal communication). In short, forest harvesting generally increased peak flows, particularly small ones, but there were large variations in peak flow responses. This is mainly due to the very short time duration definition (seconds or minutes) for peak flows compared with that for mean flows (annual or seasonal). When the time duration is so short, the effects of many variables are pronounced and consequently can lead to large response variations.

**Effects on Low Flows.** Low flow is often called base flow, loosely defined as the streamflow out of an area that is derived from ground water in and streamflow into the area during time periods without precipitation. Almost all paired watershed studies showed that forest harvesting increased low flows, and replanting or planting trees where previously there were none, decreased low flows. There were exceptions. For example, in "foggy" forests located in Oregon, forest harvesting decreased low flows as a result of losses of drips of fog condensate from the trees (Harr, 1982; Ingwersen, 1985). Bruijnzeel (2004) indicated that when forest harvesting severely altered soil and organic layer conditions in some tropical forests, removal of vegetation can lead to reduction in low flows because of less ground-water recharging from rain. It is commonly accepted that the relationship between forest harvesting or reforestation and low flows is related not only to vegetation change, but also to alteration of soil conditions. Unfortunately, most paired watershed studies did rarely include soil in the evaluation of the relationship between vegetation changes and streamflow, so their results may not be applicable to where both soil and vegetation are severely disturbed.

### *Forestation Impacts*

The traditional "paired watershed" approach to examining forest-water relations has been widely used in studying the immediate effects of deforestation and hydrologic recovery after harvesting. Few studies have examined the effects of forestation (Andreassian, 2004; Farley *et al.*, 2005). Understanding the effects of forestation is critical to balance the many ecosystem services (i.e., timber production, carbon sequestration, soil erosion control, and water quantity and quality) that forest lands provide us (Jackson *et al.*, 2005).

**Effects on Annual Water Yield.** In general, forestation practices caused decreases in annual water yield due to increases in evapotranspiration. For example, across the 26 catchment datasets and 504 observations used in Farley *et al.* (2005) global analysis, annual water yield was reduced by 44 and 31% when grasslands and shrublands, respectively, were afforested.

The magnitude of effects of forestation in reducing annual water yield varied as a function of vegetation, climate, soil, and management practices. Fast growing plantations that use more water have higher impacts. For example, Eucalypt plantations reduced water yield by 75% when planted in grasslands whereas Pine reduced it by only 40% (Farley *et al.*, 2005). Forestation practices reduced absolute water yield amount most at wetter sites, but the relative reduction was highest at drier sites (Farley *et al.*, 2005). Several field and modeling studies in the southern U.S. have clearly shown that the forest impact on water was most pronounced during dry periods when trees can use deeper soil water (Trimble and Weirich, 1987; Sun *et al.*, 1998). Andreassian (2004) argued that if the soils are shallow, trees, and grasses have limited differences in transpiration, and the impact of land conversion would be limited mainly to their different canopy interception and soil evaporation rates. Conversely, deep soils allow deep-rooted trees to remove soil water in deeper layers that cannot be reached by shallow-rooted grasses.

**Effects on Peak Flows.** Limited studies on reforestation suggest revegetation has minimal effect on floods, and none on large ones (McGuinnes and Harrold, 1971) because the storage capacity of forests are filled during large storm events and there will be little differences between a forest and other land use (Scott *et al.*, 2004; Eisenbies *et al.*, 2007). Scott *et al.* (2004) suggest that reforestation has large potential to improve soil water storage capacity for watersheds with deep soils by increasing infiltration rates, reducing soil erosion, and increasing in evapotranspiration. It seems unlikely that forestation on degraded lands will affect large peak flows until soil properties improve. However, revegetation may alter the watershed water balances, and any engineering used in forestation practices may help to reduce peak flows. More research is needed to test this hypothesis.

**Effects on Low Flows.** Most literature suggested that the effects of forestation on annual flow are largely on low flow since this is an important component of annual water yield for most forested watersheds. By citing published literature in the United Kingdom and United States (McGuinnes and Harrold, 1971; Johnson, 1998) and South Africa (Scott *et al.*, 1998), Andreassian (2004) concluded with high confidence that forestation generally decreased low flow.

In many parts of the world, there is a perception that a benefit of reforestation on degraded lands is a recurrence of natural springs. We argue that springs may return with an increase of soil infiltration when overland flow is reduced and subsurface flow increased. Engineering methods such as terracing might play a bigger role than vegetation cover in this regard. Bruijnzeel (2004) and Scott *et al.* (1998, 2004) suggested that the potential to increase low or base flow was very limited by forestation since an increase in infiltration might balance the increase in water loss through evapotranspiration.

