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Hydrological Services by Mountain Ecosystems in Qilian Mountain of China: A Review

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Abstract: Hydrological service is a hot issue in the current researches of ecosystem service, particularly in the upper reaches of mountain rivers in dry land areas, where the Qilian Mountain is a representative one. The Qilian Mountain, where forest, shrubland and grassland consist of its main ecosystems, can provide fresh water and many other ecosystem services, through a series of eco-hydrological process such as precipitation interception, soil water storage, and fresh water provision. Thus, monitoring water regulation and assessing the hydrological service of the Qilian Mountain are meaningful and helpful for the healthy development of the lower reaches of arid and semi-arid areas. In recent 10 years, hydrological services have been widely researched in terms of scale and landscape pattern, including water conservation, hydrological responses to afforestation and their ecological effects. This study, after analyzing lots of current models and applications of geographical information system (GIS) in hydrological services, gave a scientific and reasonable evaluation of mountain ecosystem in eco-hydrological services, by employing the combination of international forefronts and contentious issues into the Qilian Mountain. Assessments of hydrological services at regional or larger scales are limited compared with studies within watershed scale in the Qilian Mountain. In our evaluation results of forest ecosystems, it is concluded that long-term observation and dynamic monitoring of different types of ecosystem are indispensable, and the hydrological services and the potential variation in water supplement on regional and large scales should be central issues in the future research.

Keywords: hydrological service; water regulation; hydrological response; Qilian Mountain

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1 Introduction

Ecosystem services have become one of the worldwide frontiers in ecological researches. Hydrological service is an important and invaluable component of ecosystem services that are globally and regionally threatened (Garmendiaa *et al.*, 2012). In hydrological service, water resource researches, including carrying capacity, water security, water resource allocation, and numerous related subjects, particularly in arid and semi-arid regions, have become important factors in scientific and policy debates. Eco-hydrological feedback and responses are closely related to landscape changes and biogeochemical processes in water-deficient regions (Turnbull *et al.*, 2012; Wang *et al.*, 2012; Wilcox *et al.*, 2012). Water is the primary medium of connectivity, as it controls physical and biological processes across various scales (Austin *et al.*, 2004; Miller *et al.*, 2012). Thus, hydrological services of ecosystems in mountains have always been a central research. Hydrological responses to water budgets and climate-driven land-cover changes also have become important subjects of debate in the

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research of ecosystem services. Climatic and landscape scenarios in the next century indicate that the sustainability of the equilibrium between available resources and water demand will be seriously threatened (López-Moreno *et al.*, 2008). The interactions between the atmosphere and land surfaces on regional or smaller scales are considered to be important, since no effective management of the hydrological cycle exists on the global scale (Krecek *et al.*, 2010). Forests and water are important natural resources for human existence and development (Gao *et al.*, 2001). The former is a major producer of terrestrial ecosystems, while the latter is the main carrier and circulator of matter and energy flow in ecosystems. Meanwhile, the increasing demand of forestry products or other ecological services, such as biodiversity, has encouraged worldwide forest protection and reforestation (Yu *et al.*, 2010). Mountain forests can reallocate precipitation in the hydrological cycle and more than half humanity relies on freshwater from mountains (Liniger *et al.*, 1998). However, the effect of forests on surface runoff has caused a long dispute around the world. In fact, reduction of water availability is a complex issue for the water diversity related to precipitation, temperature, and snow cover as well as vegetation density in headwater regions, for example, in the Mediterranean region (López-Moreno *et al.*, 2008). Otherwise, Farley *et al.* (2005) have found that forestation can reduce mean annual runoff by up to 44% in humid regions compared to grassland. Thus, there should be a trade-off in the role of forests in hydrological services in mountain ecosystems, and this should be objectively assessed in different spatio-temporal scales. Being a key of forests in mountain ecosystems, water regulation can be generalized into three steps: precipitation interception, soil water storage, and fresh water provision in light of hydrological processing. The first two steps are considered to be water retention/conservation, however, in previous studies, the capacity for freshwater provision is also discussed in the context of water retention/conservation.

