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Impacts of forest changes on hydrology: a case study of large watersheds in the upper reach of Yangtze River Basin

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Abstract

Quantifying the effects of forest changes on hydrology in large watersheds is important for designing forest or land management and adaptation strategies for watershed ecosystem sustainability. Minjiang River watershed located in the upper reach of the Yangtze River Basin plays a strategic role in environmental protection and economic and social wellbeing for both the watershed and the entire Yangtze Basin. The watershed lies in the transition zone from Sichuan Basin to Qinghai-Tibet Plateau with a size of 24 000 km^2. Due to its strategic significance, severe historic deforestation and high sensitivity to climate change, the watershed has long been one of the highest priority watersheds in China for scientific research and resource management. The purpose of this review paper is to provide a state-of-the-art summary on what we have learned from several recently-completed research programs (one of them known as "973 of the China National Major Fundamental Science" with funding of $3.5 million USD in 2002 to 2008). This summary paper focused on how land cover or forest change affected hydrology at both forest stand and watershed scales in this large watershed. Inclusion of two different spatial scales is useful because the results from a small spatial scale (e.g. forest stand level) can help interpret the findings at a large spatial scale. Our review suggests that historic forest harvesting or land cover change has caused significant water increase due to reduction of forest canopy interception and evapotranspiration caused by removal of forest vegetation at both spatial scales. The impact magnitudes caused by forest harvesting indicate that the hydrological effects of forest or land cover changes can be as important as those caused by climate change, while the opposite impact directions suggest their offsetting effects on water yields in the Minjiang River watershed. In addition, different types of forests have different magnitudes of ET with old-growth natural coniferous (*Abies*) forests being the lowest and the coniferous plantations (e.g. Spruce) being the highest among major forest types in the study watershed, suggesting that selection of different types of forests can have an important role in ET and consequently water yields. Our synthesis indicates that future reforestation and climate change would likely produce the hydrological effects in the same direction and thus place double pressures on water resource as both key drivers may lead to water yield reduction. Implications of the findings are also discussed in the context of future land cover and climate changes.

1 Introduction

It is commonly accepted that in forest dominated large watersheds (greater than 1000 km^2 forest change or land cover change and climatic variability are two main drivers for hydrological changes at watershed scales. Consequently, understanding their individual effects on hydrological changes requires quantitative separation of the interactive influence on watershed hydrology between land cover change and climatic variability. In small watersheds (less than 100 km^2, a paired-watershed experimental approach (involving a control watershed and a comparable but treated watershed) is commonly used to remove the climatic influence so that the effects of land cover or forest change (e.g. harvesting or plantation) on hydrology can be quantified. However, such an experimental approach is not suitable for large watersheds simply because of the difficulty in locating a comparable control watershed for an impacted watershed. In order to overcome this methodological challenge, various approaches have been explored, including hydrological modeling (Tuteja et al., 2007), statistical analysis (Wei and Zhang, 2010; Zhao et al., 2010), sensitivity tests (Milly and Dunne, 2002) and trend analysis (Wilcox and Huang, 2010).

Many studies have demonstrated that forest changes can significantly affect streamflow by altering its pattern, magnitude, frequency and quality (Bethlahmy, 1974; Cheng, 1989; Scott and Lesch, 1997; Moore and Wondzell, 2005; Doerr and Shakesby, 2006). However, the majority of these conclusions have been based on small watersheds with much less attention given to the large watersheds (Wilk et al., 2001; Costa et al., 2003; Sun et al., 2005; Tuteja et al., 2007; Lin and Wei, 2008). In the past few decades, large watershed studies have been receiving growing attention because many environmental issues have cumulative effects and operate at large spatial scales. Watershed resource managers are eagerly seeking scientific information on large watersheds to support resources management for protection of water resources and mitigation of floods and droughts. This is particularly evident when climate change and anthropogenic activities are dramatically altering watershed processes at large spatial scales.

