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中国主要森林生态系统水文功能的比较研究

刘世荣[1]　孙鹏森[1]　温远光[2]
（1 中国林业科学研究院森林生态环境与保护研究所，北京　100091）
（2 广西大学林学院，南宁　530001）

摘　要　基于中国不同区域生态站的观测资料，着重从降雨截留（林冠截留、枯枝落叶层截持和土壤蓄水）、调节径流和蒸散等 3 个方面对我国主要森林生态系统的水文生态功能进行了比较研究。各生态系统林冠年截留量在 134～626 mm 间变动，由大到小排列为 热带山地雨林，亚热带西部山地常绿针叶林，热带半落叶季雨林，温带山地落叶与常绿针叶林，寒温带、温带山地常绿针叶林，亚热带竹林，亚热带、热带东部山地常绿针叶林，寒温带、温带山地落叶针叶林，温带、亚热带落叶阔叶林，亚热带山区常绿阔叶林，亚热带、热带西南山地常绿针叶林，南亚热带常绿阔叶林，亚热带山地常绿阔叶林。枯落物持水量可以达到自身干重的 2～5 倍，但也因林型而异。土壤非毛管持水量变动在 36～142 mm 之间，平均 89 mm。常绿阔叶林的非毛管持水量通常高于 100 mm，而寒温带/温带落叶阔叶林和常绿针叶林通常低于 100 mm. 土壤的非毛管持水量通常占生态系统中截持水量的 90%，其次是枯落物和林冠层。这说明，森林土壤在调节降雨截留中占有重要地位，其水文功能的大小取决于土壤结构和空隙度，而这些恰恰又受枯落物和森林植被特征的影响。森林皆伐后，一般地表径流会显著地增加，而适当抚育措施则对地表径流影响不大。流域径流受诸多因素的影响，包括植被、土壤、气候、地形、地貌以及人类影响导致的流域景观变化，比较研究表明森林变化对流域径流的影响尚未得到一致的规律性的结果。通过对比研究不同森林的蒸散变化，发现随降雨量的增加，森林蒸散量略有增加，而相对蒸散率却在下降，相对蒸散率在 40%～90%间变动。

关键词　森林生态系统　降水截留　持水量　径流　蒸散

COMPARATIVE ANALYSIS OF HYDROLOGICAL FUNCTIONS OF MAJOR FOREST ECOSYSTEMS IN CHINA

LIU Shi-Rong[1]　SUN Peng-Sen[1] and WEN Yuan-Guang[2]
（1 *Research Institute of Forest Ecology*，*Environment and Protection*，*the Chinese Academy of Forestry*，*Beijing* 100091，China）
（2 *College of Forestry*，*University of Guangxi*，*Nanning* 530001，China）

Abstract　Based on case studies from nearly 20 forest ecological stations in different bioregions of China，the characteristics of eco-hydrological functions of forest ecosystems were studied in terms of canopy interception，soil-water storage and holding capacity. Annual canopy rainfall interception ranged from 134 to 626 mm，and was ranked in the descending order as follows：tropical mountain rain forest，subtropical western mountain evergreen coniferous forest，tropical semi-deciduous monsoon forest，temperate mountain deciduous/evergreen coniferous forest，cold-temperate/temperate mountain evergreen coniferous forest，subtropical bamboo forest，subtropical/tropical eastern mountain evergreen coniferous forest，cold-temperate/temperate mountain deciduous coniferous forest，temperate/subtropical deciduous broadleaf forest，subtropical mountain evergreen broadleaf forest，subtropical/tropical south-west mountain evergreen coniferous forest，south subtropical evergreen broadleaf forest，and subtropical mountain evergreen/broadleaf forest. The moisture holding capacity of litter was about two-to-five times its dry-weight，but varied with forest type. The soil non-capillary moisture capacity of forests ranged from 36 to 142 mm with an average of 89 mm. Non-capillary capacity of evergreen broadleaf forests was more than 100 mm，but was less than 100 mm in the cold-temperate/temperate deciduous broadleaf and evergreen coniferous forests. From an ecosystem point of view，the soil non-capillary holding capacity counted for more than 90% of the total，followed by forest litter，which ranged from 3 to 10 mm，and canopy interception only occupied a small proportion（less than 2 mm）. This indicates that forest soils play a significant role in regulating rainfall interception. The hydrological role of forest soil depends on its structure and porosity，which is further affected by litter-fall and forest vegetation on sites. There was no consistent re-

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sult with respect to the relationship between forest cover and annual runoff based on paired comparison of forest watersheds or direct measurements of the same forest watershed with a change of forest cover over time. Soil surface runoff was found to increase remarkably after forest logging, in particular, after clear-cut on a large scale irrespective of forest types or regions. An appropriate thinning or tending practices, however, could reduce soil surface runoff to a certain degree in forest watersheds. With increasing precipitation, forest evapo-transpiration increased slightly, while the Relative Evapo-transpiration Ratio (RER) decreased with the RER variation ranging from 40% to 90%.

