Forest and Water Relationships: Hydrologic Implications of Forestation Campaigns in China

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

a* CONTACT: Ge Sun, Southern Global Change Program, USDA Forest Service, 920 Main Campus, Venture II, Suite 300, Raleigh, NC 27606, USA; Emil: Ge_Sun@ncsu.edu Tel: (919)5159498; Fax: (919)5132978

a. Steve G. McNulty, Southern Global Change Program, USDA Forest Service, 920 Main Campus, Venture II, Suite 300, Raleigh, NC 27606, USA;

b. Southern China Botany Garden, Chinese Academy of Sciences, Guagzhou, P.R. China
c. College of Soil and Water Conservation, Beijing Forestry University, Beijing, P.R. China
d. University of British Columbia (Okanagan), 3333 University Way, Kelowna, British Columbia, Canada
e. Coweeta Hydrologic Laboratory, USDA Forest Service, Otto, NC 27606, USA

ABSTARCT:

Reforestation and afforestation (referred to forestation thereafter) campaigns in the past two decades have resulted in great increases in both forest land area and forest ecosystem productivity in China. Although the ecological benefits of forests are well accepted, the hydrologic consequences of man-made forests by forestation are unclear. Debate and confusion on the hydrologic effects of forestation practices in China remain due to lack of convincing experimental data. This paper reviews worldwide research on the relationship between forest cover and watershed hydrology with special focus on hydrologic effects of reforestation. We limited our review to research conducted using the 'paired watershed' approach. We found most of the existing literature suggests that forestation has potential to reduce annual water yield and baseflow, but have limited effects on peakflow rates and flooding events. We found that the variability of the hydrologic effects is large due to differences in watershed hydrologic processes which are controlled by climate, soils, and the stage of vegetation development. We predict that forestation campaigns in China are not likely to cause large scale changes in streamflow water yield, baseflow, and flood peaks before the hydrologic properties of degraded soils are fully improved. However, baseflow and annual water yield may be reduced in small watersheds to affect local water supply. This situation may be especially true for the semi-arid Loess Plateau region and other areas of Northern China where water shortages are already common. We suggest forest hydrology research should focus on the impacts of forestation on hydrologic processes using a paired watershed approach. Comprehensive science-based evaluation of the positive or negative roles of forest on regulating regional water resources is critical to the current forestation endeavors in China.

KEY WORDS: Forest Hydrology, Forestation, Hydrologic impacts, China

Introduction

Forest inventory records indicate that forested area fell from 102 million hectares in 1949 to about 95 million hectares in 1980 in China due to accelerated population growth, industrialization, and resource mis-management during this period (Fang, 2001; Liu and Diamond, 2005). Consequently about 38% of China's land mass is considered badly eroded (Zhang et al., 2000) due to deforestation and rapid urbanization (Liu et al., 2005). However, forest coverage is recovering (Liu and Diamond, 2005), and China now has the largest forest plantations in the world, approximately 45 million ha or one fourth of the world total (FAO, 2004; http://www.fao.org/) (Figure 1). A new forest policy, called Natural Forest Conservation Program (NFCP) has been adopted since 1998 after the huge floods in China (Zhang et al. 2000). The new policy's objectives included restoring natural forests in ecological sensitive areas such as the headwaters of several large river basins such as the Yangtze River and the Yellow River, planting trees for soil and water protection, increasing timber protection in forest plantations, banning excessive cutting, and maintaining multiple use of forests. China's massive forestation plan (Program for Conversion of Cropland to Forests) aiming to increase forested areas by 440,000 km^2 or 5% of its landmass in the next 10 years (Lei, 2002). This means that 14.66 million ha of croplands will be converted to forests and 17.33 million ha of barren land re-vegetated during the next ten years.

Plot-scale studies in China have documented that reforestation and afforestation (referred to as forestation thereafter) can reduce soil erosion and sediment transport (Zhou ad Wei, 2002) and enhance carbon sequestration (Fang et al., 2001). However,

surprisingly, few rigorous long-term Chinese studies have examined the relations between water quantity and quality and forestation activities at the watershed and regional scales. The impacts of the massive forestation efforts described above on watershed hydrology and water resources have not been well studied in China as well as in the forest hydrology community. Scientific debates on the hydrologic role of forests intensified when floods struck, such as in the cases of 1981 and 1998 floods.

The objectives of this study are: (1) to synthesize existing world-wide literature on the relations between forestation and watershed hydrology; (2) to identify factors affecting hydrologic responses to forestation; (3) to discuss the potential hydrologic consequences of large-scale vegetation-based watershed restoration efforts in China; and (4) to recommend future forest hydrologic research activities to guide watershed ecological restoration campaigns.

Forests and Watershed Hydrology: Experimental Evidence around the World

Many 'paired watershed' manipulation studies have been conducted in the past 100 years in various part of the globe and data syntheses on forest-water relations are available in English (Hibbert, 1967; Bosch and Hewlett, 1982; Ffolliott and Guertin, 1987; Whitehead and Robinson, 1993; Stednick, 1996; Sahin and Hall, 1996; Scott et al., 2005; Brown et al., 2005) and in the Chinese (Wang and Zhang, 1998; Li, 2001; Liu and Zeng, 2002). Below are examples of the highlights of historical studies on the effects of forestation on watershed hydrology grouped by continent. Watershed hydrologic impacts

studies are discussed in terms of changes in total annual water yield, stormflow rates and volume, and base flow rates and volumes.

North America

North America contains a diverse mixture of forest ecosystems from snow dominated boreal forests in Canada to hot semiarid-arid shrub lands in southwestern US. Long-term experimental stations (Figure 2) as represented by the Coweeta Hydrologic Laboratory, Hubbard Brooks, Andrews Experimental Forests, in the U.S., and the Turkey Lakes Watershed Study in Canada were strategically designed to answer watershed management questions especially related to water quantity and quality. Many of the experiment watersheds have over 50 years of continuous forest hydrologic data. Majority of our current understanding of modern forest hydrological and ecosystem sciences has been derived from these keystone watershed studies.