Research on evaluating cumulative hydrological impacts of forest changes or land cover change and climatic variability in large watershed systems is challenging and limited, mainly because of insufficient data and complexity. Moreover, research results on forest disturbance and hydrological effects in large watersheds are less consistent when compared with the small watershed studies. For example, studies have demonstrated that hydrological impacts of deforestation in large watersheds were insignificant (Wilk et al., 2001; Buttle and Metcalfe, 2000; Robinson et al., 2003; Thanapakpawin et al., 2007). In contrast, significant hydrological responses to deforestation have been identified in many other large watershed studies (Eschner and Satterlund, 1966; Ring and Fisher, 1985; Matheussen et al., 2000; Huff et al., 2000; VanShaar, 2002; Siriwardena et al., 2006; Li, 2007). Those inconsistent results may be due to significant complexities in large watersheds as well as different research methods applied. They also demonstrate that the forest-water relationship in large watersheds is likely watershed specific, and thus more case studies need to be investigated in detail.

Minjiang River is the largest tributary of upper Yangtze River in terms of its water yield (approximately 8.9 %). The watershed provides critical water supply to the downstream Chengdu and nearby regions for agricultural and industrial development. However, due to historic deforestation and increasing population, there are various environmental problems such as floods, soil erosion, water pollution and seasonal shortage of water supply. In addition, the watershed is sensitive to changes in climate due to its high elevations. For example, the Qinghai-Tibet Plateau has become warmer in the past 30 yr at a rate of 0.19–0.25 °C/10 yr in the subalpine forest zone (Tan et al., 2000). Water resources in the Tibetan Plateau decreased with shrinking glaciers and permanent snow snowpack (Shi and Li, 1994; Kang, 2005). Thus, because of its significance, growing pressures and high sensitivity to climate change, Minjiang River watershed has always been a high-priority in the Yangtze River Basin and western regional development of China.

The research of the Minjiang River watershed can be traced back to the 1960s, which was one of the frontiers in Chinese forest hydrological research. Recently, the Ministry of Science and Technology funded an integrated watershed-wide research program ($25 million Chinese RMB, about $3.5 million USD) to study various watershed processes in the Minjiang River watershed (2004–2010) to improve science and management in large watersheds. The program was led by the Chinese Academy of Forestry (Dr. Shirong Liu) with involvement from more than 20 research institutes across China.

The purpose of this summary paper is (1) to provide the research findings on eco-hydrological processes at the forest stand level; (2) to present the results on the effects of forest change or land cover change and climatic variability on hydrology at the large watershed scale; and (3) to integrate all results at both spatial scales to discuss management strategies for long-term water and watershed sustainability. Although our review mainly focused on the large watershed scale, inclusion of the results from the small forest stand scale will help the interpretation of the results at large spatial scales.

2 Characteristics of Minjiang River watershed

Minjiang River watershed is located in the upper reach of Yangtze River Basin, with the area of 24 000 km^2 (Fig. 1). The watershed lies in the transition zone from Sichuan Basin to Qinghai-Tibet Plateau, covering elevations ranging from about 500 m to 5500 m with the high elevations covered by glaciers and permanent snow. The eco-environment in Minjiang River watershed is typically vulnerable due to its high elevation, steep topography, and high hydraulic gradient and abundant rainfall. The main watercourse of the upper watershed is 340 km in length, and the elevation differences are up to 4000 m.

The climate in Minjiang watershed is characterized by typical alpine climate with high spatial and vertical variations, with one exception in the elevation band of 1800–2300 m where the arid valley has a subtropical climate. There are also alpine frigid and tierra helada above the alpine tree line (Fig. 2). Average annual temperature decreases from southeast to northwest. The maximum annual temperature of the whole watershed is 15 °C and the minimum is less than 4 °C. The climate is mainly affected by westerly circulation, Southwest and Southeast Monsoons, which lead to a rainy season from May to October covering 75–90 % of the total annual precipitation.

The major type of soil is mountainous brown coniferous forest soil originating from limestone, phyllite and basalt. Various soil types are distributed vertically along elevations. Yellow brown soil normally distributes in the low elevation areas or areas where the precipitation amount is high. Mountainous cinnamonic soil mainly distributes in the elevations of 1500–2000 m, while leaching cinnamonic soil and carbonate cinnamonic soil can be found in the elevations of 2000–2800 m. Mountainous brown soil distributes in the elevations of 3000–3700 m, and subalpine meadow soil, alpine meadow soil and alpine frost desert soil can be found above 3800 m.