The Qilian Mountain (36°26′–40°01′N, 94°52′–103°09′E) are located in the northeast of Qinghai Province and the west edge of Gansu Province, being composed of several northwest-southeast parallel mountains and wide valleys and stretching for almost 1000 km. The altitudes of peaks in the Qilian Mountain are mostly 4000 m and the peaks are covered with glaciers or snow throughout the year. Deep in the northwestern China, the Qilian Mountain have the characteristics of a typical continental climate, with annual precipitation ranging from 150 mm to 800 mm and average annual temperature ranging from 6℃ to –5℃ with the elevation rising. Vertical vegetation distribution is obvious but differs from the east to west, as on the southern-northern slopes (Xu *et al.*, 2006) (Fig. 1). The landscape patterns and ecosystem types are differed from upstream to downstream. The forests in the Qilian Mountain mainly consist of six kinds of stands: wet shrub, moss-spruce forest, shrub-spruce forest, grass-spruce forest, juniper forest, and dry shrub. Grassland is widely distributed in high and low elevations, sunny and shady slopes, and in the eastern and western part of the Qilian Mountain. The order of total biomass is that the forest is higher than shrub but lower than grass. The forest biomass in the eastern is higher than in the western, and mainly distributed in the middle-mature and middle canopy density forest. The spatial pattern of forest biomass along topographical factor indicates the character of forest landscape pattern in arid mountain areas. The area proportion of shrub is far higher than that of forest. The value of water supply and soil and water conservation of shrub is the highest, while their unit area value of high forest is the highest (Tang, 2007). The water storage capacity of forests in the Qilian Mountain is approximately 5.52×10^8 m^3 (Che *et al.*, 1992). Under the Pacific monsoon climate, the increasing water effect of the mountains makes the eastern Qilian Mountain a wet island in arid and semi-arid northwestern China (Wu *et al.*, 2005). The water resources in the Qilian Mountain principally consist of atmospheric precipitation, glaciers, and surface water. Precipitation controls glacier development and runoff formation, distribution, and variation (Chen, 1996). Mountain ecosystems provide the service of water conservation and hydro-stability. As the source of several inland rivers, including the Heihe River, Shiyang River, Shule River, and so on, the Qilian Mountain is the most important source of water and green shelter in arid and semi-arid northwestern China, controls the development of oasis, and prevents desert expansion in Inner Mongolia and the Qaidam Basin, giving rise to the Hexi Corridor and Silk Road. Special geographical location and typical land-cover distribution make the Qilian Mountain an important object of researching ecosystem service in China.

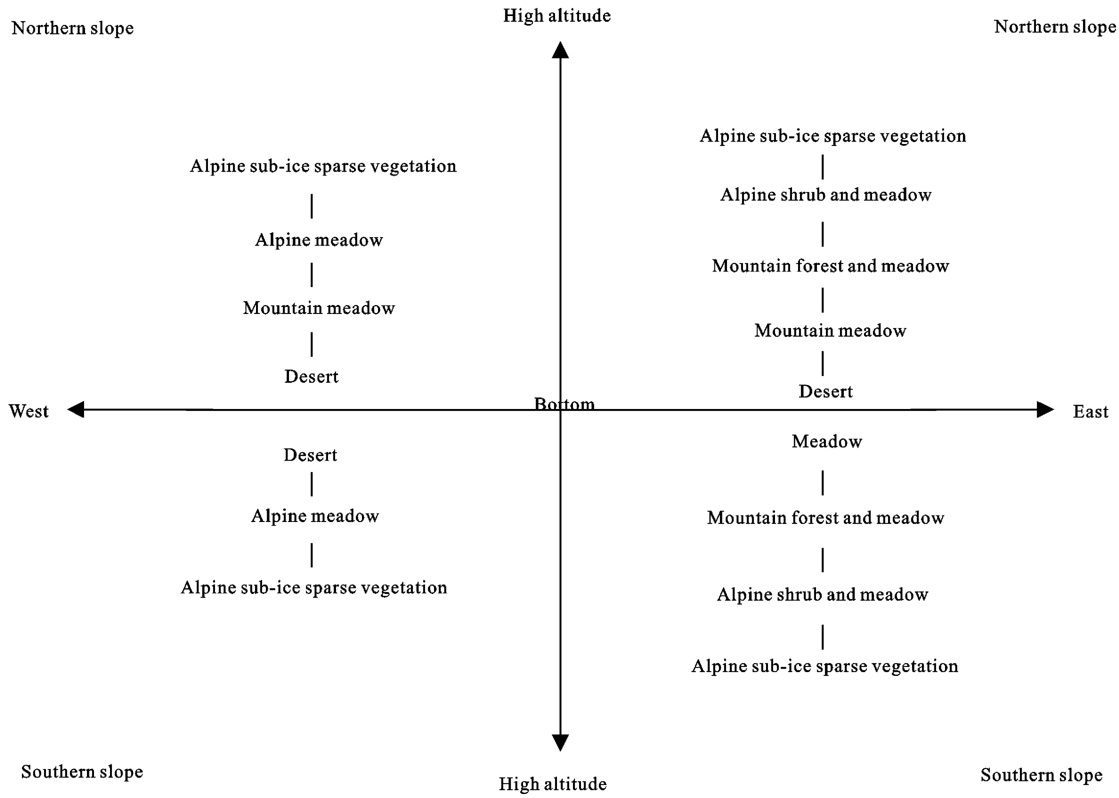

Fig. 1 Vegetation belt of Qilian Mountain. Any belt maybe absence in certain areas

This study provides a summary of researches pertaining to water resources and hydrological service in the Qilian Mountain, including the analysis of water resource characteristics, water regulation service of different ecosystem types within catchment scales, catchment and regional scale monitoring and modeling. Then, we analyzed the dispute on hydrological service of mountain ecosystems through scientific progress and implications. At last, a scientific evaluation of forest ecosystem in mountain ecosystem services is achieved. Based on the current researches, the prospect for future research in the Qilian Mountain is discussed by combing integrating international forefronts and hot issues with the core issues of hydrological service.