Experimental results in the U.S. have been synthesized by Hibbert (1967), Bosch and Hewlett (1982), Post and Jones (2001), a special issue of the American Water Resource Bulletin (1983), and recently in a book by Ice and Stednick (2004). Canadian forest hydrology research activities were summarized by Buttle et al. (2000, 2005). Long-term empirical data across the physiographic gradients in the U.S. suggest diverse watershed hydrologic response to forest removal (Figures 2). For example, a 46-year of paired watershed study at the Coweeta Hydrologic Laboratory in a humid subtropical climate with deep soils clearly shows that repeated cutting of mountain forests can increase streamflow 200-400 mm/year. The hydrologic effects lasted more than 20 years (Swank

et al., 1988). Streamflow decreased with the regeneration and regrowth of deciduous forests, and a second cutting returned the forest retuned to pre-treatment water yield faster than the first cutting cycle (Figure 3). Hydrologic responses differ across regions (i.e. upland vs. wetlands) and climatic conditions (Sun et al., 2005). Several field and modeling studies in the southern US have clearly showed that forest impacts on water yield were most pronounced during dry periods when trees can use deeper soil water (Trimble and Weirich, 1987; Sun et al., 1998; Burt and Swank, 2002). North America literature on forestry impacts on floods is more contentious (Jones and Grant, 1996; Thomas and Megahan, 1998; Beschta et al., 2000) than on annual water yield. However, it is generally accepted that forest management has effects on small to moderate peakflow rates but little impact on large floods (Hewlett, 1982; Burt and Swank, 2002).

Reviews of Canadian forest hydrology by Buttle et al. (2000; 2005) concluded that watershed-scale studies are lacking in Canada to evaluate the hydrologic effects of large-scale forest removal and fire disturbances. Existing watershed manipulations studies suggest that ditching increased baseflow, but not peakflow in a Quebec peatland. Peakflow rates were not affected significantly in a watershed in New Brunswick with a 23.4% forest removal. Buttle et al. (2005) cautioned that importation of results from other regions in the U.S. to Canada may not be appropriate due to the unique geological (i.e. glacier vs. non glacier), climatic conditions (e.g. snow dominated vs. rain dominated), and because the treatment methods used in the 1960s and 1970s by U.S. researchers are no longer in use.

Europe

Forest is a major land cover type in Europe, and recent droughts and floods have drawn new interest in the role of forests in influencing river flow regimes. In a synthesis study across the European continent, Robinsons et al. (2003) found that conifer plantations on poorly drained soils in northwestern Europe and Eucalyptus in southern Europe may have marked local impacts on water yield similar to those reported in North America. However, changes of forest cover will not likely to have great effect on extreme flows (i.e. floods and droughts) at the regional scale. Robinsons et al. stress the dilution effects of water flow for large basins, and conclude that forests have a relatively small role in managing risks of large scale floods and droughts across the region.

South Africa and Tropics

It is estimated that 40-50 million ha of forest plantations grow in the tropics and warmer subtropics with 2-3 million ha planted every year (Scott et al., 2005). The hydrologic impacts of forestation are more pronounced in this region due to high water uses of tropical trees. For example, some studies have recorded water yield increase of 80-90 mm/year per 10% forest removal. The response is much higher than the 25-60 mm/year range in the classic review by Bosch and Hewlett (1982). Review of literature on the humid tropical regions suggests the prospects of enhanced rainfall and augmented baseflow from reforestation are generally poor in most areas (Scott et al., 2005). A long term (since the 1930s) paired watershed study for converting natural grasslands to forests with negative or exotic tree species in South Africa provided a comprehensive

understanding of the hydrologic effects of afforestation (Smith and Scott, 1997; Scott et al., 1999). This study found annual streamflow reduction rates increased over time following a similar sigmodial pattern of tree growth. The highest flow reductions occurred when the plantations reached maturity. Per 10% level of planting, the reductions varied from a 17 mm or 10% per year in a drier watershed to 67 mm or 7% per year for a wetter watershed. The low and high values are similar to those found in South India and Fiji respectively, and are within the range reviewed by Bosch and Hewlett (1982). This South Africa afforestation study found that it took two years to have an appreciable reduction in streamflow after *Eucalyptus grandis* was planted over 97% of a native grassland watershed. However, it took eight years to have a clear streamflow impact after *Pinus patula* was planted over 86% of a native grassland watershed. The former reached the maximum streamflow reduction potential in about 15 years while the later did not reach the maximum reduction 25 years after planting. A recent update on this study reported that the reductions are diminished after the plantations reached maturation, suggesting productive, vigorous growing forests use more water than mature or old less vigorous growth forests (Scott et al., 2005). Finally, this long-term study concluded that afforestation reduced total stream water yield, mostly in the baseflow component, and can result in the complete loss of streamflow during the summer. Scott et al. (2005) postulated that the effect of afforestation on streamflow decreased with storm size, and afforestation had little effect on large storms when the soil conditions are not affected. Storm flows were mostly affected by soil water storage capacity and antecedent soil moisture conditions. Researchers (Bruijnzeel, 2004; Scott et al., 2005) in the tropics stressed the importance to differentiate 'degraded lands' with bad soils vs.

'undisturbed good soils' that have very different soil hydrologic properties and processes when evaluating the effects of forestation on watershed hydrology. However, few definitive conclusions can be made from the literature on how forestation affects stormflows and baseflows. Limited evidence suggests that revegetating degraded watersheds is not likely to augment baseflow and reduce storm flow volumes.

Australia

Paired watershed manipulation studies in Australia produced large amount process-based information and useful models on the effects of forestation on streamflow (Vertessy, 1999, 2000; Zhang et al, 2001). Several Australian studies concluded that vigorous tree regrowth on cleared watersheds that were previously covered by old growth forests (e.g. Mountain ash) resulted in decreased water yield due to increased evapotranspiration. Water yield from eucalypt forest was found to be closely related to tree age (Cornish and Vertessy, 2001; Vertessy et al., 2001). Vertessy and Bessard (1999) warned about the potential negative hydrologic effects of large-scale plantation expansion in Australia basins.

Andreassian (2004) and Brown et al. (2005) reviewed world wide paired watershed experiments located in various geographic regions around the world. Highlights of the recent synthesis studies were summarized below with a focus on forestation effects.

1. The paired watershed experiments have crucial values in understanding the forest-water relationships. Existing paired watershed experiments are mostly designed for studying effects of deforestation. Studies on reforestation are rare. Flow

duration curve analysis methods provide insights on the seasonal effects of vegetation changes.

2. In general, deforestation increases annual water yield, and reforestation decreases it in proportion to vegetation cover change (Figure 4). Seasonal water yield response is variable (Brown et al., 2005), and is strongly influenced by precipitation patterns.
3. In general, deforestation increases flood volumes and peaks due to soil disturbances, but the effect is extremely variable. Limited studies on reforestation suggested re-vegetation had minimal effect on small to moderate floods, and had no effect on flooding events.
4. Deforestation increases low flow (baseflow), and reforestation decreases it.