The Minjiang River watershed is located in the transition area from southeast humid forest region to northwest arid grassland with a distinct vertical pattern (Fig. 2). The watershed consists of evergreen broad-leaved forest, coniferous forest, mixed coniferous and broad-leaved forest, shrubland, grasslands, alpine meadow, croplands, and other land cover types (Fig. 2). The dominant vegetation types are meadows, coniferous forests, and shrublands. In total, they occupy 90 % of the land cover and their proportions of the total are 36.6 %, 30.7 %, and 22.8 %, respectively (Zhang et al., 2008). The dominant tree species is *Abies faxoniana* Rehd. et Wils.

3 Land use or forest and climate changes

The upper Minjiang valley was historically covered by dense natural forests and vast grasslands. After the foundation of China (1949), forest harvest became the primary practice in the upper Minjiang River watershed. With the population growth and more demand on wood supply, many forested lands were converted to farmlands, with massive timber harvest mainly occurred from the 1950s to the 1970s. The forest stock volume decreased 3.0×10^6 m^3 per year and the forest coverage reduced by approximately 0.47 % per year from 1949 to 1980 (Fan et al., 2002). As a result, the forest coverage reduced to 18.8 % and the forest stock volume was only 47 % of the original volume in the watershed. With reforestation, the forest coverage then rose to 27 % in 1990. Following the severe flood of the Yangtze River in 1998, the Chinese central government decided to ban any logging in upper Yangtze River and launched a series of reforestation and forest protection programs. Implementation of those reforestation programs dramatically increased forest coverage to 34 % in 2006 in the Minjinag River watershed. It is expected that this coverage rate will continue to grow in the study watershed as China sets an ambitious goal of 28 % forest coverage by 2050 in the whole China (Liu et al., 2008).

Minjiang River watershed is sensitive to climate change. The Qinghai-Tibet Plateau has become warmer in the past 30 yr at a rate of 0.19–0.25 °C/10 yr in the subalpine forest zone, which lies at the elevations between 2600 and 3600 m (Liu and Hou, 1998; Tan et al., 2000). Annual precipitation has decreased by 23.5–28.6 mm over a period of 10 yr in the past 20 yr (Lü and Lü, 2002). The atmospheric temperature in Qinghai-Tibet Plateau is expected to increase 2–3.6 °C by 2100 according to the results of a General Circulation Model (GCM) (Johns et al., 1997).

4 Impacts of forest changes on water at a forest stand level

Information in hydrological processes in a forest stand level provides important mechanisms for understanding ecohydrological processes in large spatial scales. The stand-level forest hydrological processes summarized here include forest canopy and litterfall interception, water movement and water use strategy, evapotranspiration and water production.

Forest canopy interception is the water intercepted by forest canopy during rainfall or snowfall events. The intercepted water goes back into the atmosphere through the evaporation process. The forest canopy interaction reduces kinetic energy of raindrops and thus protects soils from soil erosion. However, it also represents a portion of water lost from a water production perspective. The percentages of forest canopy interception vary with leaf area index, precipitation characteristics and types of forests. According to Hörmann et al. (1996), the canopy interception ratios of temperate broad-leaved and coniferous forests are 11–36 % and 9–48 %, respectively. In the Minjiang River watershed, the canopy interception ratios ranged from about 20 % to 50 % depending on types of forests studied (Table 1). Those studies are consistent with earlier research on *Abies faxoniana* in Western Sichuan where 20–70 % interception ratios were reported (Liu et al., 2001), but are higher than in most studies forest ecosystems in China and elsewhere (Liu et al., 2001), which may be related to dominance of low intensity rainfall events and thick, dense forests in this high-elevation watershed. The higher forest canopy interception may indicate potential more water production if forests are removed in this area.

Like forest canopy, litter layer on soil surface plays a similar role in hydrological cycling. In evaluating the role of litterfall in water interception, water-holding capacity of litterfall is commonly used. The water holding capacity of litterfall is mainly affected by forest types, amount of litterfall, and decomposition condition (Richard, 1980; Ma, 1993). The major forest type of the study area is *Abies faxoniana* forest. It has a much greater maximum soil water-holding capacity, maximum litter water-holding capacity and maximum moss layer water-holding capacity than other vegetation types such as the second growth forests and plantation forests in the study watershed (Liu et al., 2001). Zhang et al. (2009) compared the water-holding capacities of different vegetation types using both field investigation and laboratory experiments in subalpine region of Western Sichuan, and found that the maximum water holding capacities at the litter layer and soil layer of 0–40 cm were significantly higher in natural forests than those in plantation forests. Those results clearly indicated that natural forests have a higher water-holding capacity in litter layers than plantation forests mainly because the former have more litterfall accumulation than the latter do in the study area.