Key words Forest ecosystems, Rainfall interception, Moisture holding capacity, Runoff, Evapo-transpiration

With increasing population and development of urbanization, human needs for exploration and utilization of forest resource are greatly amplified, which can result in forest damage, shifts from forest to cultivation, drainage of wetlands, agricultural irrigation, air pollution and climate change, etc. These anthropogenic activities have disturbed the balance among evaporation, surface runoff and recharge of underground water, and have altered natural runoff and evaporation processes and consequently lead to water and soil erosion, water pollution, drought and desertification, and frequent flood and storm catastrophes followed by famine and human suffering in many areas of China where forest hydrological functions have been neglected or misused during the past several decades. This is increasingly concerned throughout China and at the same time, it stimulates extensive research in the field of eco-hydrological functions of forest ecosystems (Liu *et al*., 1996).

Long-term measurements on hydrological function of forest ecosystems in China were initiated in the middle of 20th century, but the extensive work was made after 1970s. Since 1970, a number of forest ecological stations have been established all over the country, covering from boreal zone to tropical zone and they offer the most favorable conditions to study the characteristics of hydrological functions of forest ecosystems depending on different physiographical environments. These forest ecological stations have long been making observations and measurements of forest hydrological processes in terms of rainfall interception, soil water dynamics, water cycle, water quality, as well as regulation of flood and runoff, and a large amount of available hydrological data information from case studies in each station has already accumulated up. Their individual efforts over the past 20 years provide a solid basis to make comparative and comprehensive analyses of forest hydrological functions at regional and national scales.

In this study, we aimed at comparatively analyzing spatial variation of hydrological characteristics of the main forest ecosystems in different geographical zones in China according to the three structural layers, i.e. canopy, litter and soil; quantifying effects of forest structure and precipitation process on rainfall interception and runoff out of forest ecosystem, and assessing effects of forest practices on soil and water resources. The study helps to explore sustainable management strategies of forest ecosystem ensuring sustainability and stability of forest watershed, and to develop the scientific basis for an integrated management of optimizing forest hydrological functions.

1 Method

Based on case studies from nearly 20 forest ecological stations (listed in the acknowledgement) of different bioregions in China, the hydrological characteristics of forest ecosystems that include 13 major natural forest types were studied in terms of rainfall interception, soil water storage and holding capacity. Measurement of rainfall, through fall, stem flow, litter fall and its water holding capacity, soil pore, soil moisture and soil water permeability were carried out in controlled forested catchments in each station, and runoff processes were measured both in a small- and large-scale watershed. The typical experimental design was unified among stations according to methodological guidelines formulated by the Department of Science and Technology, the Ministry of Forestry (Ma, 1994).

Empirical and semi-empirical models of canopy interception were developed to describe quantitative relationship between canopy interception and precipitation. Canopy interception, litter-fall water holding capacity, soil water storage and soil water permeability between forests were compared and analysis of multiple comparison variance was used to determine statistically significant differences between each pairs of forests.

GIS-based models were developed and used to simulate geographic pattern of canopy rainfall interception (Liu *et al*., 1996; Wang *et al*., 1997).

Water balance model and energy balance model (Penman-Monteith equation) were used to simulate the stand evaportranspiration (Fang & Gao, 1988; Zeng, 1994; Xu & Zeng, 1985).

2 Results

2.1 Rainfall interception

2.1.1 Canopy interception

Canopy interception is an important process of forest hydrological function. Measurements of canopy interception expressed a consistent intendancy that there was a strong positive relationship between precipitation and canopy interception, i.e. canopy interception increased with increasing precipitation but it tended to attenuate with increasing duration of rainfall until up to saturation point where forest canopy reached its maximum water holding capacity. The correlation models of canopy interception and precipitation varied with forest types, some were linear (Xu & Hu, 1992; Xiao & Song, 1993; Lu & Zeng, 1982), and others were exponential (Kong *et al.*, 1990; Ma, 1993; Cao, 1991).