Debate on Forest-Water Relations in China

Flooding and drought events cause huge economic losses each year in this heavily populated country. The Chinese people have long recognized the importance of forest and water for the environment and human society development. Chinese traditional wisdoms intuitively linked flooding and drought to loss of forest vegetation. The general public and many scientists hold the perception that forestation enhances precipitation, occurrence of natural springs, augments of streamflow, and even combats droughts and floods.

In the 1980s, science-based studies on the forest-water relations began to emerge in China (Ffolliott and Guertin, 1987). Most of the studies have focused the benefits of forests in retaining water for discharge during non-rainfall seasons (water redistribution) and in reducing floods during rainy seasons. Unfortunately, empirical observation and

limited data on the environmental influences of forests, especially on hydrologic cycles, are often inconclusive and even contradictory (Wei et al., 2003; Wei et al., 2005) due to the highly diverse hydrologic processes caused by the large geographic and climatic variability in China.

Nevertheless, several influential studies have demonstrated the uncertainty and variability of potential hydrologic responses in 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 amount (25 mm/yr.) and water yield/precipitation ratio were less than adjacent non-forest regions. This work was based on water balance data of several large basins in the upper reaches of the Yellow River, northwestern China. It was further estimated that forests in the Loess Plateau region may reduce annual streamflow by 37%. A three-year study in small watershed in the middle reach of the Yellow River concluded that well-vegetated watersheds dominated by black locust (*Robinia pseudoacacia*) plantations and native pine species had over 100 mm/year higher evapotranspiration than the non-vegetated watersheds (Yang et al. 1999). Stormflow volume and peakflow rates were lower in the vegetated watersheds. The averaged annual precipitation was about 400 mm, and over 95% of precipitation evapotranspirated, and less than 5% precipitation became streamflow as infiltration-excess overland flow. High planting density of plantations in the Loess Plateau region has resulted in low soil moisture in the rooting zone, low productivity. These conditions could threaten soil erosion control and economical benefits of forest plantations goals.

A rare paired watershed experiment at a hardwoods forest site in northeastern China (annual Precipitation = 700-800 mm) concluded that a 50% thinning caused total

runoff to increase 26-31 mm/yr. (cited in Ma, 1993). However, several rather contradictory reports also exist. For example, Ma (1987) compared runoff between an old-growth fir forest watershed and a clearcut watershed in the subalpine region of southwestern China, a tributary of the Yangtze River. This study was conducted in 1960, and found that water yield from the 331 ha forested watershed was much higher (709 mm/yr. and runoff ratio 70.2%) than the 291 ha clearcut watershed (276 mm/yr. and runoff ratio 27.3%). In 1969, 60% of the forested watershed was harvested and water yield decreased by 380 mm/yr. Detailed explanation of the causes of the hydrologic changes were not available.

A comparison of streamflow from ten large basins (674-5322 km^2) in the Yangtze River showed that basins with higher forest coverage generally had a higher runoff-rainfall ratio (> 90%) (cited in Ma, 1987). Similar positive correlations between forests and water yield for large basins (> 100 km^2) were reported for northern China as cited in Wei et al. (2003). These findings corroborate Russian literature that suggests streamflow is generally higher for large forested basins (Wei et al., 2003). One unsubstantiated argument on the increase of streamflow from forests was that forest increased 'fog drip' precipitation and forests have lower evapotranspiration. Reports from studies in Russian on the forest-water relations had large impact in China before the 1980s when access to western literature was not readily available.

Wei et al. (2003) attributed the inconsistence of the studies described above to several reasons: 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 may obscure the forest cover effect.

Sun et al. (2006) examined the sensitivity of water yield response to forestation across China by employing a simple evapotranspiration model (Equation 1) developed by Zhang et al. (2001) and a set of continental-scale databases including climate, topography, and vegetation (Sun et al., 2002). The Zhang et al (2001) model was recently evaluated by Brown et al (2005) using world-wide paired watersheds studies. They found that the model predicts the hydrologic effects of afforestation of hardwoods and eucalypts well, but under estimates the effects for conifers. The model application study by Sun et al. (2006) concluded that forestation would have variable potential impacts across the diverse physiographic region (Figures 5 and 6). On average, the absolute values of reduction in water yield due to forestation ranged from approximately 50 mm/year in the drier northern region to about 300 mm/year to the southern humid region. This represents a 40% and 20% water yield reduction in the north and south, respectively. The predicted water yield reduction values reflect the climate (i.e. precipitation and potential evapotranspiration) controls on hydrologic responses to forest landcover changes. The predicted hydrologic responses are in the lower end of reported values when compared to the world-wide literature (Figure 4).

$$\Delta Q = ET_1 - ET_2 = -\left(\frac{1+2.0\frac{PET}{P}}{1+2.0\frac{PET}{P}+\frac{P}{PET}} - \frac{1+0.5\frac{PET}{P}}{1+0.5\frac{PET}{P}+\frac{P}{PET}}\right)\times P \qquad (1)$$

Where, ΔQ = annual water yield change; ET_1, ET_2 = evapotranspiration of forest lands and grass lands, respectively; P = annual precipitation; PET = potential

evapotranspiration calculated using Hamon's method as a function of monthly air temperature (Federer and Lash, 1978).

This analysis was based on the assumption that future precipitation and potential ET do not change. A changing climate will certainly result in a different scenario on the forestation impacts. There is some evidence that the overall ecosystem productivity is increasing across China in the past decade (Fang et al., 2003). The increasing trend of productivity may indicate an increasing trend of water use.

Implications of Forest-Water Relations to Forestation Campaigns in China

Great progress has been made worldwide on understanding forest-water relationships in the past century. We now know that, in general, forests provide the best water quality since soil erosion in undisturbed forests is extremely low. However, they do use more water than other non-irrigated crops that have less root mass and shallower rooting depth. Reforestation activities have limited effects on volume and peaks of large floods. Also, there is much variability of hydrologic responses to reforestation. The influence of forestation on precipitation is uncertain because only limited empirical data are available on this issue.

Based on reviewed literature, we expect that large spatial and temporal variability of hydrologic response to reforestation will follow the large gradients in climate, topography, soils, and disturbances in China. The differential responses will depend on several key factors including: climate, soil conditions, and stage of vegetation recovery. Those factors are well discussed in Andreassian (2004) and Scott et al. (2005). Although

caution is needed to extrapolate studies from one region to others, existing literature has important implications to the current reforestation efforts in China.