2 Current Researches of Hydrological Service in Qilian Mountain

2.1 Special water resource: glacier and mountain snow cover in high altitude

Mountain glaciers greatly contribute to water resources. Under the background of worldwide climate change in the recent decades, the hydrological processes and patterns have been greatly influenced by the reduction of mountain glaciers and snow cover, especially in the arid and semi-arid regions (Parry *et al.*, 2007). The previous studies of glaciers and snow cover mainly focus on three aspects: dynamic monitoring, the interactions between ice/snow and atmosphere temperature, and the future scenario prediction. Many studies have been conducted on different scales in recent years. For example, the response of glaciers to climate change and its possible impact on sea-level rise on global scale, and the melt water reduction in the Qilian Mountain (10^9 m^3 since the 1970s) on the regional scale (Zou, 2005). The annual change of regional glacier snowline have been conducted on many mountains on small scale, for example, a rising trend at an average speed of 2.0–6.5 m/yr has been revealed in a catchment of the Qilian Mountain, while in some areas, the average annual increase even reaches 12.5–22.5 m, such as on the Lenglongling glacier (Water-resources-in-northwest-region Task Group of Chinese Academy of Engineering, 2003).

Mountain glaciers and snow play important roles in water resources (water balance and hydrological circulation) of the Qilian Mountain areas for its location far away from the oceans. Glacier hydrology research in China began in 1958 when massive investigation of snow and ice were started. According to recent statistics, the number of glaciers is 3066, covering 2062.72 km^2, holding 1.145 × 10^{11} m^3 water (Shen *et al.*, 2006). A large amount of precipitation is stored in the form of glaciers. The Qiyi glacier, for example, is approximately 3.8 km in length, with an average thickness of 78 m, holding 1.6 × 10^8 m^3 water (Chen *et al.*, 2007; Wang *et al.*, 2010). The change of glaciers and mountain snow cover of the Qilian Mountain has been studied (Han *et al.*, 2011; Yang *et al.*, 2012; Cao, 2013; Wang *et al.*, 2013), and some basic data have been received by the investigation and monitoring below landscape scale in many regions, but compared to other hydrological researches, the simulation and estimation of glacier runoff process in hydrological or land surface models remain limited (Zhang *et al.*, 2012a; 2012b). In the estimation of mass balance (such as water equivalent mass balance, glacier mass balance) or glacier runoff, temperature-index models are always used and are considered to be better than energy-balance models benefits for its lower data requirements, computational simplicity, and good performance on the catchment scale in high-mountain regions (Zhang *et al.*, 2006; Zhang *et al.*, 2012a; 2012b). A monthly degree-day model coupled with area-volume scaling for glacier melting (Zhang *et al.*, 2012a; 2012b) and with meteorological data (monthly precipitation and temperature) can be used to estimate long-term mass balance and melt water changes in glacier areas. The application of the model in two watersheds (Yarkant River and Beida River basins) effectively described the glacier ablation from 1961 to 2006 and found the main reason of glacier change is due to summer air temperature increase. An average rising rate of 2.28 m/yr for the summer atmospheric 0℃ level height (FLH) was found on the northern slope of the Qilian Mountain over the past 50 years, and the ascending/descending of the summer FLH is an efficiency factor on summer runoff change (Chen *et al.*, 2012). However, as a distinct proportion of glacial melt water runoff, the elastic coefficient of summer runoff and summer FLH change in the Qilian Mountain is different from those in other regions, meaning that regional differences exist. Seasonal snow cover dynamics are largely controlled by four factors: seasonal development and decline in oasis vegetation and associated production of water vapor, mass transport of water vapor to the Qilian Mountain, snowfall accumulation, and snow-cover melt (Bourque and Mir, 2012). In the western China, the annual streamflow variation of the Shiyang River (which begins in the Qilian Mountain) Basin has shown a significant upward trend since 1986, and precipitation shows a decreasing trend in the mountain region but an increasing trend in the plains region, while climate change is responsible for a large proportion (68% and 63%) of the flow decreases in the upstream section of the catchment during the 1980s and 1990s (Huo *et al.*, 2008). Nevertheless, according to the impact of climate change on alpine streamflow over the past 40 years in the middle section of the Qilian Mountain, hydrological condition variations lead to dissimilar tendency in streamflow, as well as seasonal climate change—increasing in the Heihe River and decreasing in the Taolai River (Ding *et al.*, 2000). Increasing precipitation has caused annual flow increase, and rising temperature have reduced the annual flow, although rising temperature in spring and summer positively affect streamflow due to the increase in snowmelt, glacier ablation, and annual precipitation. The negative effect on streamflow of rising temperature can not be eliminated (Ding *et al.*, 2000). As sensible climate change indicators, the relation of glaciers/snowlines and catchment/regional runoff need to be further studied, not only in history reproduction, but also in future change prediction.

Above the forest line on elevation, mountain glaciers were hardly studied in the subjects of eco-hydrological service because of the rigorous climate and landform conditions. Therefore, the hydrological effects of mountain glacier and snow cover change are relative lack of research. The integrated monitoring of glaciers change on different scales and in different areas, with the use of satellite images and models, is one developing direction that should be strengthened. Based on the verification of the past, accurate prediction of the future scenes will be of great significance. The impact of glaciers and mountain snow cover to hydrological processes, vegetation-cover/land-use type change could be coupling in the water circulation and water balance study in the Qilian Mountain. The glaciers and snow cover in the Qilian Mountain should also be included in the assessment of hydrological service change, especially on the aspects of water supplement and water conservation ability, and the relationship between hydrological service and the other ecosystem services should be discussed since hydrological factor is an important one influencing the stability of the whole mountain ecological system. Glacier-atmosphere-water is worth to study in different scales, since landscape characteristics may be various with scaling-up and scaling-down. Catchment scale increase/decrease trend of glacier and snow cover can not represent the changing trend on landscape and even larger scales; and in regional scale researches, remote sensing and modeling approaches would be better than manual field monitoring. As special water resource, the protection work of glacier and snow cover should be included in the regional environmental planning and management. It is the important measures of maintaining the ecological balance and increasing the stability of mountain ecosystem to rationally exploit and utilize the water resource (Zhu *et al.*, 2002).