The average canopy interception of forests in China ranged from 134 mm to 843 mm. Canopy interception ratio was between 11% and 37% (Fig. 1). There were no statistically significant differences in canopy interception between each pairs of forests for the majority of forests. Variation coefficients of interception and interception ratio were 14%-41% and 7%-55%, respectively, indicating a large variation of canopy interception that resulted only from several forest types, such as semi-deciduous monsoon rain forest, oak forest (*Quercus aliena* var. *acuteserrata*), Chinese scots pine and larch forest. As for the average canopy interception ratio, the descending sequence was: subtropical western mountain evergreen coniferous forest (Sub-alpine), tropical semi-deciduous monsoon forest (Monson F.), tropical mountain rain forest (Rain F.), temperate mountain deciduous/evergreen coniferous forest, cold-temperate/temperate mountain evergreen coniferous forest (CT.E.CF), subtropical bamboo forest, subtropical/tropical eastern mountain evergreen coniferous forest, cold-temperate/temperate mountain deciduous coniferous forest (CT. D.CF), south subtropical evergreen broadleaf forest, subtropical mountain evergreen/broadleaf forest (Fig. 1). In addition to precipitation, canopy interception was also affected by canopy structure and coverage. Natural forests with multiple spatial structure and dense canopy coverage have a larger canopy interception compared to secondary natural regenerated forests and plantation (Table 1).

The GIS-based simulation indicated that the geographic pattern of canopy interception largely depended on precipitation pattern, i.e. decreased with increasing latitude, and increased with increasing elevation. High interception rate could not be simply interpreted as a good indicator of water conservation function. In arid area or during dry season, 20%-30% precipitation loss through canopy interception suggests that it is of disadvantage to tree growth and limited water resource conservation.

Due to predominant effects of the southeast monsoon in summer and the complexity of undulating topography, there is uneven distribution of precipitation in terms of spatial and temporal pattern among regions. However, the regular spatial pattern of annual precipitation still exists in China. The annual precipitation decreases gradually from 2 000 mm of the seashore southeast to 200-100 mm or below 50 mm of inland northwest, from 1 000 mm of the south wet area to 250-350 mm of the north dry area. Consequently, this resulted in occurrence of the similar geographical pattern of canopy interception. Canopy interception decreased from east to west, from south to north. The interception ratio, however, changed in the reverse direction. The following model of canopy interception was developed based on 47 case studies in China covering boreal forests in the north down to rain forests in the south.

$$I = 3.67\times10^{-5} N^{-1.692\,93} E^{4.487\,5} A^{0.011\,585\,4} \ (r = 0.751\,1^{**}\ F = 28.469\,5^{**}\ n = 47)$$

Where I is canopy interception, N is latitude, E is longitude and A is altitude.

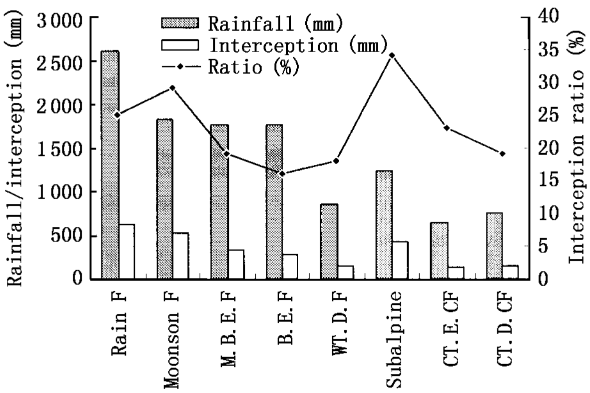

Fig.1 Canopy interception ratio of different major forest types in China

Rain F: Tropical mountain rain forest Monsoon F: Tropical semi-deciduous monsoon forest M.B.E.F: Subtropical mountain evergreen/broadleaf forest B.E.F: South subtropical evergreen broadleaf forest WT.D.F: Warm temperate mountain deciduous/evergreen coniferous forest Subalpine: Subalpine coniferous forest CT.E.CF: Cold-temperate-temperate mountain evergreen coniferous forest CT.D.CF: Cold-temperate/temperate mountain deciduous coniferous forest

Table 1 Comparison of canopy interception ratios among different temperate forests

Forest type	Ratio
Natural forest	20%-30%
Secondary forest	19%-25%
Pine plantation	18%-23%

2.1.2 Litter interception

Amount of standing crop of litter on forest floor varies with forest types and litter composition varies with forest types as well. Field measurements of litter biomass indicated that an average amount of major forest types in China ranged from 3.5 $t\cdot hm^{-2}$ to 26.8 $t\cdot hm^{-2}$, with variation coefficient between 18% and 68% among forests. The descending sequence order was: cold-temperate/temperate mountain deciduous coniferous forest, temperate mountain deciduous/evergreen coniferous forest, subtropical/tropical eastern mountain evergreen coniferous forest, subtropical bamboo forest, south subtropical evergreen broadleaf forest, tropical semi-deciduous monsoon forest, and tropical mountain rain forest.