1. *In general, forestation or converting from rain-fed croplands to tree plantations will likely reduce total annual streamflow.* Most literature clearly shows this conclusion because the fact that trees generally use more water than crops that have short growing season and shallow rooting depth (Andreassian, 2004). In China, exotic, fast growing tree species such as larch, eucalyptus, and poplars are often used for timber production. Trees used for soil erosion controls also often have economic considerations either for wood or fruit production. Those trees usually use more water than the native tree or shrub species.

2). *In general, forestation is not likely to reduce stormflow volumes and peaks, thus forestation may not reduce the potential for large-scale floods.* It is noteworthy to point out that majority of the lands considered as viable candidates for forestation in China have chronic server soil erosion problems. Such soils normally have degraded soil hydrologic properties that promote infiltration-excess overland flow (Scott et al., 2005). Re-vegetation can improve soil properties such as increasing hydraulic conductivity and macro-porosity. However, it may even take a long time for vegetation to affect soil infiltration capacity, and eventually stormflow peaks and volumes. Stormflow volumes and peak flow rates are mostly controlled by soil water storage capacity (i.e. soil depth and porosity). Large floods occur normally when the soil water storage has been filled, thus vegetation has very limited influences on flooding during large storm events. Antecedent soil moisture conditions are important when evaluating roles of forests in reducing peakflow rates.

3. Forestation is not likely to augment baseflows and spring occurrences. In contradiction to general perception that forests augment lowflow or have more springs, forestation may actually reduce baseflow in the short term. Baseflows are streamflows during non-rainfall periods originated from groundwater and soil water storage reservoirs. Reforestation on degraded lands is not likely increase groundwater storage capacity, and soil water storage in the short term. The increased filtration due to vegetation establishment may be exceeded by the increased water loss by evapotranspiration of the newly established forest (Scott et al., 2005). We predict that baseflow reductions are most pronounced in northern China where water stress is common throughout the growing season. Tree plantings on old floodplain and dried channel beds, and the Loess Plateau regions with deep soils are most likely to have impacts on groundwater recharge, soil moisture, and baseflow. Forestation in wetland dominated watersheds may have little effect on overall watershed hydrology since water balances (i.e. evapotranspiration) will not likely change significantly (Sun et al. 2000). Actual evapotranspiration in wetlands is generally close to potential evapotranspiration regardless of vegetation conditions.

4). *The hydrologic effects of forestation will be small in the short-term.* Deforestation has immediate effects on streamflow, but it takes many years for trees to grow back to a mature forest. It takes even longer for degraded lands to develop into well-functioning forests across the temperate and boreal regions in northern China. It may take less time for tree establishment in the warm, humid southern China where the climate is optimum for tree growth. However, nutrients are often limiting tree growth due to past chronic soil erosion. Therefore, we expect that the watershed hydrology of

many newly forested sites will not cause large changes in the short-term unless significant mechanical site preparation activities (i.e. terracing) have altered the soil hydrologic properties. This is especially true for degraded soils that have been chronically eroded and whose soil physical properties are damaged. A recent review on the impacts of mechanical disturbance on soil properties suggests that soil natural recovery from compaction may take several decades (NCASI, 2004). A simple conceptual model was developed to illustrate the effects of forestation on water yield over time across major regions in China (Figure 7). The model suggests hydrologic recovery rates depend on climate, soil, and vegetation reestablishment.

Our discussion on forestation has been focused 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 campaigns because large areas of croplands are needed to meet the food demands in the rural areas. As showed in Figure 4 in Andreassian's (2004) review, forestation effect on streamflow closely correlates to the percentage of landcover change. Our discussion has ignored the effects of soil and water conservation practices such as contouring, terracing and other bio-engineering methods. Those practices may enhance infiltration, increase surface roughness, and consequently may have impacts on water balances, stormflow and baseflow characteristics.

Forest Hydrology Research Needs in China

Most of the existing forest hydrologic studies in China focus single processes at the field scale (Zhang et al., 2000; Zhou et al., 2002; Zhou et al., 2004; Chen, 1995). Integrated watershed-scale experiments and monitoring to evaluate the overall hydrologic

response to forestation are rare. There is an urgent need to rigorously evaluate the hydrologic consequences of forestation that is key component of national 'Environmental Reconstruction' (Zhou et al., 2001).

Andreassian (2004) raised seven important issues that require attention in studying forest-water relations at the watershed scale: 1) watershed size, 2) using models to mimic a control basin, 3) forest descriptors, 4) gradual changes, 5) long-term impacts, 6) distinguish forest stands from forest soils, 7) Number of watersheds. Those recommendations are quite pertinent to understanding and predicting the effects of reforestation in China.

World-wide forest hydrology study in the past century demonstrated that the paired watershed approach is the best way to detect landcover change effects on hydrology (Brown et al., 2005). The paired watershed approach removes the climatic variability effects on watershed hydrology between two watersheds that have different vegetation covers. However, to date, there are no long-term 'paired watershed' experiments that could give substantial answers on the impact of forests on watershed hydrology for any of the regions in China. Existing national ecological monitoring networks, such as China Ecological Research Network (CERN), and China Forestry Ecological Network (CFEN) promise to provide useful results on forestation impacts on hydrology. A paired watershed approach with a long-term plan should be adopted across China.

Another way of examining landuse change on hydrology is by simulation models. Computer modeling has been well accepted by the hydrologic community as an effective way to examine individual hydrologic process and separating the roles of various factors

(soil, climate, and plant growth status) (Sun et al., 1998; Deng and Li, 2003; Yu et al., 2003). Computer simulation models may play a key role since most of the rivers in China are not gauged, especially in remote areas where hydrologic characteristics are unique. However, development, parameterization, calibration, and validation for simulation models require a large amount of field data that are often expensive to obtain. Models must be built upon quality experimental data and model simulations require accurate input climatic drivers and parameters. To fully understand the role of landcover change on the water cycles, such as precipitation, meso-scale distributed computer models are needed to account for the feedbacks between land and climate. Such types of models require even more close integration of remotely sensed spatial databases and energy and water balances. Meso-scale models are becoming increasing operational at the regional scale (Chen et al., 2005; Yongqiang Liu, personal communication, 2005).