2.2 Water regulation service of vegetation based on site scale monitoring

Vegetation plays important functional roles in terrestrial ecosystems, and forests serve as the main body in mountain ecosystems, providing multiple ecosystem services such as water regulation, carbon sequestration, and habitat provision. Site scale monitoring is fundamental to in-depth research on water regulation services in mountain ecosystems and can be divided into four steps: canopy interception, stem flow, water transport, and storage in ground litter, and water transport and storage underground shown in Fig. 2. The capacity of water flow regulation by mountain ecosystems could be calculated by integrating the rate of canopy interception, litter absorption, ground accumulation, and diversion. The capacity of water flow regulation by forest ecosystems varies greatly due to the forest type, soil texture, and slope (Guo *et al.*, 2000).

Canopy of vegetation is the first interface of water transport in the forest ecosystem of the Qilian Mountain, and has a great impact on water transport through other interfaces. Canopy interception is closely related to precipitation characteristics, vegetation structure, coverage rate, plant species, and vegetation density (Liu, 1987; Wen and Liu, 1995; Liu *et al.*, 1996). Many scientists have calculated the interception rates of different plants (Wang, 2000; Dang *et al.*, 2004; Hu *et al.*, 2004; Peng, 2010). As the main constructive species, Qinghai spruce (*Picea crassifolia*) and Qilian juniper (*Juniper usprzewalskii*) are the most studied (Jin *et al.*, 2001; Qin *et*

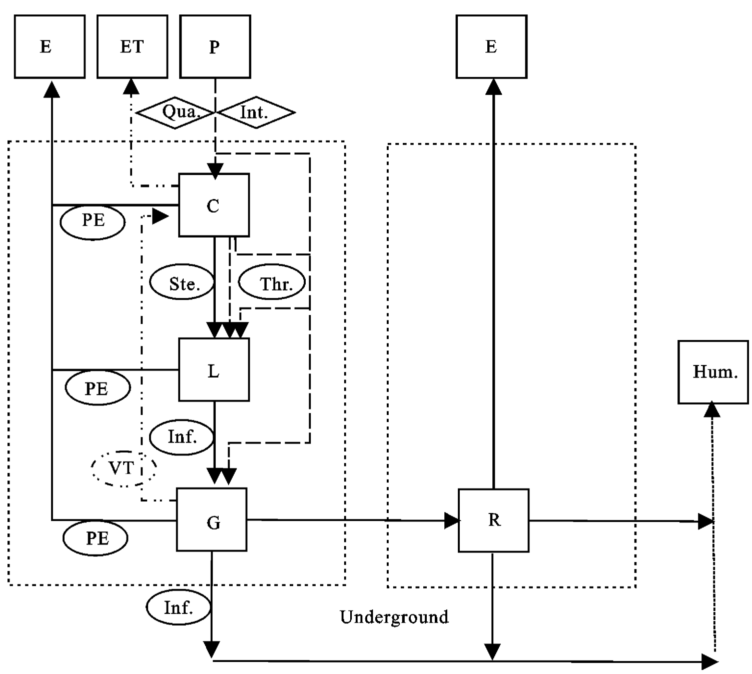

Fig. 2 Diagram of water regulation process. P, precipitation; Int., intensity of precipitation, Qua., quantity of precipitation; ET, evapotranspiration; E, evaporation; PE, physical evaporation; VT, vegetation transpiration; C, amount of rain intercepted by canopy; Ste., stemflow; Thr., throughfall; L, amount of water contained by litter; Inf., infiltration; G, amount of soil water underground; R, water in rivers; Hum., human use, including industrial use, agricultural consumption, and domestic use of water

al., 2007; Tan *et al.*, 2009; Peng, 2010; Sun *et al.*, 2010; Tian *et al.*, 2011). Canopy closure and precipitation intensity can influence the interception capabilities of forests according to site scale monitoring in Qinghai spruce forest (Tan *et al.*, 2009). Approximately 10%–40% of rainfall or snowfall will be intercepted by forest canopy, according to previous studies (Jin *et al.*, 2001), although an interception rate is measured as high as 66.5% for shrubs (Chang *et al.*, 2002). The canopy interception/evaporation can increase precipitation, and more than one-quarter of total precipitation directly returns to the atmosphere by canopy evapotranspiration (Tian *et al.*, 2011). However, under the different site conditions, the evapotranspiration rate varies greatly due to different precipitation, temperature, and solar radiation. Moreover, seasonal differences and fluctuations also exist in evapotranspiration.