It was found that water holding capacity (WHC) of litter can be 2-5 times larger than its dry mass. The maximum value of water interception by litter reached 4 mm and its interception ratio of fully water-saturated weight to its dry mass can be more than 400% (Fig.2). The larger the standing crop of litter, the greater the WHC of litter. Even though WHC of forest litter largely depended on the quantity of litter, it was also affected to the certain extent by the quality of litter. WHC of mixed broadleaf/coniferous forests or broadleaf forests was larger than that of coniferous forests.

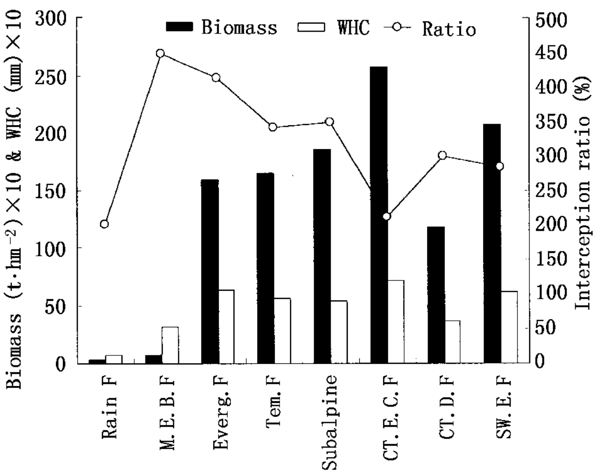

Fig.2 Water holding capacity and interception ratio of forest litter

2.1.3 Water storage in forest soil and Permeability

There is a close correlation between soil water storage and soil porosity. In fact, soil water storage largely depends on soil macro-pore or non-capillary pore, rather than capillary because soil macro-pores is main channels for gravitational water flow and therefore it is critical to conservation and regulation of water resource. Forests in the tropical and subtropical areas had well-developed soil porosity with non-capillarity ranging from 12% to 26%, compared to forests in the temperate and cold-temperate regions with non-capillarity of less than 12%. Therefore, tropical and subtropical forests had larger soil water storage (from 100 mm to 150 mm) than the cold-temperate/temperate forests (from 36 mm to 90 mm) (Fig. 3).

Soil water storage and permeability varies with vegetation types. In temperate region, natural forest had the largest values of both soil water storage and steady-state permeability, i.e. 628 $t \cdot hm^{-2}$ and 4-5 $mm \cdot min^{-1}$, respectively, followed by secondary forest, shrub, pine plantation and grassland (Table 2).

2.2 Runoff

There were many factors underlying the mechanism of ecosystem runoff processes, including forest structure, age, spatial coverage and pattern, and other factors in terms of climate, topography, geology, soil structure and all kinds of disturbances. The following comparisons were made in paired watersheds with similar geographical characters or in the same watershed but with change of forest coverage over time.

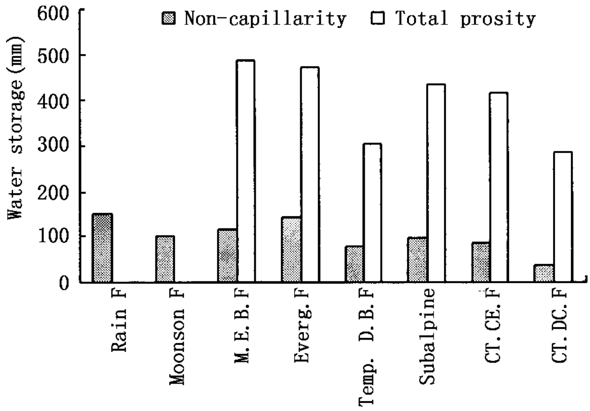

Fig.3 Water storage in forest soil (0-60 cm)

Table 2 Soil water storage and permeability

Vegetation types	Water storage ($t \cdot hm^{-2}$)	Permeability ($mm \cdot min^{-1}$)
Natural forest	628	4-5
Secondary forest	552	3-4.5
Shruband	447	4
Pine plantation	386	3-4
Grass land	320	2

In Yellow River, annual discharges of runoff in forested watersheds were found to be significantly lower than that in less forested or non-forested watersheds irrespective of watershed scale. However, flood discharge modulus in forested areas were greatly reduced by up to 90% compared to non-forested areas.