When evaluating the hydrologic effects of forestation on degraded lands in China, it is important to recognize the different roles of vegetation and soils. Systematic and long-term research is needed to document the recovery process of soil hydrologic properties along with changes of forest water use during the entire life cycle of plantation trees. In addition, the hydrologic effects of soil and water conservation measures (e.g. contouring and terracing) that are often employed in forestation on degraded lands need to be evaluated. It is necessary to separate the roles of vegetation from engineering in influencing watershed hydrology to maximize the ecologic benefits of forestation and forestation planning.

The diverse physiographic regions in China provide an excellent location to test hypothesis generated elsewhere around the world. Several unique watershed settings

such as the Loess Plateau (i.e., dry, deep soils) and the upper reaches of the Yangtze River (i.e., wet, cold, steep slopes, shallow soils) may have unique responses to forestation. A process-based approach is needed to address the delicate differential responses to vegetation management among these different geophysical conditions (Wilcox, 2002).

Acknowledgements

This study is supported by the USDA Forest Service Southern Global Change Program, and in collaboration with the Southern China Botany Garden, Chinese Academy of Science. Partial support is also provided by the China Key Basic Research Program (973 Program) 'Influence and Control of Forest Vegetation Covers on Agricultural Ecological Environments in Western China (2002CB111502)'.

References

Andreassian, 2004. Waters and forests: from historical controversy to scientific debate. J. of Hydrology. 291:1-27.

Beschta, R.L., M.R. Pyles, A.E. Skaugset, and C.G. Surfleet. 2000. Peakflow responses to forest practices in the western Cascades of Oregon, USA. J. of Hydrology 233:102-120.

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

Buttle, J.M., I.F. Creed, and J.W. Pomeroy. 2000. Advances in Canadian forest hydrology, 1995-1998. Hydrological Processes 14(9): 1551-1578.

Buttle, J.M., I.F. Creed, and R.D. Moore. 2005. Advances in Canadian forest hydrology, 1999-2003. Hydrological Processes 19: 169-200.

Burt, T. and W.T. Swank. 2002. Forest and floods? Geography Review. 15 (5): 37-41.

Chen, L. 1995. Infiltration rates of loess soils in a plantation for soil and water conservation. J of Beijing Forestry University 17(3): 51-55.

Chen, M. D. Pollard, and E.J. Barron. 2005. Hydrologic processes in China and their association with summer precipitation anomalies. J. Hydrology 301:14-28.

Cornish, P.M. and R.A. Vertessy. 2001. Forest age-induced changes in evapotranspiration and water yield in eucalypt forest. J. of Hydrology 242:43-63.

Deng, H. and X Li. 2003. Simulation of hydrologic response to land cover changes. Scientia Geographica Sinica. 58(1):1-5.

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

Fang, J., S. Piao, C.B. Field, Y. Pan, Q. Guo, L. Zhou, and C. Peng. 2003. Increasing new primary production in China from 1982 to 1999. Frontiers Ecological Environment 6:293-297.

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

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

Hewlett, J.D. 1982. Forests and floods in the light of recent investigation. In Hydrological Processes of Forested Areas, pp. 543-559. National Research Council of Canada Publication no. 20548, Ottawa, NRCC.

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. and J.D. Stednick. 2004. A Century of Forest and Wildland Watershed Lessons. Society of American Foresters. Bethesda, Maryland. P287.

Jones, J.A. and G.E. Grant. 1996. Long-term stormflow responses to clearcutting and roads in small and large basins, western Cascades, Oregon. Water Resources Research. 32: 959-974.

Lei, J. 2002. China's Implementation of Six Key Forestry Programs. http://www.newscientist.com/article.ns?id=dn2291

Li, W. 2001. A summary of perspective of forest vegetation impacts on water yield. J. Natural Resources. 16:398-405.

Liu, J. and J. Diamond. 2005. China's environment in a globalizing world. Nature 43:1179-1186.

Liu, C. and Y. Zeng. 2002. Effects of forests on water yield. Special issue of Hydraulic Research in China. October 2002. P 112-117.

Liu, C-M. and J. Zhong. 1978. Effects of forests on annual streamflow in the Loess Plateau region. 33:112-126.

Liu, J., H.Q. Tian, M. Liu, D. Zhuang, J.M. Melillo, and Z. Zhang. 2005. China's changing landscape during the 1990s: Large-scale land transformation estimated with satellite data. Geophysical Research Letters, *32*, L02405, doi:10.1029/2004GL021649.

Ma, X. 1993. Forest Hydrology. China Forest Publication House. P398.

Ma, X. 1987. Hydrologic processes of a conifer forest in the sub-alpine region in Sichuan, China. Scientia Silvae Sinicae. 23:253-265.

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.

Post, D. A. and J.A. Jones. 2001. Hydrologic regimes of forested, mountainous, headwater basins in New Hampshire, North Carolina, Oregon, and Puerto Rico. Advances in Water Resources 24 : 1195-1210.

Robison, M. A.-L. Cognard-Plancq, C. Cosandey, and 13 others. 2003. Studies of the impact of forests on peak flows and baseflows: a European perspective. Forest Ecology and Management. 186:85-97.

Sahin, V. and M.J. Hall. 1996. The effects of afforestation and deforestation on water yields. J of Hydro 178(1/4), 293-309.

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 SA 24, 187-199.

Scott, D.F., L.A. Bruijnzeel, and J. Mackensen. 2005. The hydrologic and soil impacts of reforestation. In: Forests, Water and People in the Humid Tropics, M. Bonell and L.A. Bruijnzeel (Eds). Cambridge University Press, 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., 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.; Riekerk, H.; Korhnak, L.V. 2000. Groundwater table rise after forest harvesting on cypress-pine flatwoods in Florida. Wetlands. 20(1): 101–112.

Sun, G, S.G. McNulty, J. Moore, C. Bunch, and J. Ni. 2002. Potential impacts of climate change on rainfall erosivity and water availability in China in the next 100 years. Proceedings of the 12th International Soil Conservation Conference. Beijing, China, May 2002.

Sun, G., S.G. McNulty, J. Lu, D.M. Amatya, Y. Liang, R.K. Kolka. 2005. 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., 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 (Accepted).

Swank, W.T., L.W. Swift Jr., and J.E. Douglass. 1988. Streamflow changes associated with forest cutting, species conversion, and natural disturbances. In: Swank, W.T.; Crossley, D.A., Jr., ed. Forest hydrology and ecology at Coweeta. Ecological studies. New York: Springer-Verlag: 297–312. Vol. 66.

Thomas, R.B. and W.F. Megahan. 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: a second opinion. Water Resources Research 37(1):175-178.