**Caveats to the General Conclusions.** Effects of forestation on streamflows are not stationary. They change over time with the changes of watershed conditions as the plant ecosystem structure changes (Vertessy *et al.*, 2001). Sun *et al.* (2006) argued that it can take a long time for the effects of forestation to reveal themselves in northern China. A conceptual model suggested that for plantations in southern China, changes occurred rather quickly initially but slowed as the plantations approached maturity. Furthermore, Australian scientists have documented that as eucalyptus plantations aged, their capacity to reduce runoff decreased, allowing streamflow to recover. Forest management options such as thinning might accelerate the recovery processes (Vertessy *et al.*, 2001; Andreassian, 2004).

## PROGRESS MADE DURING THE PAST 40 YEARS IN CHINA?

The severe soil erosion problems caused by deforestation in many parts of China have drawn significant attention to forest hydrology research in the past four decades. Although research on forest hydrology could have been more extensively referenced during this period, forest hydrology-related publications have grown significantly. Figure 1 shows how the related research literature has grown substantially since the early 1980s, the time of the "widespread debate on forests and water in China." A large portion of these publications were from research conducted in the 20 forest ecological stations across various forest types. The following two sections summarize what we have learned from both harvesting and forestation hydrological studies in China.

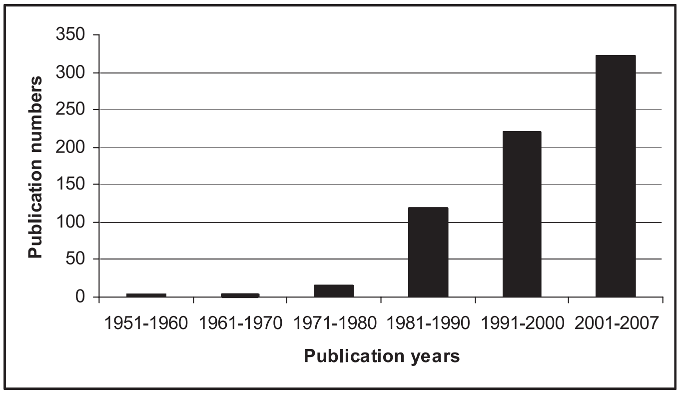


FIGURE 1. Numbers of Publications on Chinese Forest Hydrology Over the Last Five Decades (it was based on literature searching in the "China journal database").

*Harvesting Hydrology*

Various topics including forest canopy interception, stemflow, throughfall, evapotranspiration, water balance, etc. have been studied. Several reviews in Chinese summarize the research findings (Zhang and Yu, 1988; Zhou *et al.*, 1994; Liu *et al.*, 1996, 2003; Zhang, 2001; Zhang *et al.*, 2004). A recent synthesis was provided by Wei *et al.* (2005a), based on the results from seven selected forest ecological stations. The relationship between forest changes and streamflow in China were also discussed by Li *et al.* (2001), Zhou *et al.* (2001), Chen and Li (2001), and Wei *et al.* (2003, 2005b).

**Harvesting and Annual Water Yield.** Forest harvesting increased annual water yield. This result is consistent with the general conclusion of the global paired watershed studies discussed previously. However, there were a few studies indicating opposite results. For example, the studies from the Shichuan Miyaluo ecological station, located in the upper reaches of the Yangtze River, indicated that harvesting tended to reduce water yield (Ma, 1987). A careful examination of the paired watersheds indicated that these were not true paired watersheds. No calibration period was applied and the control site was a shrub catchment area where logging took place 4-12 years ago. Therefore, the result from this study is unlikely to reflect the harvesting effects on annual water yield because the control was not a comparable unlogged area. Another example is the study from Cao *et al.* (1991) who analyzed the relationship between forest vegetation cover and streamflow based on data from the 30 large-sized watersheds (from 100 to 177,000 $km^2$) in the Songhuajiang Basin, Northeast China. They concluded that there was a significant positive relationship between forest cover and streamflow and that annual water yield increased 1.46 mm with every 1% increase in forest cover. However, there is a question as to whether the streamflow data were naturalized before their use for regression analysis. When rivers are regulated by reservoirs or water is withdrawn for irrigation and other uses, streamflow data must be naturalized prior to data analysis to account for those water reductions. Thus, further checking and perhaps reanalysis may be needed before the conclusions are acceptable. In short, forest-streamflow research in China clearly showed harvesting increased streamflow. A few exceptions to this conclusion existed, but those exceptions are questionable, requiring further examinations.