In Yangtze River, annual runoff in forested watersheds was frequently larger than that in the watersheds with reduction of forest coverage. For example, several case studies in Minjiang River indicated that annual discharge was reduced after forest logging regardless of watershed scale. In addition, forest logging also modified runoff process in Minjiang River. A 10%-15% reduction in forest coverage was accompanied by an increase in the ratio of surface runoff to underground discharge from 7:2 to 8:2, and increasing flood discharge in rainy season as well, but discharge reduced during dry season (Ma, 1963). In Wenjin River, another tributary of the upper reaches of Yangtze River, 4.66% reduction of forest cover over the period of 1960s to 1980s resulted in 46 mm increment of the annual runoff with no significant change in annual precipitation (Liu *et al*., 2001).

Logging intensity is an important factor affecting runoff. An appropriate forest thinning and tending tended to decrease surface runoff in forested watersheds. Clear cut, however, led to an increase in surface runoff. Experiments in small catchments indicated that surface runoff, inter-soil flow and total runoff in natural oak stand increased by 7.8%, 3.3% and 14.5%, respectively, after clear cut, while deep soil flow, which eventually goes into underground water, was reduced by 12.1% (Wei & Zhou, 1991). The similar results were found in Korea pine stand after clear-cut that there was a large increase in surface runoff (Table 3).

Table 3 Surface runoffs of forest catchments or watersheds under different cutting intensities

Types	Area (m^2)	Rainfall (mm)	Surface runoff (mm)	Ratio (%)
Oak contrast	500	651	13.60	2.91
Oak tending (50%)	500	651	13.14	2.01
Oak clear cut	500	651	34.40	5.25
Korea pine contrast	1 000	728	13.10	1.80
Korea pine clear cut	1 000	728	88.80	12.4

2.3 Evaportranspiration

Evaportranspiration was often calculated as the residuals of water balance of an ecosystem and direct measurements were hardly made in early time. Evaportranspiration varies with tree species, age, altitude and precipitation; it is a synthetic result of biological and environmental interaction. It is difficult to explore its geographical pattern of spatial variation as the result of lacking of adequate field measurement data. Table 4 is the list of nearly dozen of case studies in China. It was found that forest evaportranspiration increased slightly with the increasing of precipitation, while the relative evaportranspiration ratio (RER, percentage of evaportranspiration to the total precipitation) decreased. In general, the variation of RER was between 40% and 90% (Table 4).

3 Discussions

The effects of forest on rainfall interception is an integrated processes including canopy, forest litter and soil profile. Even though canopy interception varied with forest types in the comparative analysis of 47 case studies that indicated a statistically significant difference in canopy interception among forests, but only several forest types were found to cause such a significant difference in canopy interception with other forests when multiple variation comparison was employed to make mutual comparison of forest types in pair. They included the semi-deciduous monsoon rain forest, subtropical mountain evergreen forest, oak forest (*Quercus aliena* var. *acuteserrata*), Chinese scote pine and larch forest. The further insight suggested that microenvironment accounted largely for this phenomenon rather than forest types. Subtropical mountain evergreen forests was supposed to possess a powerful capacity of intercepting rainfall because of its multiple spatial structure, but it was offset by very wet environments that made canopy fully saturated with water. In the opposite, even though scote pine plantation had a sparse canopy structure, it could intercept and absorb more rainwater because of growing in arid climate and the resultant dry canopy.

Compared to forest canopy and litter, forest soil played a significant role in intercepting and absorbing rainfall, which accounted for more than 90% of the total. However, canopy and litter performed different functions in an ecosystem. Except rainfall interception as the first boundary layer, canopy support matter production and water and carbon exchange processes, in particular, evaportranspiration mainly through canopy. Litter has a special role in reducing impulsive force of falling rainwater lashing at the soils, leading to water and soil erosion (Ma, 1993). Actually, forest canopy, litter and soil interact each other and work in a consolidated way. To this end, structure and function of forest soils are largely dependent on root system and litters, which are further affected by canopy processes (Liu *et al*., 1996). Based on the comparative results that both natural forests and mixed stands have a better hydrological function than pure conifer, shrub and grassland, it is encouraged that well-structured forest composed of multiple spatial layers and diversified tree species should be established for water and soil conservation.