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., 1999. The impacts of forestry on streamflows: a review. In: Croke, J., Lane, P. (Eds), Forest Management for the Protection of Water Quality and Quantity Proceedings of the Second Erosion in Forests Meeting, Warburton, 4-6 May 1999, Cooperative Research Centre for Catuchment Hydrology, Report 99/6, pp. 93-109.

Vertessy, R.A. 2000. Impacts of plantation forestry on catchment runoff. In: Sadanandan Nabia E.K., Brown, A.G. (Eds.), Plantation, Farm Forestry and Water Proceedings of a National Workshop, 20-21 July, Melbourne, pp. 9-19.

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.

Vertessy, R.A. and Y. Bessard. 1999. Anticipation the negative hydrologic effects of plantation expansion: results from GIS-based analysis on the Murrumbidgee Basin

Wang, L. and Z. Zhang. 1998. Advance in research on the eco-hydrologic effects of forests. World Forestry Research 11(6):14-23.

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

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

Wilcox, B.P. 2002. Shrub control and streamflow on rangelands: a process based viewpoint. J. Range Management. 55:318-326.

Whitehead, P.G. and M. Robinson. 1993. Experimental basin studies---an international and historical perspective of forest impacts, J. Hydrol. 145:217-230.

Yang, H., L. Sun, and X. Yu. 1999. Water balances of three watersheds in the western Shanxi Province, China. Bulletin of Soil and Water Conservation. 14(2):26-31.

Yu, X. G. Cheng, Y. Zhao, and Z. Zhang. 2003. Distributed hydrological model for forested watersheds. Science of Soil and Water Conservation. 1(1):35-40.

Zhang, Z., L. X. Wang, X. Yu, and Y. Li. 2000. Effective roughness coefficients of overland flow for forested hillslopes. Scientia Silvae Sinicae 36(5):22-27.

Zhang, Z. and others, 2001. A review on the research advances of forest-hydrologic process relations. Natural Resources. Vol. 16(1): 71-78.

Zhang, P., G. Shao, G. Zhao, D. C. LeMaster, G. R. Parker, J. B. Dunning Jr., Q. Li. 2000. China's forest policy for the 21st Century. Science 288(5474):2135-2136.

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

Zhou, G.Y., and X. Wei. 2002. Impacts of Eucalyptus (*Eucalyptus exserta*) Plantation on Soil Erosion in Guangdong Province, Southern China -----A Kinetic Energy Approach. CATENA 49 (3): 231-251.

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, H. Zhao, and H. Sun. 2001. Proper assessment of the hydrologic effects of forests. Natural Resources. Vol. 16(5): 420-426.

Figure 1. Landcover of China as classified by the IGBP system. The majority of the forestlands are located in the hilly remote southwestern and northeastern regions.

Figure 2. First year water yield response to deforestation (clear-cut) varies across the physiographic gradient in the United States.

Figure 3. World-wide review of paired watershed experiments on the streamflow response to deforestation and reforestation (from V. Andreassian, Journal of Hydrology 2004(291):1-27)

Figure 4. Annual streamflow responses to repeated harvesting of mixed hardwood forest on Watershed 13 at the Coweeta Hydrologic Laboratory located in the southern Appalachians Mountains, USA (Adapted from Swank et al., 1988).

Figure 5. Predicted potential annual water yield reduction (mm/yr.) due to the conversion grasslands to forest lands, showing a strong increasing gradient from the dry and cold northwest to the warm and wet southeast. Regions with annual precipitation less than 400 mm/year are not appropriate for reforestation and were excluded from the analysis.

Figure 6. The potential water yield reduction as percentage of water yield from previous grasslands following reforestation, shows a strong decreasing gradient from the dry and cold northwest to the warm and wet southeast. Reforestation activities in the Yellow River basins will have a more pronounced impact than in the Yangtze River basins. Regions with annual precipitation less than 400 mm/year are not appropriate for reforestation and were excluded from the analysis.

Figure 7. A conceptual model illustrating the gradual reductions of annual water yield following forestation across the major geographic regions in China.