Stemflow is defined by the rainfall that passes through leaves and trickles down along the tree trunk after canopy interception, which may finally reach the ground. Stemflow is also considered to be an important component of canopy interception. It is only when rainfall exceeds a certain amount and intensity that stemflow occurs in Qinghai spruce forest, accounting for about 0.51% of the total rainfall (Chang *et al.*, 2002). Although stemflow is a small component in the calculation of water balance or hydrological process, it has important ecological functions of reducing erosion caused by raindrops, bringing nutrients from the canopy directly into the soil, and promoting nutrient accumulation (Wang, 2000; Zhou *et al.*, 2004).

Ground litters have diverse forms of eco-hydrological effects, including water retention, ground flow resistance, evaporation restraint, erosion prevention, increased soil organic matter, and improved soil structure and properties (Wen and Liu, 1995; Chang *et al.*, 2001; Chang *et al.*, 2002; Zhou *et al.*, 2004; Qin *et al.*, 2007; Sun *et al.*, 2010). Leaves are the main components of ground litter, thus the capacities of water retention vary greatly over ecosystem types according to the different physiological traits of leaves. In previous studies, ground litters of moss spruce forests, shrub spruce forests, young spruce forests, Qilian juniper forests, and sub-alpine shrubs have been greatly studied, including indicators on average thickness, storage, and maximum water capacity (Wen and Liu, 1995). Generally, moss spruce forests have a better capacity for water retention. However, the conclusions of different scientists may not always be consistent, because canopy coverage and site conditions are different in experiments. As the temperature conditions for alpine shrubs and subalpine shrubs are lower compared with coniferous and broadleaved forests, the litter decomposition rates of alpine shrubs and subalpine forests are extremely slow, which results in a high water retention rate (Chang *et al.*, 2001). Broadleaf forests are mainly distributed in low-elevation areas and grow quickly. However, when the canopy closure rate reaches a high degree, the growth speed declines, which results in lower water retention rate on litter (Xu, 1984). The soil water retention rate of litter is in the following order: alpine shrubs > Qinghai spruce > Qilian juniper > sloping pasture (Sun *et al.*, 2010). The Qinghai spruce forests, however, usually have the greatest water storage compared to that of other forests, although the alpine shrubs have the highest water retention rates due to their great variation in current storage. The maximum water retention capacity of moss-spruce forest can reach as high as 124.98 t/ha. The effects on runoff reduction and erosion prevention of litter are significant. By site experiment, the runoff will increase by 180%, but the erosion will increase by 787% with litters removed from the Qinghai spruce forest (Chang *et al.*, 2001).

Permeability is the basic factor influencing the water regulation capacity of soil. It is closely related to clay content and soil porosity (total porosity, noncapillary porosity, and capillary porosity) (Qin *et al.*, 2007; Sun *et al.*, 2010). Soil porosity is greatly affected by plant species (Niu *et al.*, 2001; Dang *et al.*, 2004; Qin *et al.*, 2010), vegetation density, vegetation age, and site conditions, thereby affecting the soil water storage capacity (Hu *et al.*, 2004; Qin *et al.*, 2007). Usually at soil depths of 1 m, moss-spruce forest, shrub-spruce forest, and alpine shrub forests have larger water storage capacity than Qilian juniper or other types of forest ecosystem (Qin *et al.*, 2010). Soil water retention capacity is expressed by in the following order: shrubs > coniferous forest > broadleaved forest (Qin *et al.*, 2007).

Hydrological process in site scale is the basic to recognize the mechanism of hydrological service. Thus, the indicators of hydrological service such as water retention capacity of ecosystem are paid more attention. Researchers have conducted controlled experiments (examining different vegetation species or coverage rates) on water retention capacity in recent years (Dang *et al.*, 2004; Miao *et al.*, 2006). Notably, controlled experiments are not always suitable in China, especially in the important water resource areas. Other effective methods need to be explored in future research, and improved analysis approach is needed based on the mechanism above. Mountain woodland and grassland are covered with different degrees of bryophytes and litter, where a thick humus layer makes it easier to store water from precipitation (Song Caifu *et al.*, 2003). Due to the steady annual accumulation and low decomposition rates under low temperatures in forests, litter becomes the more typical and greater water conservation bodies accumulate compared to slope pasture (Zhang *et al.*, 2010). The influence of coverage rate on surface runoff is also significant in forests. In abnormal dry or wet years, stream flows in high coverage forests change slightly and usually near the yield in normal years. The regulation of seasonal variation of stream flow and runoff is significant (Miao *et al.*, 2006), especially in the rainy season. Starting from the mechanism research, we can forecast the more accurate and scientific response of hydrological service according to the variation of ecosystem and landscape pattern.