**Harvesting and Peak Flows.** Many studies in China have had the goal of demonstrating that forests could reduce floods by reducing overland flow and increasing ground-water flow. The research to date all shows that forest harvesting can increase peak flows as well as overland flows. Interestingly, there has been no exception to this conclusion to date. However, no differentiation was made to separate the relative role of peak flows at different return intervals (e.g., small *vs.* large peak flow events). Such absence of differentiation may generate misleading conclusions.

**Harvesting and Low Flows.** Because well forested watersheds generally have clear and continuous flows, the perceptions that forests can provide more base flow and offer more natural springs are prevalent in China. Unfortunately, the studies on forest-low flow relations were much less focused when compared with annual and peak flows. The effects of harvesting on low flows have varied: some studies showed reductions in low flows after harvesting (Ma, 1987) while others suggested increases in low flows (Zhou *et al.*, 2001). Very few studies applied solid statistical tests to assess the relationship between low flow responses and forest harvesting. A commonly used approach was to compare the differences in low flows (mm) between watersheds with dense and sparse forest cover. Such an approach is not reliable as it cannot exclude other possible confounding variables such as watershed topography, geology, and climate. Therefore, limited researches have been conducted in China. Because of the inappropriate methods applied, the results of research on forest changes and low flows may not be reliable.

*Forestation Hydrology*

With several large-scale reforestation programs in place, forestation hydrology has been an important research focus in the last 5-10 years. Unfortunately, no paired watersheds were used for this specific purpose, and consequently, no conclusions or published results on the forestation-streamflow relationship were obtained from the experimental studies. Plantation of Eucalypts significantly reduced streamflow in Southern China (Zhou *et al.*, 2002). Based on continental scale simulations with a generalized evapotranspiration model, Sun *et al.* (2006) concluded that 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.

Methods used in forestation practices also affected the magnitude of runoff reduction. Soil conservation practices such as terracing, farm ponds, check dams, and other bioengineering methods associated with forestation in the Loess Plateau region contributed to the decrease in streamflow (Huang and Zhang, 2004), and the periodic drying up of the lower reaches of the Yellow River (McVicar *et al.*, 2007a).

In spite of the lack of published results from paired watershed studies, several on-going research efforts on reforestation hydrology are worth mentioning. The Chinese Academy of Forestry in Beijing is conducting a large forest hydrology research program in the Minjiang river basin in the upper reaches of the Yangtze River (Sun and Liu, 2003; Liu and Sun, 2005; Li *et al.*, 2006; Zhang *et al.*, 2006). Among various topics, a project to compare the differences in hydrological effects among forest types, crops, and other land uses is being conducted. The results from this project will be used to assess the impacts of the "Sloping Land Conversion Program" on hydrology as well as on other ecological matters of interest (Zhang *et al.*, 2006 and this issue). Another large project to examine the impacts of reforestation programs on hydrology is also being conducted by the Chinese Academy of Forestry and other research institutes. A decision support tool for China's revegetation program "ReVegIH" has been developed by McVicar *et al.* (2007b). Such a tool can be useful for evaluating the impacts of forestation on average annual streamflow. A simulation approach to examine the possible tradeoffs of reforestation programs between water and carbon is being conducted at Nanjing University.

## LESSONS LEARNED DURING THE PAST 40 YEARS IN CHINA

Although significant progress has been made in understanding forest-water relations, particularly for forest interception, stemflow, evapotranspiration, etc. (Liu *et al.*, 1996, 2003; Wei *et al.*, 2005b), little solid, long-term scientific data are available after 40 years of studies in China. The most important barrier to progress has been the lack of standard paired watershed experiments, although other problems (i.e., lack of sufficient research funding, stable research policies, the complex nature of the forest-water relations, etc.), have also impeded progress. It is widely accepted that the paired watershed approach is the most reliable technique for assessing the relationship between forest change and streamflow in relatively small-scale watersheds. Many robust results on forest-streamflow relationship in the world have been obtained from the paired watershed studies, but few have been established in China. Some existing experimental watersheds were "paired," but no calibrations were applied. Some analyses were even based on a single watershed by using the before-after approach. These nonstandard paired watershed designs and analyses are unlikely to provide reliable results.