Studying water movement in soil profile using isotope composition (δD) can be useful for determining sources of water and flow-paths in a watershed. Using the isotopic method, Xu et al. (2011a) analyzed the responses of δD to different rainfall intensities in different soil layers (litter, humus, illuvial, mineral soil and shallow aquifer) in a subalpine dark coniferous forest in the Wolong Natural Nature Reserve of the study watershed. They found that different soil layers had different responses (change rates and lengths of residence time) to rainfall intensities and subsequent evapotranspiration with quick responses in top layers and slow responses in deep layers. Their results clearly show that light rainfall (5–15 mm) events only temporally altered the shape of δD profile curve of soil water, and their impacts on the upper soil depth were quickly depleted through evaporation and plant uptake. In contrast, heavy rainfall (about 30 mm) events greatly affected the shape of δD profile curve of soil water in all layers (Xu et al., 2011a). Surprisingly, groundwater in shallow aquifers was not significantly altered at this heavy rainfall intensity.

In a separate study, Xu et al. (2011b) used the isotopic method to examine water use strategies of three different plant species in the same forest community described earlier. In this study, Xu et al. (2011b) focused on the resultant patterns of soil water redistribution to examine the processes of soil water redistribution. The results showed that the patterns of water use by three species (*Abies faxoniana, Betula utilis* D. Don. and *Bashania fangiana* (*A. Camus*) Keng f. et Wen) displayed strong agreement with their fine root distributions in the soil profile. The over-story species of *Abies faxoniana* showed a balanced reliance on both groundwater and rainfall, and displayed little difference in its water use strategy between the wet season (August) and the dry season (March). In contrast, the mid-story species of *Betula utilis* and the under-story species of *Bashania fangiana* were highly responsive to rainfall, especially in the wet season. Those contrasted results suggest that the complementary water use strategies and the lack of dependency on rainwater by the foundation species of the subalpine coniferous forest ecosystem should act together to promote species co-existence and maintain community resiliency under potentially increasing water stress caused by climate change.

Evapotranspiration is an important component of water budget in a forested watershed. Zhang et al. (2008) studied the evapotranspiration in the Minjiang River watershed and found that the forests had a higher ET than crops and shrubs. This result suggests that conversion of crops or shrubs to forests will cause water reduction and vice verse. Forests in the Minjiang River watershed were massively cut between the 1950s and 1980s. After 1999, various reforestation programs including returning some croplands to forests have been implemented in the study watershed and elsewhere in China. Successful implementation of those reforestation and protection programs will lead to the significant conversion of crop or shrub lands to forest lands, and consequently will cause water reduction. This result is consistent with the studies from Sun et al. (2005, 2008).

There are large variations in ET and consequently water production among different types of forests. Zhang et al. (2011) compared ET among different major types of forests in the Minjiang River watershed and found that ET in old-growth natural coniferous forests (*Abies*) was the lowest, followed by shrubs, broadleaved forests, mixed of coniferous and broadleaved forests and coniferous plantations (e.g. spruce) (Fig. 3). The lowest ET in old natural coniferous forests indicates that the old-growth coniferous forests have the highest water production potentials, and any harvesting of this type of forest can cause initial water yield increasing due to removal of all vegetation, followed by long-term water yield decreasing as a result of succession and re-growth of other types of forests. The highest ET in the coniferous plantation highlights that coniferous plantations could greatly cause water reduction in the study watershed. In addition, monoculture coniferous plantations may cause some ecological problems such as decline in biodiversity, simplified forest structures and habitat and decline of soil quality. Thus, from an ecological perspective, more mixed forests or broadleaved forests should be encouraged in the study region.