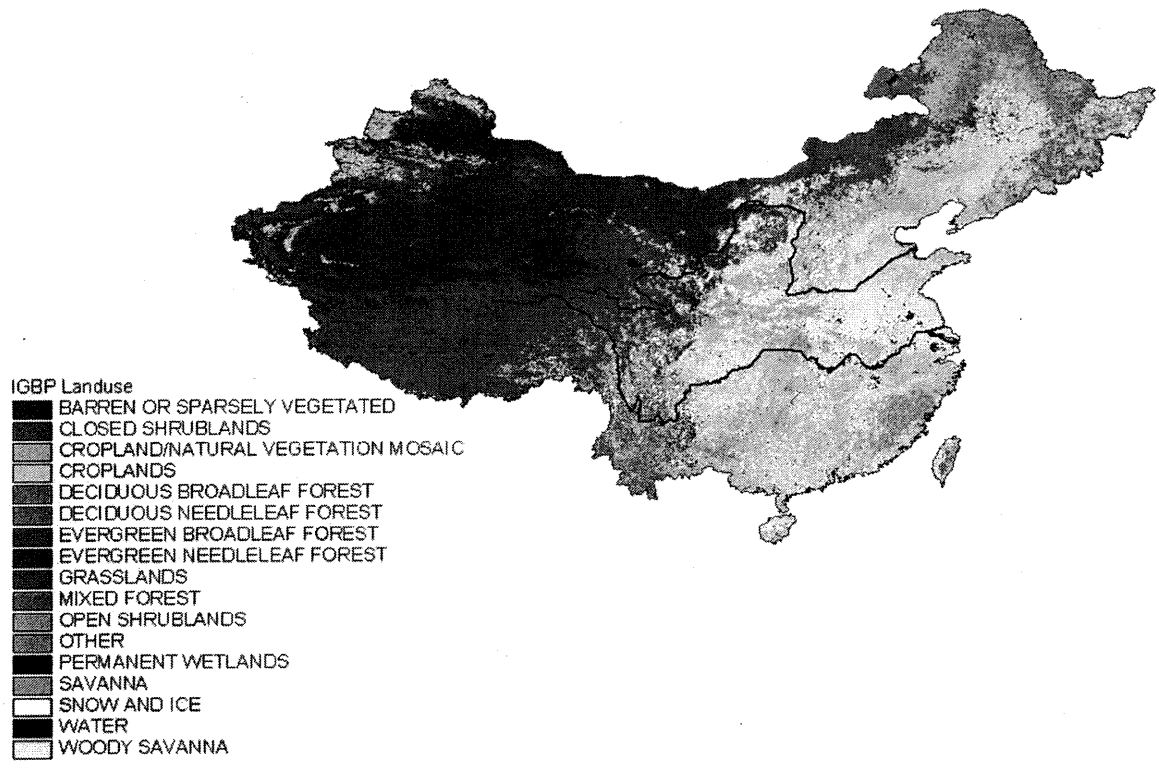

IGBP Landuse
BARREN OR SPARSELY VEGETATED
CLOSED SHRUBLANDS
CROPLAND/NATURAL VEGETATION MOSAIC
CROPLANDS
DECIDUOUS BROADLEAF FOREST
DECIDUOUS NEEDLELEAF FOREST
EVERGREEN BROADLEAF FOREST
EVERGREEN NEEDLELEAF FOREST
GRASSLANDS
MIXED FOREST
OPEN SHRUBLANDS
OTHER
PERMANENT WETLANDS
SAVANNA
SNOW AND ICE
WATER
WOODY SAVANNA

Figure 1.

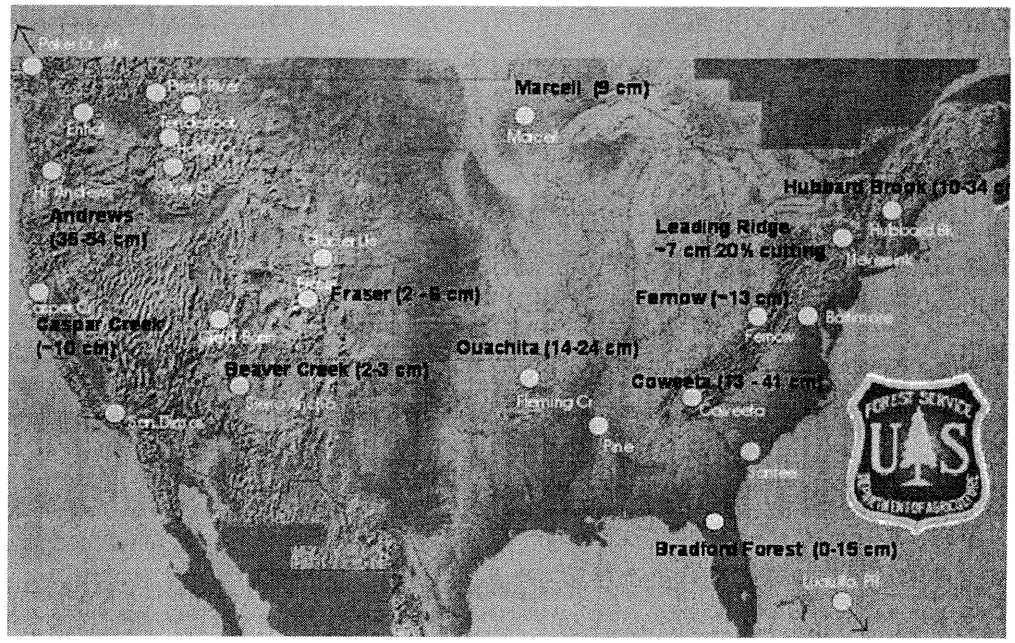

Marcell (9 cm)
Hubbard Brook (10-34 cm)
Leading Ridge
~7 cm 20% cutting
Andrews
(35-54 cm)
Fraser (2 - 6 cm)
Fernow (~13 cm)
Caspar Creek
(~10 cm)
Ouachita (14-24 cm)
Beaver Creek (2-3 cm)
Coweeta (73 - 41 cm)
Bradford Forest (0-15 cm)

Fig 2

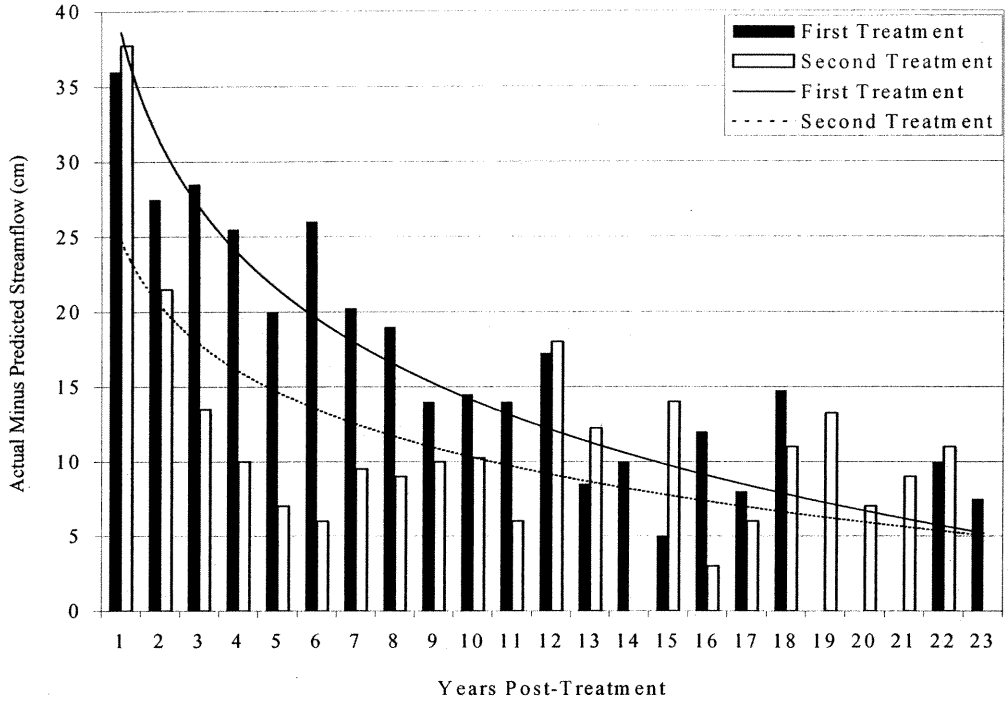

First Treatment
Second Treatment
First Treatment
Second Treatment
Actual Minus Predicted Streamflow (cm)
0
5
10
15
20
25
30
35
40
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Years Post-Treatment