It is well understood that effects of forest on runoff in a small forested catchments. In general, annual discharge was frequently found to increase after logging in warm-humid southern area, while it usually decreased in semi-arid and arid area. Nevertheless, there were still some exceptional cases as indicated in our comparative analysis based on several case studies. There were no consistent results and generalized conclusions having been made so far with respect to the relationship between runoff and forest cover change if spatial scale was extended from a small watershed to a large watershed (Li *et al*., 2001). It was believed that runoff in a forested watershed is a very complex process, which is affected many factors, including climate, soils, topography, land-cover and land use change, forest composition, age and spatial landscape pattern, as well as structural characteristics of river course (Ma, 1993; Liu *et al*., 1996). Thus, there were many factors accounting for the formation and development of runoff processes in a large watershed and any change of those influencing factors could result in changes of river runoff. Even though we have common understanding of effects of forest logging on surface runoff and forest coverage is good indicator for forest, it was very hard to extrapolate that the observational result of either an increase or

Table 4 Comparison of evaportranspiration among different types of forest ecosystems

Forest types	Locations	Latitude (N)	Longitude (E)	Age (a)	Altitude (m)	Annual temp. (℃)	P (mm)	E (mm)	RER (%)	Sources
Korean pine	Xiaoxing'anling	47°51′	129°52′			1	716	602	84	Zhu, 1982
Japanese birch	Maoershan	45°24′	129°98′	40	373	2.6	700	554	89	Ren & Zhang, 1991
Oak	Maoershan	45°24′	129°98′		373	2.6	700	504	77	Wei & Zhou, 1991
Larch	Maoershan	54°16′	129°34′	21	350	2.8	666	426	64	Liu *et al*., 1992
Chinese pine	Longhua, Hebei province	41°7′	117°5′	26			500	465	93	Fang & Gao, 1988
Chinese pine	Xishan, Beijing	39°54′	116°28′	33	375	11.8	630	315	50	He & Lu, 1992
Armand pine	Qinling (South)	34°10′	106°28′		1 710-2 000		672-757	398-630	54-74	Zhang, 1989
Fir	Miyaluo, Sichuan province	31°43′	102°39′	160	3 600	6.5	700-900	520-564	30-40	Ma, 1963
Chinese fir	Huitong, Hunan province	26°50′	109°45′			16.8	1 158	896	77	Tian & Kang, 1993
Monsoon forest	Hainan province	18°40′	129°29′			24.5		520-540	41-58	Xu & Zeng, 1985
Monsoon forest	Hainan province	18°40′	129°29′			24.5	1 590	677	42.6	Zeng, 1994

RER: Percentage of evaportranspiration to the total precipitation

decrease in river runoff was due directly to change of forest cover.

In fact, the mechanism underlying the interaction of forest and runoff in a heterogeneous landscape has been poorly understood. Forest was a concern of all comparative analysis either in paired watersheds or in the same watershed, but it was just defined as a single and simple cover indicator, rather than whole ecosystem processes, i.e., without the consideration of phonological variation, physiological change, forest composition and spatial pattern. In addition, heterogeneities of climate, soils and topography were not adequately addressed in a large watershed.

4 Future issues to be explored

Due to complexity and interaction of so many influencing factors it is essential to understand the mechanism of forests regulating runoff processes with other environmental factors. Development of eco-hydrological process-based models is an important approach addressing the interaction of ecological and hydrological processes in a heterogeneous watershed. The simulation could improve the understandings of eco-hydrological processes and mechanisms that forest vegetation may acts. Because of the nonlinear characteristics and scaling effects of terrestrial eco-hydrological processes, the process-based distributed hydrological model based on slope profile or small catchments could not be directly applied to make an explicit prediction of runoff process in a large watershed. On the other hand, the eco-hydrological function of forest vegetation could not be quantitatively evaluated if the ecological and hydrological processes are not adequately coupled. This is because eco-hydrological process is rather than a physical process of water movement. Therefore, the following issues should be highly concerned and need to be explored in future research: development of macro-scale eco-hydrological model, scaling effects in terms of definition and comparability of spatial scale and temporal scale, integration of process-based modeling with geographic information system, elaboration of high resolution data sets including land use, land use change and vegetation cover, soil texture, potential evaportranspiration, precipitation, temperature.

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