5 Effects of forest change on hydrology at watershed scale

Quantifying the effects of land cover or forest changes on hydrology at large watersheds require explicit consideration or removal of the effects of climate change. Because of the difficulty in applying the paired-watersheds experimental approach to large watersheds, researchers normally use the isotopic method, statistics, modeling and remote sensing techniques to assess the effects of forest changes on hydrology. While these different methods have their own strengths and weaknesses, their applications are largely dependant on the study objectives and availability of high quality data.

Watershed-scale ET provides critical information for understanding water budget and water production at watershed scales. It is closely related to climate (energy and water availability) and vegetation. Liu et al. (2006) analyzed basin-wide ET of the upper Minjiang valley using different methods including Thornthwaite and SEBAL model, and found that the spatial-temporal patterns of ET were complex. In this study, the daily ET of the non-growth season was estimated to be about 1 mm day^{-1}, which was much lower than that in the growth season (2–3 mm day^{-1}). Sun et al. (2008) detected a positive correlation between ET and remote sensing-based Normalized Difference Vegetation Index (NDVI, an index showing vegetation activity) in the Minjinag River watershed. Their study also showed that vegetation activity of alpine vegetation increased significantly due to the climate warming, but no significant response was found in a lower altitude. They further suggested that temperature played a more important role than precipitation in NDVI change in the alpine area as it increased vegetation activity and associated evaporative water loss. However, water availability may play a more important role than temperature in regulating vegetation change in lower elevation areas according to the study by Sun et al. (2008). Thus, they concluded that high mountain vegetation types were the most vulnerable from climate change impacts.

Change in ET could lead to important alterations in streamflow. According to the study from Sun et al. (2008), a significantly negative relationship between river flows and NDVI was detected in the growing seasons due to increasing temperatures and vegetation activity, and resultant increasing ET. In addition, Sun et al. (2008) found that annual watershed ET increases significantly due to forest composition and structure shifts from degraded forest stands to fast growing shrubs and grasses. Based on those findings, Sun et al. (2008) predicted that increasing vegetation cover will likely decrease river flow in this large watershed. In a separate research, Liu et al. (2006) applied both isotope and remote sensing techniques to develop the relationship between forest types and streamflow in seven sub-watersheds of the Minjinag River watershed. They found that reduction in the covers of total vegetation, mixed forests and subalpine coniferous forests could cause increasing in surface and subsurface water yields, while the water yield increased with the alpine shrub and meadow covers. Clearly, both above-mentioned studies (albeit different approaches) suggest that land cover change can cause significant hydrological alteration at the watershed scales.

Using both water balance and combination of remote sensing data with an improved Thornthwaite model, Zhang et al. (2008) estimated both ET and PET for 4 meso-scale watersheds in the Minjing River watershed. Their results show that both ET and PET for three studied meso-scale watersheds are relatively low (39.5–43.8 % and 28.2–47.7 %, respectively). Those results are consistent with several previous studies at small watersheds in the Minjiang valley (Chen and Ren, 1990; Ma, 1987; Yang et al., 2004). The relatively low ET may be due to dominance of mature or old growth natural coniferous forests as the latter have the lowest ET (see Fig. 3) as described earlier (at the forest stand scale). The low ET across various spatial scales in the Minjiang valley may be also related to the foggy and moist climate in the high-elevation topography of the unique, deeply-cut valley environment (Liu et al., 2001). The relative low ET and thus high water production in the old or mature natural coniferous forests are unique in eco-hydrological studies.

The glaciers and permanent snow distributed at the top of the mountains of the watershed are an important source of water resource in the Minjiang valley (Zhang et al., 2002). Using data on δD and δ^{18}O sampled over a river network across a large spatial scale in Heishui watershed, a major tributary to the study watershed, Liu et al. (2008a,

b) examined the runoff generation, dynamics and hydrograph separation. They found that the contribution of glaciers and snow meltwater to baseflow was dominant, ranging from 63.8 % to 92.6 %, while rain contributions vary from 7.4 % to 36.2 %. Snow and glacier meltwater was still the main contributor to base flow during the high flow period of the wet season, while the rain provided the main part of variation of the runoff in the watershed. The results from this study have important implications for future water resource availability as climate change continues and glaciers and permanent snow cover may be diminished under global warming.