In the absence of paired watershed experiments, some researchers applied alternative analytical methods to assess the relations between forest changes and streamflow. Unfortunately, some of the methods used were not appropriate which makes their conclusions questionable. We sampled at random 20 Chinese papers published in the 1980s and 1990s on forest-water relations. Fifteen either did not use a robust statistical analysis or standard paired watersheds. For example, one commonly used method was to compare the difference in streamflow (in mm, over the watershed area) between two or more watersheds with different forest covers in a similar climate region, and then to use the differences to infer the effects of forest changes on streamflow. If the watershed with higher forest cover had greater (or less) streamflow, the conclusions were that forests increased (or decreased) streamflow. Although this method is quick and can be easily performed, it may not show or isolate the effects of vegetation changes because of confounding factors, such as climatic difference and the different geology. Another common example was to analyze raw streamflow data without considering river regulations (reservoirs, dams, etc.), water withdrawal, and other water uses. For any statistical tests, streamflow data must be naturalized first to account for other water uses. This issue was discussed earlier with the example from Cao *et al.* (1991). Inappropriate application of analytical methods could lead to incorrect conclusions. If the debate in the 1980s was criticized as "fighting with foreign weapons," the current debate might be called "fighting with the wrong weapons."

Due to limited research capacity, process-based watershed-scale studies are rare in China. Individual process data often gave an incomplete picture of the role of forests on streamflow. For example, the findings that forest lands often showed low overland flow, high soil infiltration rates, high rainfall interception rates, and high transpiration could be interpreted in more than one way. One may conclude that forests increased base flow because the trees helped to increase infiltration. Others may conclude that forests used more water, thus reducing base flow. Without a watershed ecosystem research approach that includes more components such as soil, vegetation, study scale, etc., the role of forest vegetation in regulating hydrological processes cannot be fully understood.

Snow hydrology is an important part of the hydrological process or water balance in northern China. However, snow hydrology was largely ignored. Without data on snow accumulation, snow interception, snowmelting processes, evapotranspiration in the winter seasons, etc., it is impossible to completely understand the streamflow and its responses to forest changes during the snow accumulation and melting period as well as on an annual basis.

## FUTURE FOREST HYDROLOGY RESEARCH IN CHINA

Soil erosion and water shortages are the most pressing environmental and resource issues that will hinder China's sustainable development in the 21st Century. The current large-scale intensive reforestation campaigns in China will no doubt have a positive impact on the ecological environment and human life by improving many of the forest functions (e.g., reducing soil erosion and increasing carbon sequestration) and service values (e.g., providing clean water). However, such a costly effort must be conducted with a scientific understanding of ecosystem restoration principles; otherwise the desired benefits cannot be achieved.

Scientific knowledge on the complex forest-water relationship has significant implications for land managers and policy makers. Forest hydrologic research and watershed science in China is still at an early stage, but lessons learned in the past century elsewhere can be adopted. Based on the science and societal needs identified above and the research capacity in China, we think the following issues should receive special attention by the forest hydrology community:

### *Forestation Hydrology*

The hydrologic effects of reforestation in watersheds are not adequately addressed although a massive replanting effort is being made throughout China. We hypothesize that the hydrologic recovery processes after reforestation will not be the simple reversal of that of deforestation. There is an urgent need to document the effects of reforestation on watershed hydrologic processes at multiple spatial and temporal scales. Clearly, an excellent research opportunity exists in China to take various approaches, one of which would be paired watersheds to study the effects of forestation on hydrology as part of the several large-scale reforestation programs presently under way.

To reverse the degradation of the environment, many countries or regions are implementing reforestation programs. The incentives for growing more trees have increased as many countries try to use forestation programs to build more carbon credits and bio-energy resources. However, increasing forestation programs may lead to water shortages in some semiarid and arid regions. Including hydrological studies in these programs will greatly help tradeoff analysis between benefits and costs of forestation.

### *Wide Application of the Standard Paired Watershed Experiments*

The paired watershed approach should be widely adopted in forest hydrology research. As China has many different forest ecosystems, we suggest that paired watershed experiments should be carefully designed and established in the major types of forests for evaluation of both harvesting and forestation effects. The existing ecological networks in China such as Chinese Ecosystem Research Network and Chinese Forest Ecosystem Research Network have already provided a basic platform for executing such an initiative, but the paired watershed experiments require stable funding support and long-term commitment.