2.3 Catchment and regional scale analysis and modeling

Recently, three general methods are available for eco-hydrological research at the catchment/regional scale: watershed experiments, time series analysis based on characteristic variables, and modeling approaches (Chen and Chen, 2004). In the perspective of model-building, lumped hydrological and distributed hydrological models are two main formats (Yuan, 1990; Wang *et al.*, 2003b; Xie *et al.*, 2007). Modeling approaches can be classified as physical modeling and mathematical modeling methods (Liu and Lu, 1996). Distributed models are most widely used, according to the records in the researches (Abbott *et al.*, 1986; Bathurst *et al.*, 1995; Wang *et al.*, 2003b). The Soil and Water Assessment Tool (SWAT) is a common distributed model. It was successfully used in the Heihe River and Shiyang River basins, and it could well reflect the ecological effects of vegetation cover on hydrological responses (Wang *et al.*, 2003a; Wang *et al.*, 2010). However, the SWAT model needs quantitative and long-time series data (DEM, land-use, soil property, meteorological data, *etc.*) because basic material support for analysis, and the final results of modeling are usually not perfect due to data limitations. The SWAT model is accurate in long-term runoff simulation, poor in short-term runoff simulation, and almost unusable in glacier-melt runoff simulations. The Soil Conservation Service (SCS) model, proposed by the U.S. Soil and Water Conservation Bureau, is an extensively applied hydrological model in calculating surface runoff. It is a mathematical model established for the simulation of watershed hydrological processes. Simple and loose requirements on parameters and observation datasets make it popular in hydrological applications (Liu *et al.*, 2010).

As the monitoring work on a regional scale can not be as particularized and concrete as on a site scale, ensuring and improving the scientific research of ecoydrological services is an important issue. Based on surface energy balance (precipitation and evaporation data), the SCS model (surface runoff data) and GIS platform (Thematic Mapper (TM) and Enhanced ThematicMapper (ETM) satellite data, DEM data), Nie (2010) describes a practical method for quantitative regional water conservation assessment in the Qilian Mountain, where the results basically reflect the changes in the spatial distribution and water conservation capacity of the study area. Although there are differences between the results of Nie and actual values, the SCS model based on surface energy balance can be considered an effective method for eco-hydrological studies.

He *et al.* (2012) have modeled the water balance using the water balance formula and assessed the contribution of different types of vegetation to the annual water yield in Pailugou catchment (a small catchment of 2.8 km^2 in the Qilian Mountain). In their study, the Qinghai spruce (conductive species in the Qilian Mountain, covering 38.5% of the catchment area) was found to contribute little to the annual water yield, although this can not be reflected on the site scale. As forests may decrease water supply in downstream areas, it is suggested that forests should be under an appropriate coverage rate at the regional level—but more did not mean better. According to the controlled experiments in Dayekou catchment (68.06 km^2) and Haichaoba catchment (131.06 km^2) of the Qilian Mountain by Yang *et al.* (2005a), the main landscapes affecting hydrological processes differed from one catchment to another according to vegetation change (Landsat ETM+ 1：50 000, topography 1：50 000) and water budgets from the years of 1987–2001. In the Dayekou catchment, grassland and Qinghai spruce in the lower-elevation areas have the closest relationship with water budgets, while in the Haichaoba catchment, the shrubland and barren land in the higher-elevation areas are the most relevant landscapes with regards to water budget.

Evapotranspiration is a key factor in water balance or the energy balance equation, and is also the most difficult parameter to determine in modeling. After the modified Penmane Monteith Equation is used to simulate canopy transpiration and soil evaporation (Tian *et al.*, 2011), the modeled evapotranspiration (ET) of Qinghai spruce forest during the growing season in 2008 is 313.6 mm, which is acceptably consistent with the directly measured ET (298.2 mm) by the eddy covariance system. Because of the close relationship between forest and hydrothermal conditions, tree rings can reflect quantity information regarding the past hydrological characteristics of mountains.

Estimation models based on tree rings can be used to reconstruct past stream flow. Tree-ring widths are strongly related to soil moisture conditions according to the water balance modeling using 1955–2002 meteorological data (Yin *et al.*, 2008). Tree-ring chronologies explain up to 80% of the variation in soil moisture by their regression analysis, and the reconstruction of long-time soil moisture conditions (556AD-2001) reveals the major dry and wet periods. The tree-ring (Qilian juniper) based reconstruction of climate by Qin *et al.* (2010) in the upstream of the Heihe River in the central Qilian Mountain found that nearly half the stream flow variance could be explained in the period of 1958–2006. Moreover, the reconstruction reveals six dry periods in the Heihe River over the past 1000 years.

In eco-hydrological researches, site scale observation and catchment/regional scale modeling are complementary to each other. The relationship between small (site/slope scale) and large scales (catchment/regional scale) is not the direct accumulation according to the scaling theory of landscape ecology. On catchment/regional scales, mountain ecosystems will have different hydrological features from monitoring sites. The models based on the hydrological processes should well reflect the ecological effects of vegetation cover on hydrological responses, and can be used to predict the hydrological service change but not only simulating the past. Satellite images can help to achieve the information of ecosystem. Therefore, how to integrate the models of different ecosystems is a big problem in model application on landscape and region scales. In studies, historical data should be first used to determine whether the model is applicable for the study area.

2.4 A dispute: afforestation and its ecological effect

In the early 1950s, the area of water retention forests in the Qilian Mountain amounted to 2.1×10^8 ha. However, when the Qilian Mountain National Nature Reserve was founded in 1988, the forest area decreased to 8.61×10^7 ha. The open forestland and shrubland decreased from 3.367×10^8 ha to 1.874×10^8 ha during that period, which results in a drop of forest coverage rate from 22.4% to 14.4% (Li, 1998). Only a few forests in the lower mountains remain (Wang, 2001). Since the 1980s, a series of management and protection rules were issued by the government. However, overgrazing is still serious in the lower mountains, particularly the degradation of shrubland. In certain areas, the degradation of shrubland is over 50% in the Qilian Mountain (Liu *et al.*, 2007).