Zhang et al. (2012) conducted a retrospective study to quantify the relative contribution of forest harvesting and climatic variability to hydrology based on the long-term historic data (1953–1996) on climate, streamflow and forest change history in Zagunao sub-watershed situated in the upper reach of the Minjiang River watershed. The method they employed includes the combination of time series analysis and double-mass curves (Wei and Zhang, 2010). The research showed that the average annual mean flow was significantly increased by forest harvesting, and the increase magnitude attributed to forest harvesting was 38 mm yr^{-1}, while the annual mean flow variation attributed to climatic variability was -38.3 mm yr^{-1}. Both positive and negative values suggested an offsetting effect between forest harvesting and climatic variability. The similar change magnitudes clearly demonstrated that the effects of forest harvesting on hydrology are as important as those from climatic variability. The results from Zhang et al. (2012) also disclosed that the positive effect of forest harvesting on streamflow decreased with forest recovery and eventually diminished about 20 yr following an intensive harvesting period.

6 Implications for management and adaptation strategies

The results from both the forest stand level and watershed scale clearly showed that forest change or land cover change plays an important role in regulating water resource. Forest harvesting can significantly increase annual streamflow, while reforestation or conversion from croplands will do the opposite in the study watershed. This conclusion is consistent with the wide-held "trade-off" relationship between forest and water summarized by Jackson et al. (2005), which means more trees equal less water, and less trees equal more water. This result should have an important implication for forest and water management as China has been implementing several large-scale reforestation programs since the mid 1990s. These programs include the Natural Forest Protection Program, the Sloping Cropland Conversion Program, the Desertification Combating Program, the Key Shelterbelt Systems Construction Program, the Wildlife Conservation & Nature Reserve Construction Program. It is expected that successful implementation of those programs will significantly increase forest coverage, especially coniferous plantation areas in the study watershed, and consequently lead to less annual streamflow in the future.

Our review both forest stand and watershed scales found that different forest types have different ET estimates and thus water yields. At the forest stand scale, ET in old-growth natural coniferous forests (*Abies*) was the lowest, while ET in coniferous plantations (e.g. spruce) was the highest (Fig. 3). The lowest ET in old natural coniferous forests indicates that the old-growth coniferous forests have the highest water production potentials. The highest ET in the coniferous plantations highlights that coniferous plantations can greatly cause water reduction in the study watershed. At the watershed scale, forest dominated sub-watersheds have higher ET than those dominated by shrub or grasses or meadows, and consequently any conversion from forests to shrubs or grasses would lead to water increase at the watershed scale. Therefore, selection of different forest types has an important role in affecting water yields.

Forest or land cover and climate change are interactively affecting watershed hydrology. However, their integrated effects are largely dependant on their individual strengths and directions. The effects can be offsetting or additive. The research by Zhang et al. (2012) showed that historic climatic variability and forest disturbance produced an offsetting effect on annual mean flow in the study watershed. However, in the future, the effects from continuous reforestation plantations and climate change will likely be shifted to be negatively additive (Fig. 4). With continuous reforestation programs, more coniferous plantations will be established, which lead to higher ET and less streamflow. On the other hand, future climate change effects (temperature increasing) will accelerate melting processes from glaciers and permanent snow, and eventually cause the decline or diminish of those important water sources in the long term. This decline has been reported in the Tibetan Plateau due to shrinking glaciers and permanent snow snowpacks (Shi and Li, 1994; Kang, 2005). Future temperature increasing will also increase vegetation activities and ET and consequently decrease water yield. Thus, both climate change and forest change will place double pressures on future water resource supply in the watershed. Management and adaptation strategies must consider both land use and climate change and their interactive effects over time.

7 Conclusions

In the upper reach of Yangtze River Basin, forest or land cover change has greatly affected hydrological processes at both the forest stand level and large watershed scales. At the forest stand level, forest change through harvesting or land conversion has affected canopy interception, ET, water use strategy of tree species, and consequently water yield. The general conclusion is that forest harvesting would initially increase water yield while regeneration or reforestation can eventually lead to increasing of ET and thus decreasing of water yield at the forest stand level. At the large watershed scale, land cover or forest change plays a similar role in streamflow as its role at the forest stand level, and its effects are as important as those from climate change in terms of magnitude. More importantly, our summary identifies that land cover or forest and climate change played an offsetting effect on streamflow in the past, but their effects will become negatively additive in the future with increasing re-growth of regeneration and future reforestation, and temperature increasing, and thus place double pressures on future water resources in the study watershed. Future research and watershed management strategies must consider this dynamic, interactive effect.