Recent on-going studies conducted in China by eddy covariance and other integrated methodology to quantify forest ecosystem evapotranspiration can be used to validate water balance established by paired watershed experiments. Consequently, they might be great help to answer forest-streamflow relationship in China. From this perspective, it is desirable to link the evapotranspiration studies with paired watershed experiments. This is especially important given many watersheds in China are under the influences of both dramatic vegetation changes and climate warms. A recent long-term streamflow analysis for a humid subtropical watershed in southern China suggested that watershed-scale evapotranspiration might have increased as the vegetation recovered from degraded forests to fast growing shrublands under a warming climate (Sun *et al.*, this issue).

*Large-Scale Forest Hydrology*

The small scale (10 km$^2$) paired watershed experiments have limitations in answering large-scale questions. As the size of a watershed increases, the hydrological processes become more complex because of the inclusion of more landforms (wetlands, ponds, lakes, etc.) and land uses (agriculture, urban areas, mining, etc.). This implies that the results from small paired watersheds may not be applicable to large-scale watersheds (>1,000 km$^2$). However, many important hydrological issues such as urban floods, navigation, and sedimentation occur at large watershed scales. This highlights an important need to conduct large-scale forest hydrology. Because of difficulties in applying the paired watershed approach at these larger scales, researchers have to explore other alternative methods such as long-term monitoring, statistical analysis, and modeling techniques to study large-scale forest hydrology (Miao and Carstenn, 2006). To date, less than 20 scientific papers on large-scale forest hydrology have been published, and only a couple of retrospective studies could link forest and watershed hydrology at a basin scale (Siriwardena *et al.*, 2006).

To monitor hydrologic changes in large basins after reforestation or other land use changes, we need networks of weather stations plus vegetation monitoring schemes using remote sensing to be conducted concurrently. Distributed hydrologic simulation models should be developed to simulate the hydrologic processes and describe the interactions of water movement in the atmosphere and on the ground at a meso-scale (>1,000 km$^2$). Such an effort requires the close collaboration of multiple disciplines including climate change research and also needs a long-term commitment.

*A Holistic and Process-Based Approach on Forest Hydrology*

The paired watershed studies rarely consider ground-water processes, soils, and details of forest disturbance (road construction, forest regrowth rates, site preparation, and harvesting locations in the watersheds) when evaluating the relation between vegetation change and streamflow. The complex interactions of the components clearly indicate that a holistic approach is needed to study the relations between forest vegetation changes and streamflow. DeWalle (2003) suggested that a reanalysis of existing watershed management data on a more holistic basis is needed for a wide range of conditions throughout the world, possibly leading to a more thorough program of process studies and watershed comparisons.

An example of this holistic approach is to consider surface water and ground-water integration in the watershed forest hydrology study. In the past, the paired watershed methods normally have assumed that soil water storage remains the same during the study period. This assumption may not hold true for some situations where there are active surface water and ground-water interactions within the study watershed and where soil properties are greatly altered by harvesting or planting trees. In those situations, ignoring ground-water recharging and discharging may introduce unacceptable errors in water budgets. Future paired watershed studies should explicitly consider vegetation change, soil property changes, snow hydrological processes, and geology to construct a complete water budget including both surface water and ground water so that the relation between vegetation changes and streamflow can be fully evaluated. Such a broader context is useful for a better understanding of the variations in the general vegetation-streamflow relations.

To take a holistic approach to forest hydrology, traditional paired watershed methods need to be combined with other techniques such as isotope tracing, hydrological simulation, etc. The integration of various research methods or disciplines may be the only way to fully evaluate the interaction of watershed processes.

*Long-Term Commitment and Data Quality Control*

We stress the importance of basic long-term forest ecosystem research such as water balances and forest water use of major plant species for reforestation at several scales. The major gap between China's forest hydrological research and that of other countries is a stable research program with long-term commitment. Long-term data are extremely valuable in answering many future questions such as climate change and new forest management options.

We also call attention to data quality control and data assurance in hydrologic research in China. We need to train students who understand watershed functions and processes, and have skills across multiple disciplines.