Hydrological services present different features (e.g., water retention ability) with different afforestation measures, forest ages, and species in the Qilian Mountain. By comparing eight typical closed forest sites and unclosed forest sites in the eastern Qilian Mountain, Zhang *et al.* (1999) found that the dry weight of litters in close forests is approximately 0.37 t/ha, which is 0.19 t/ha higher than that in the control. The moss-litter weight of the closed forests amounted to 24.51 t/ha, which is 10 t/ha higher than the comparison. The litter moisture content in the closed forests reaches to 718%, while the control only approaches to 524%. Meanwhile, the soil moisture content in the closed forests was 52.1% in the surface 50 cm depth, or 10.9% higher than the control. Therefore, the closed forests significantly increased water retention capability. According to the controlled research on the north slope of the eastern Qilian Mountain, natural regeneration saplings will increase by 5.6 times in closed forests compared with the control area; coverage and height growth of shrubs will increase 2.2 times and 1.8 times; and the survival rate, save rate, and height growth of 6- to 20-year-old spruce saplings to increase by 26%, 75%, and 28.7%, respectively (Li, 2008). A comparison of the three modes (closed: grazing is forbidden; semi-closed: grazing can be allowed in certain times; rotated closed: divide the hill into several alternately closed parts) of hill close indicates that completely closed forests could quickly form complex multilayers in forests, which results in the most effective degree of soil sickness, vegetation coverage, and plant species. The afforestation areas of the Qilian Mountain is classified into five patterns: forest land, shrubland, open forest land, non-forest land, and land unsuitable for forest growth in the perspective of afforestation (Song Kechao *et al.*, 2003). If appropriate measures are taken, the afforestation survival rate can reach 96%, and the preservation rate can reach 61%, even in the case of high mountains, steep slopes, and soil erosion areas. Soil and water conservation forest (*Caragana jubata*, *Sabina przewalskii*, *etc.*) was suitable for plantation in the sunny slope, while water conservation forest (*Potentilla fruticosa*, *Picea crassifolia*, *etc.*) was suitable for cultivation in the shady slope in the eastern Qilian Mountains (Zhang *et al.*, 2010).

The central issue of afforestation is the role of the forest in hydrological services. Runoff regulation, flood detention and soil conservation are the positive effects of forests in Qilian Mountain (Zhong *et al.*, 2003; Lu *et al.*, 2005; Miao *et al.*, 2006). However, four different views are mainly discussed on whether afforestation can increase the total runoff. Experiments in different areas of the world have achieved different results, as shown in Table 1. Forests may be expected to either reduce runoff through evapotranspiration losses, or increase runoff at larger and longer time scales, where evaporation losses increase precipitation elsewhere in the catchment, which may vary depending on regional aridity/humidity. By comparison of three watersheds with different forest coverage in the Sidalong Forestry Ecological Research Station of the Qilian Mountain, the effects of forest coverage on total annual runoff are not significant since precipitation is the controlling factor. Therefore, the effects of forest coverage on seasonal runoff are obvious by the comparison of river coefficients (Miao *et al.*, 2006).

With the increased acute environmental problems, the primary aim of afforestation is to obtain ecological benefits (e.g., carbon sequestration, biodiversity conservation, eco-hydrological services, and eco-tourism services) (Sun, 2001; Rechards and Stokes, 2005; Yang *et al.*, 2005b). Long-term effects of forests degradation or afforestation in the Qilian Mountain should be considered. The relationship of hydrological service with soil properties or other ecosystem services is an important subject of debate (Körner, 2004; Kang *et al.*, 2007), as water is a scarce resource in arid and semi-arid northwestern China. Beside the ecological effects, studies need to be conducted on the metrological evaluation of economic value and the ecological effects of afforestation (Wang *et al.*, 2001). For the hydrothermal condition variation of the eastern and western part of the Qilian Mountain, lots of field experiments must be performed and catchment/regional scale monitoring work should be done in order to recognize the regional characteristic and differences in the eco-hydrological response. Assessment of afforestation and ecological effect also should be based on regional characteristics and differences. Sustainable development is still needed to supplement and optimize the hydrological services of mountain forests.

Table 1 Impact of forest on runoff

Researcher	Time	Region	Result	Reference
Hudson	1997	Great Britain	Reduce	Hudson *et al.*, 1997
Molchanov	1960	U.S.A.	Increase	Molchanov, 1960
Li	2001	China	Reduce	Li, 2001
Zhou	2001	China	Increase	Zhou *et al.*, 2001
Min	2001	China	Increase	Min and Yuan, 2001

3 Conclusions and Prospects

3.1 Climate change and eco-hydrological responses

The impact of climate change on the water supply in the Qilian Mountain should be assessed, since glaciers and mountain snow are widely distributed in the Qilian Mountain and serve as important water resources, and the eco-hydrological response and vegetation conversion are both climate-driven via hydrothermal budgets (Parry *et al.*, 2007). Paleoclimatological and historical evidence indicates that glacio-hydrological and ecological conditions in mountain areas undergo major changes in response to climate change (Barry, 1990). Snow water is sensitive to mountain warming. The studies in western North America found that Pacific climate variability is responsible for 10%–60% of trends in snow water equivalent (Mote, 2006). According to the International Commission for the Hydrology of the Rhine Basin (CHR), the impact assessment of climate changes on river-flow conditions in the Rhine Basin of West Europe, and higher temperature will increase the flood risk, while low flows will adversely affect inland navigation and reduce water availability for agriculture and industry (Middelkoop *et al.*, 2001). The Qilian Mountain is the main water resource of Zhangye City, in which agriculture plays an important role in economic and social development. Therefore, the response of hydrological service of Qilian Mountain to climate change and the risk and countermeasures of cities should be the focused in the future study.