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Table 1. Canopy interception of different forest types in the Minjiang River watershed.

Forest types	Study area	Altitude (m a.s.l.)	Forest canopy coverage %	Canopy interception ratio %	Reference
Mixed plantation of *Pinus tabulaeformis* Carr. with *Pinus armandii* Franch	Dagou River valley	1984	90	50.0	Chang et al. (2006)
Subalpine forest: *Quercus aquifolioides* Rehd. et Wils.	Wolong Nature Reserve	2805	80	16.8	He et al. (2010)
Natural Alpine *Abies faxoniana* forests	Wolong Nature Reserve	2780–4080	20–70	48.2	Lü et al. (2007)
Natural *Abies faxoniana* forests	Miyaluo	1400–3000	30–70	19.8–27.4	Ma (1987)

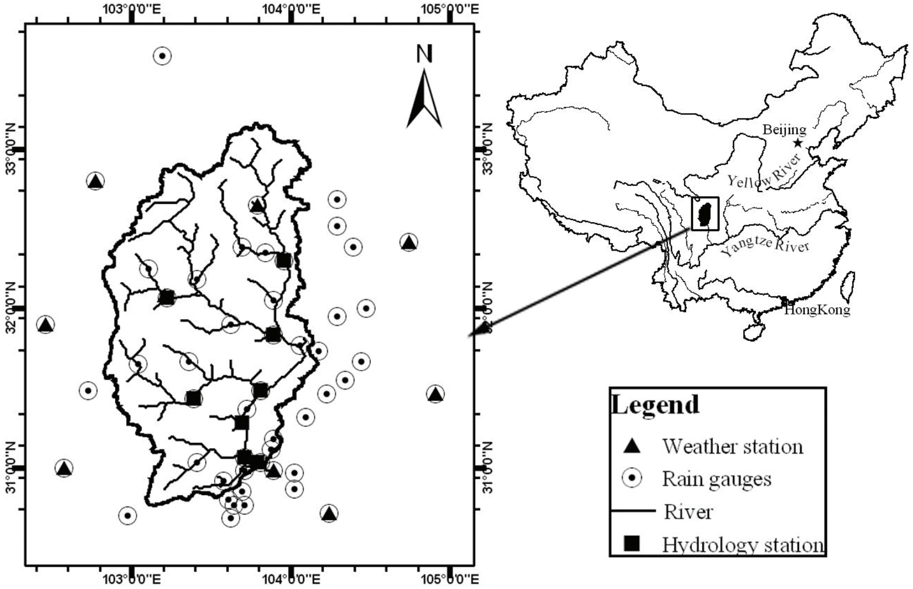

Fig. 1. Location of the Minjiang River watershed and distribution of climate and hydrometric stations.