## CONCLUSION

Great progress has been made in forest-streamflow research in China during the past four decades. Forest management objectives have been shifted from timber production or harvesting to restoration and conservation since the late 1990s, and thus forest-streamflow research has now been focusing on evaluation of the effects of reforestation on hydrology. However, the important relationship between forest changes and streamflow has not been well studied, and understood by the scientists and policy makers. Through a comparative review on the forest-streamflow research in both China and the rest of the world, we found that little solid, long-term data on forest-streamflow relationship were available in China mainly due to a lack of paired watershed experiments across the major forest ecosystems. Because of this, China should expand its existing forest ecological networks to include carefully designed paired watersheds, which examine the effects of vegetation changes, soils, snow hydrology, and surface water and ground-water interactions. A carefully designed experimental and monitoring framework ensures that the forest-streamflow relationship be correctly quantified. In addition to the paired watershed studies, future research priorities should be placed on large-scale forest hydrology, reforestation hydrology, and development and use of robust statistical methods appropriate for the forest-streamflow research. Above all, there must be a long-term commitment to collect quality data that can be reused as better analytical methods are developed.

## ACKNOWLEDGMENTS

This manuscript was prepared with support from The Overseas Scholar Funding Project from Chinese Academy of Sciences (C13HU), the China National Key Foundational Research and Development Plan Program (2002CB111504), and the National Natural Science Foundation (30125036, 30590383, and 39990490). We thank Mr. Hui Wang and Dr. Yuandong Zhang from Chinese Academy of Forestry in Beijing for conducting literature searching to calculate the publication numbers from 1950s to present.

## LITERATURE CITED

Andreassian, V., 2004. Waters and Forests: From Historical Controversy to Scientific Debate. Journal of Hydrology 291:1-27.

Austin, S.A., 1999. Streamflow Response to Forest Management: A Meta-analysis Using Published Data and Flow Duration Curves. Unpublished M.Sc. thesis. Colorado State University, Fort Collins, CO, USA.

Bosch, J.M. and J.L. Hewlett, 1982. A Review of Catchment Experiments to Determine the Effects of Vegetation Changes on Water Yield and Evapotranspiration. Journal of Hydrology 55:3-23.

Bruijnzeel, L.A., 2004. Hydrological Functions of Tropical Forests: Not Seeing the Soils for the Trees. Agriculture Ecosystems and Environment 104:185-228.

Calder, I.R., 2004. Forests and Water – Closing the gap Between Public and Science Perceptions. Water Science and Technology 49(7):39-53.

Calder, I.R., 2007. Forests and Water – Ensuring Benefits Outweigh Water Costs. Forest Ecology and Management 251(1-2):110-120.

Cao, Y., Q. Li, T. Cai, and Y. Shen, 1991. The Effects of Forest Coverage on River Flow in the Songhua Watersheds. *In*: Studies on Forest Ecosystems, X. Zhou (Editor). Northeast Forestry University Press, Harbin, pp 396-402 (in Chinese).

Chen, J.F. and X.B. Li, 2001. The Impact of Forest Change on the Watershed Hydrology – Discussing Some Controversies on Forest Hydrology. *In*: Advanced Research on Forest Hydrology and Climate Effects, Wen-Hua Li (Editor). Institute of Geographic Sciences and Natural Resources Research (CAS), Beijing, pp. 119-126 (in Chinese).

DeWalle, D.R., 2003. Forest Hydrology Revisited. Hydrological Processes 17:1255-1256.

Eisenbies, M.H., W.M. Aust, J.A. Burger, and M.B. Adams, 2007. Forest Operations, Extreme Flooding Events, and Considerations for Hydrologic Modeling in the Appalachians – A Review. Forest Ecology and Management 242:77-98.

Farley, K.A., E. G. Jobbagy, and R.B. Jackson, 2005. Effects of Afforestation on Water Yield: A Global Synthesis With Implications for Policy. Global Change Biology 11:1565-1576.

Forestry Strategic Research Group of China Sustainable Development, 2002. Forestry Strategy Research of China Sustainable Development. China Forestry Publishing House, Beijing, China, pp. 173-183, 384 (in Chinese).

Harr, R.D., 1982. Fog Drip in the Bull Run Municipal Watershed, Oregon. Water Resources Bulletin 18:785-788.

Hibbert, A.R., 1967. Forest Treatment Effects on Water Yield. *In*: W.E. Sopper and H.W. Lull (Editors). Forest Hydrology, Proceedings of a National Science Foundation Advanced Science Seminar, Pergamon Press, Oxford, pp. 527-543.

Huang, B.W., 1981. Evaluation of the Role of Forests. Geography Knowledge (1):1–3 (in Chinese).