Fig 3

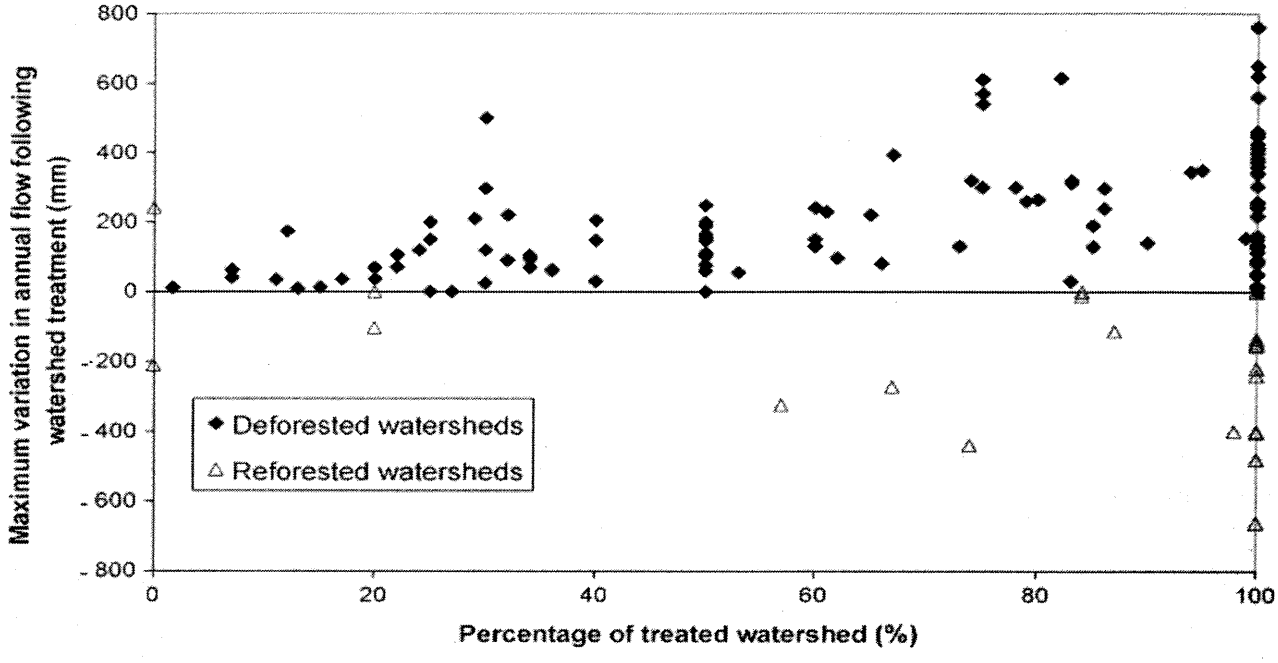
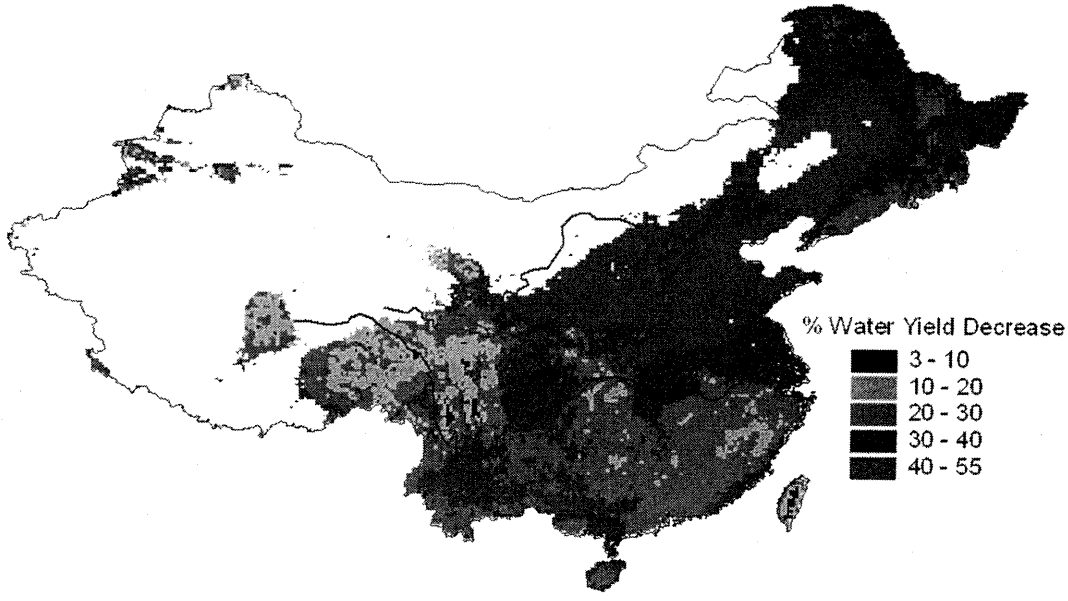
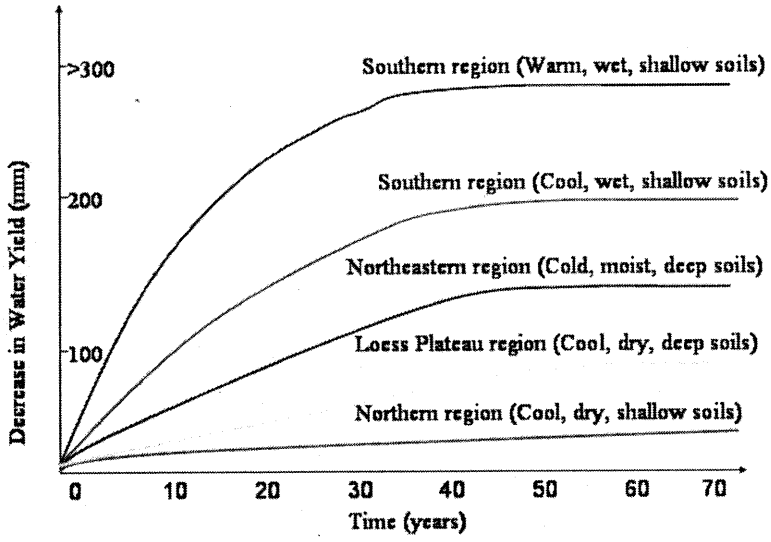

Maximum variation in annual flow following watershed treatment (mm)
800
600
400
200
0
-200
-400
-600
-800
0
20
40
60
80
100
Percentage of treated watershed (%)
Deforested watersheds
Reforested watersheds

Fig 4

Fig 5

Water Yield Decrease
(mm/Yr.)
15 - 100
100 - 150
150 - 200
200 - 250
250 - 321

Fig6



Potential Impact of Reforestatation on Water Yield in China