As glacier is a solid water resource in the Qilian Mountain, which may closely relate to surface runoff of inland rivers and lakes in Northwest China, what landscapes with changes in glaciers will happen is important. Glacier retreat can lead to temporary increase in surface runoff. However, Qinghai Lake is becoming smaller with continued glacial retreat in the recent decades. The results of Böhner (2006) indicates that glacier change probably has a time lag (10 years) in the mass balance, so short-time studies on glaciers can hardly reveal the mechanism of glacier change and its influence on water regulation. Therefore, in the future study of increasing effect of water in mountains, climate change should be considered as the background, and mountain glacier/snow cover change, vegetation/hydrology response also should be taken into consideration.

3.2 Long-term and multiscale monitoring/experiments

Controlled experiments and long-term observation are two common approaches in current studies on ecosystem service of site scale and small watershed scale (Molchanov, 1960; Miao *et al.*, 2006; Mote, 2006). Brown *et al.* (2005) and Andréassian (2004) did paired catchment studies on afforestation, deforestation, regrowth, and forest conversion experiments, and they suggest that paired catchment studies are an efficient method to find the impact of vegetation on runoff flows. However, deforestation is forbidden in China. Andréassian discussed the role that the forest has played in water supply from an historical perspective to scientific debate, while Brown focused on the changes in water yield at various time scales (annual/seasonal, water yield, and flow duration curve). In fact, with the use of remote sensing, vegetation index during a long period could be used to establish correlation with runoff in a certain controlled area; thus, the effect of vegetation change on runoff could be analyzed without paired catchment experiments and forest cut.

The Qilian Mountain is the main water resource of the Hexi Corridor. However, not all areas of the mountains produce water. All catchments can be divided into water production and water consumption areas. In the regional or inter-catchment scale, isotopes could be used to trace the water resource and identify the principal regional water source during several catchments (Eastoe and Rodney, 2014). Since water is the most critical factor in agricultural production in the Hexi Corridor, delimitation of water production zones of mountains have practical significance in the study of water regulation processes and hydrological service assessment.

Ecosystems can reallocate precipitation, the increasing amount of forest can reduce summer streamflow in many watersheds in the Qilian Mountain (Miao *et al.*, 2006), and the streamflow of small catchment can be reduced to zero when grasslands or shrubland convert to forest (Yu *et al.*, 2010). However, those are the water regulation on the site and slope scales. In a catchment of the Qilian Mountain, high-altitude areas above the forest belt usually produce runoff, while the low-altitude forest belt plays a role of water consumption. Thus, the catchment as a geographical unit usually produces runoff. Furthermore, what we should think is the primary service we need providing by mountain ecosystems—water supply? Flood control? Woody product? Or biodiversity? We can not greedily have everything at the same time. Land patterns may have an influence on hydrological processes, as Yang *et al.* (2005a) suggest that planting forests on a large scale can maximize the eco-benefits. However, landscape fragmentation may have a negative effect on water conservation. Thus, we must find a balance among different services.

In the northwestern China, agricultural activities generally take place from late spring to early autumn, which contribute the most to water consumption compared with daily human/industrial uses, and rapid urbanization requirement of large amount of water. Flood means accumulation of rich silt in the middle and lower reaches of inland rivers in the northwestern China. Conservation of floodplain wetlands appears to be far more efficient than that of small water storage ponds in the consideration of economic and hydrological criteria (Grygoruk, 2013). However, the problem is how to define the positive/negative ecological effects of forests on flood control. The trade-off between the numerous benefits associated with increasing forests and the probably negative impact on water production must be carefully discussed in regards to the Qilian Mountain—from mechanism to scenario prediction and from site scale to region.

The Qilian Mountain is the upstream of many inland rivers. Without the constraint of a natural mountain edge, the regional scale of inter-provincial studies can be carried on, according to the definition of ′green water′ and ′blue water′ (Falkenmark and Rockström, 2006), in which the water used by ecosystems to maintain the lives and energy balance is ′green water′, while the water used by humans from rivers and groundwater is ′blue water′. In this study, our work mainly includes three aspects: the first is evaluating the hydrological service capacity and its threshold, the second is estimating the responses of hydrological service to different climate scenarios and utilization modes, and the third is modeling the potential variation in the water supplement in the middle-lower reaches (annual/seasonal variation and inter-annual variation) based on the current scenario, traditional theories, and forefront international insights. All conclusions should keep a balance between the natural development of the ecosystem and the human benefits.

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