Huang, B.W., 1982. Re-evaluation of the Role of Forests. Geography Knowledge (2):1–30; (3):1-3; (4):1-3 (in Chinese).

Huang, M. and L. Zhang, 2004. Hydrological Responses to Conservation Practices in a Catchment of Loess Plateau, China. Hydrologic Processes 18:1885-1898.

Hubbart, J.A., T.E. Link, J.A. Gravelle, and W.J. Elliot, 2007. Timber Harvest Impacts on Water Yield in the Continental/Maritime Hydroclimatic Region of the United States. Forest Science 53(2):169-180.

Ingwersen, J.B., 1985. Fog Drip, Water Yield, and Timber Harvesting in the Bull Run Municipal Watershed, Oregon. Water Resources 21(3):469-473.

Jackson, R.B., E.G. Jobbágy, R. Avissar, S.B. Roy, D.J. Barrett, C.W. Cook, K.A. Farley, D.C. le Maitre, B.A. McCarl, and B.C. Murray, 2005. Trading Water for Carbon With Biological Carbon Sequestration. Science 310:944-1947.

Johnson, R., 1998. The Forest Cycle and low River Flows: A Review of UK and International Studies. Forest Ecology and Management 109:1-7.

Li, C.W., J.P. Ge, S.R. Liu, and P.S. Sun, 2006. Landscape Pattern and eco-Hydrological Characteristics at the Upstream of Minjiang River, China. Frontiers of Biology in China 1(4):455-462.

Li, W.H., L.W. Yang, and Y.T. He, 2001. Review on Hydrological Functions of Forest Ecosystems. *In*: Advanced Research on Forest Hydrology and Climate Effects, Li Wen-hua (Editor). Institute of Geographic Sciences and Natural Resources Research (CAS), Beijing, pp. 10-16 (in Chinese).

Liu, S.R. and P.S. Sun, 2005. Hydrological Response on Land use and Land Cover Changes of Minjiang River, China. Landschaftsokologie und unweltforschung 48:253-262.

Liu, S.R., P.S. Sun, and Y.G. Wen, 2003. Comparative Analysis of Hydrological Functions of Major Forest Ecosystems in China. Acta Phytoecologica Sinica 27(1):16-22 (in Chinese).

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

Ma, X.H., 1987. Preliminary Study on Hydrologic Function of fir Forest in the Miyaluo Region of Sichuan. Scientia Silvae 23(3):253-265 (in Chinese).

MacDonald, L.H. and J.D. Stednick, 2003. Forests and Water: A State-of-the-Art Review for Colorado. Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO, 65 pp. CWRRI Completion Report No. 196.

McGuinnes, J.L. and L. Harrold, 1971. Reforestation Influences on Small Watershed Streamflow. Water Resources Research 7(4):845-852.

McVicar, T.R., L.T. Li, T.G. Van Niel, L. Zhang, R. Li, Q.K. Yang, X.P. Zhang, X.M. Mu, Z.M. Wen, W.Z. Liu, Y.A. Zhao, Z.H. Liu, and P. Gao, 2007b. Developing a Decision Support Tool for China's re-Vegetation Program: Simulating Regional Impacts of Afforestation on Average Annual Streamflow in the Loess Plateau. Forest Ecology and Management 251(1-2):65-81.

McVicar, T.R., T.G. Van Niel, L.T. Li, M.F. Hutchinson, X.M. Mu, and Z.H. Liu, 2007a. Spatially Distributing Monthly Reference Evapotranspiration and pan Evaporation Considering Topographic Influences. Journal of Hydrology 338:196-220.

Miao, S.L. and S. Carstenn, 2006. A new Direction for Large-Scale Experimental Design and Analysis. Frontiers in Ecology and the Environment 4(5):227.

Scott, D.F., L.A. Bruijnzeel, and J. Mackensen, 2004. The Hydrologic and Soil Impacts of Reforestation. In: Forests, Water and People in the Humid Tropics, M. Bonell and L.A. Bruijnzeel (Editors). Cambridge University Press, Cambridge, UK, pp. 622-651.

Scott, D.F., D.C. le Maitre, and D.H.K. Fairbanks, 1998. Forestry and Streamflow Reductions in South Africa: A Reference System for Assessing Extent and Distribution. Water South Africa 24:187-199.

Siriwardena, L., B.L. Finlayson, and T.A. McMahon, 2006. The Impact of Land use Change on Catchment Hydrology in Large Catchments: The Comet River, Central Queensland, Australia. Journal of Hydrology 326:199-214.