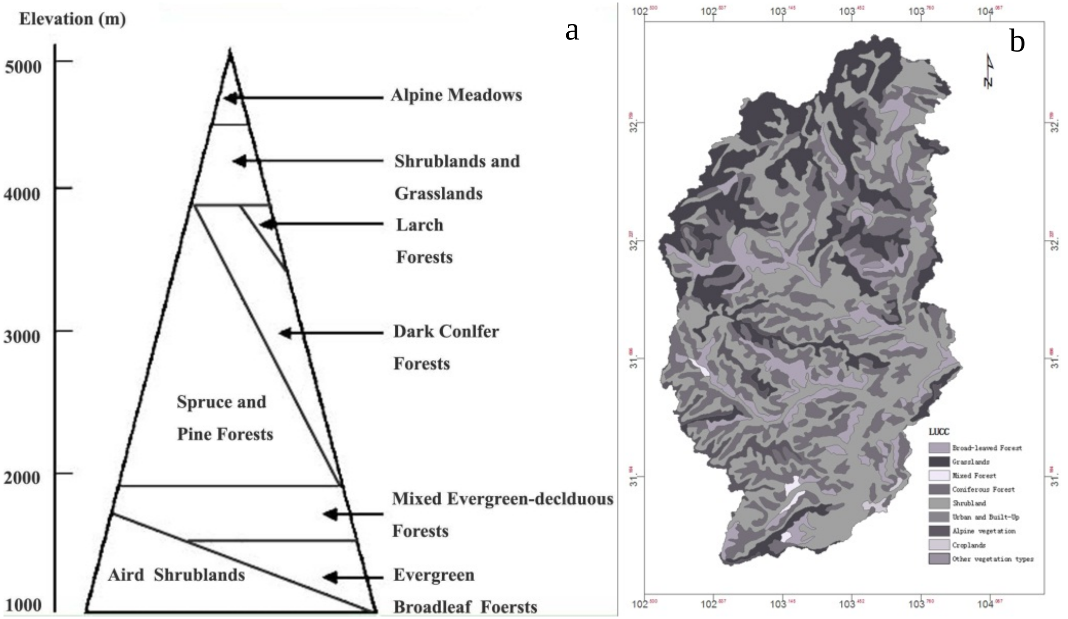

Fig. 2. Vertical distribution pattern of vegetation **(a)**, and Land use and land cover distribution **(b)** in the Minjiang River watershed.

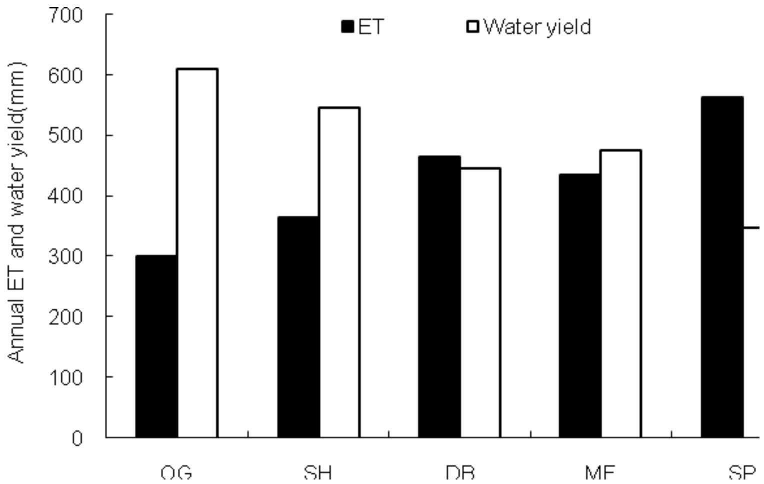

Fig. 3. Annual ET and annual water yield of main forest types in Miyaluo, upper reach of the Minjiang River watershed in 2000 (OG: old-growth natural coniferous forests (*Abies*); SH: shrub; DB: deciduous broadleaved forest; Mixed broadleaved with coniferous forests; and SP: spruce plantation forests (Cited from Zhang et al., 2011 with modification).

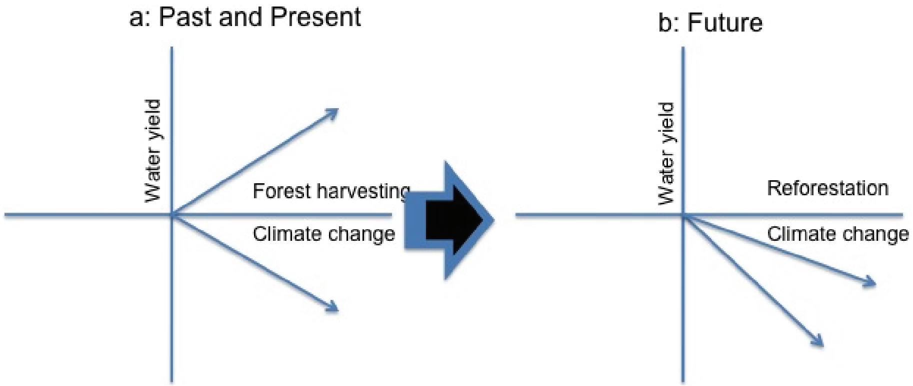

Fig. 4. A conceptual framework on how forest change and climate change interactively affect water yield – **(a)** past and present with forest harvesting and climate change; **(b)** future with reforestation and climate change.