State Forestry Administration, 2004. China Forestry Development Report.China Forestry Publishing House, Beijing (In Chinese).

State Forestry Administration, 2006. China Forestry Development Report. China Forestry Publishing House, Beijing (In Chinese).

Sun, G., H. Riekerk, and N.B. Comerford, 1998. Modeling the Hydrologic Impacts of Forest Harvesting on Flatwoods. Journal of American Water Resources Association 34:843-854.

Sun, G., G. Zhou, Z. Zhang, X. Wei, S.G. McNulty, and J.M. Vose, 2006. Potential Water Yield Reduction due to Reforestation Across China. Journal of Hydrology 328:548-558.

Sun, G., C. Zuo, S. Liu, M. Liu, S.G. McNulty, and J.M. Vose, 2008. Watershed Evapotranspiration Increased Due to Changes in Vegetation Composition and Structure under a Subtropical Climate. Journal of the American Water Resources Association 44(5):[This issue].

Sun, P.S. and S.R. Liu, 2003. Large-Scale eco-Hydrological Modeling and GIS Construction. Ecology 23(10):2115-2124 (In Chinese).

Trimble, S.W. and F.H. Weirich, 1987. Reforestation Reduces Streamflow in the Southeastern United States. Journal of Soil and Water Conservation 42(4):274-276.

Vertessy, R.A, F. Watson, and S.K. O'Sullivan, 2001. Factors Determining Relations Between Stand age and Catchment Water Balance in Mountain ash Forests. Forest Ecology and Management 143:13-26.

Wei, X.H., W.H. Li, S.R. Liu, G.Y. Zhou, and G. Sun, 2005b. Forest Changes and Streamflow – Consistence and Complexity. Journal of Natural Resources 20(5):761-770 (in Chinese).

Wei, X.H., S. Liu, G. Zhou, and C. Wang, 2005a. Hydrological Processes of key Chinese Forests. Hydrological Process 19(1):63-75.

Wei, X.H., X.F. Zhou, and C.K. Wang, 2003. Impacts of the Temperate Forests on Hydrology, Northeast of China. Forest Chronicle 79:297-300.

Yin, H.F. and C.A. Li, 2001. Human Impact on Floods and Flood Disasters on the Yangtze River. Geomorphology 41(2-3):105-109.

Zhang, Y.D., S.R. Liu, and J.M. Ma, 2006. Water-Holding Capacity of Ground Covers and Soils in Alpine and sub-Alpine Shrubs in Western Sichuan, China. Acta Ecologica Sinica 26(9):2775-2782 (in Chinese).

Zhang, Y., S. Liu, X. Wei, J. Liu and G. Zhang, 2008. Potential Impact of Afforestation on Water Yield in the Sub-Alpine Region of Southwestern China. Journal of the American Water Resources Association 44(5): DOI: 10.1111/j.1752-1688.2008.00239.x.

Zhang, Z.Q., 2001. Forest Vegetation Impacts on the Runoff Generation: A Review. Journal of Natural Resources 16(1):79-84 (in Chinese).

Zhang, Z.Q., L.X. Wang, and S.P. Wang, 2004. Forest Hydrology Research in China. Science of Soil and Water Conservation 2(2):68-73 (In English with Chinese abstract).

Zhang, Z.Z. and X.X. Yu, 1988. The Major Progress on Chinese Forest Hydrological Research. Journal of Beijing Forestry University 10(2):79-87 (in Chinese).

Zhou, G.Y., J.D. Morris, J.H. Yan, Z.Y. Yu, and S.L. Peng, 2002. Hydrological Impacts of Reforestation With Eucalyptus and Indigenous Species: A Case Study in Southern China. Forest Ecology and Management 167:209-222.

Zhou, X.F., Q. Li, and Y. Jin, 1994. Studies on Forest Hydrological Cycling. *In*: Studies on Forest Ecosystems, X. Zhou (Editor). Northeast Forestry University Press, Harbin, pp. 317-331 (in Chinese).

Zhou, X.F., H.X. Zao, and H. Sun, 2001. Rational Evaluation of Forest Hydrological Effects. *In*: Advanced Research on Forest Hydrology and Climate Effects, W.H. Li (Editor). Institute of Geographic Sciences and Natural Resources Research (CAS), Beijing, pp. 35-40 (in Chinese).