Journal of Environmental Sciences Vol.16, No.5, pp.722—729, 2004

ISSN 1001—0742
CN11—2629/X

Article ID: 1001-0742(2004)05-0722-08 **CLC number**: X171 **Document code**: A

Streamwater chemistry and flow dynamics along vegetation-soil gradient in a subalpine *Abies fabri* forest watershed, China

SHAN Bao-qing* , WANG Wei-dong, YIN Cheng-qing

(SKLEAC, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China. E-mail: bqshan@mail.rcees.ac.cn)

Abstract: Streamwater chemistry and spatial flow dynamics from a subalpine *Abies fabri* forest in an experimental watershed located in the east slope of Gongga Mountain were analyzed to gain insights into the gradient effect of primary community succession on the stream biogeochemical process. Results showed that high sand content (exceeding 80%) and porosity in the soil (exceeding 20% in A horizon and 35% in B horizon), as well as a thick humus layer on the soil surface, made the water exchange quickly in the Huangbengliu (HBL) watershed. Consequently, no surface runoff was observed, and the stream discharge changed rapidly with the daily precipitation. The flow trends of base ions in the stream water were influenced by the *Abies fabri* succession gradient. Ca^{2+}, HCO_3^- and SO_4^{2-} were the dominant anions in the streamwater in this region. A significant difference of Ca^{2+}, HCO_3^- and SO_4^{2-} concentration exported between the succession stages in the watershed can be found. But they had the similar temporal change in the stream flow. Ca^{2+}, HCO_3^- and SO_4^{2-} showed significantly negative correlations with the daily precipitation and the stream discharge.

Concentrations of Cl^-, Na^+, K^+, and Mg^{2+} were low in all streamwaters monitored and we observed no differences along the *Abies fabri* succession gradient. Low ratios of Na:(Na + Ca) (range from 0.1 to 0.2) implied cations were from bedrock weathering (internal source process in the soil system) in this region. But, a variance analysis showed there were almost no differences between rainwater and streamwaters for Mg^{2+}, Na^+, K^+, and Cl^- concentrations. This indicated that they might be come from rainfall inputs (external source). The highly mobile capacity, rapid water exchange between precipitation and discharge, and long-term export lead to this observed pattern were suggested.

Keywords: water chemistry; succession; subalpine coniferous forest; *Abies fabri*; watershed; Gongga Mt.

Introduction

Spatial patterns of streamwater chemistry can provide valuable evidence of the effects of environmental change, and a better understanding of ecosystem biogeochemical processes at different regional scale (Martin, 2000). In a forest ecosystem, there are many environmental factors which can influence material fluxes (Likens, 1995; Hudson, 1997; Hessling, 1999; Caldentey, 2001) between the time water enters a watershed as rainfall and leaves it from the outlet stream. During this period, water comes in contact with various ecosystem components. Each component has its own dynamic environment that can alter or influence water chemistry (Kimmins, 1987; Stednick, 1996; Markewitz, 2001).

Many studies have found that streamwater concentrations of some solutes are highly correlated with elevation, vegetation cover and landscape history. The concentration and flow dynamics of streamwater chemistry often shows a significant spatial and seasonal difference due to special local microclimate variation and/or plant growth (Toetz, 1995; Likens, 1995; Christmas, 1998; Havel, 1999; Mandernack, 2000; Holloway, 2001; Markewitz, 2001). This variation of material flux is a key factor for influencing the fate of base ions in the streamwater (Soulsby, 1999). For example, in high mountain regions with cold-wet conditions, the spring phenomenon of increasing ion concentrations in the stream over a short time due to snowmelt and ice thawing is found often (Holloway, 2001).

Due to these strong relationships among vegetation characteristics (e. g., community structure, species composition, stand age, etc.), hydrology and streamwater chemistry, a long history for researchers to use their links to study the biogeochemical process of base ions in the streamwater at the watershed scale has been existed (Chorley, 1964; Johnson, 1969; Sklash, 1976; DeWalle, 1988; Christophersen, 1990; Eshleman, 1993; Cassie, 1996). Comparative analysis along the natural gradient of vegetation development is an effective way to study the spatial effects of biogeochemical processes in the streamwater.

The subalpine or alpine mountain environment is a special ecosystem which is usually affected by less human intervention. Consequently, it can provide an ideal condition for studying global change and materials cycling (Toetz, 1995). An unimpacted or minimally disturbed environment is useful for understanding the interaction between habitat and water chemistry. In China, the Gongga Mountain is located in the middle and south sections of the Daxue Mountain (Big Snow Mountain) Range, and on the southeastern fringe of the Qinghai-Tibetan Plateau. The Gongga Mountain is distributed in the junction of Luding, Kangding, Jiulong and Shimian counties with the longitude of 29°20′—30°20′ N and the latitude of 101°30′—102°15′ E. Stretching from south to north the Gongga Mountain covers an area of 10000 km^2 and is the highest peak (7556 m) in the Hengduan Mountain Chain. Characterizing an intact vertical zonality from the

---

Foundation item: The National Natural Sciences Foundation of China (No. 39930130); * Corresponding author

subtropical to frigid zone, complicated geological structure, obvious transitional climate, abundant biodiversity, as well as wide-ranging low-elevation modern glaciers, the Gongga Mountain provides an ideal site for scientific research(Chen, 1992; Zhong, 1997; 1999). Since the early 20th century, many studies have been conducted on the Gongga Mountain range(Gregory, 1923; Trinkler, 1930; Rock, 1930; Heim, 1931; Lee, 1931; Burdsoil, 1935; Heim, 1936).

Due to its particular geography, hydrology and ecology, a long-term field observation station named Alpine Ecosystem Observation & Experiment Station of Gongga Mount was set up by the Chinese Academy of Sciences. As an important research and monitor site of ecological and hydrological process in China, many studies on vegetation, hydrology and glacier have been conducted in recent years (Li, 1985; Chen, 1992; 1995; Zhen, 1993; Wang, 1995; Cheng, 1996; Zhong, 1997; 1999; Wu, 1999). But, most studies focused on vegetation, meteorology, hydrology and glacial processes. Research on streamwater chemistry in this region is sparse. In this paper, we conducted a spring investigation of the streamwater chemistry characteristics, emphasizing the spatial effects along different succession serials of community. The primary objective of our study was to determine the streamwater chemistry pattern and flow dynamics in early spring in a subalpine *Abies fabri* forest watershed located in the Gongga Mountain. A secondary objective was to determine if primary community succession has observable spatial gradient effects on streamwater chemistry characteristics.

1 Materials and methods

1.1 Study area

The Gongga Mountain Region is located in the transitional region from the subtropical monsoon climate zone to frigid climate zone of the Qinghai-Tibet Plateau. The influence of east-southern monsoon from the Pacific causes this region to be characterized by high precipitation, cloudy days, cold winters and cool summers. Due to the large elevation gradient difference, the annual mean precipitation in the Gongga Mountain regions is 1940 mm; this is substantially higher than the neighboring regions. The Gongga Mountain Region has 260 rain days every year. Rain intensity is generally low and average daily precipitation ranges between 10 to 20 mm. The climate is cold and wet, and the long winter generally begins with snow from early November and thaws in early May the next year (Yi, 2000; Xie, 2001).

In this study, we examined an experimental watershed named Huangbengliu(HBL) located in Hailuogou gully on the east slope of the Gongga Mountain (Fig.1). Alpine Ecosystem Observation and Experiment Station of Gongga Mount(3000 m observation plot), the Chinese Academy of Sciences is located in this sector. It was convenient for conducting field monitoring.

The HBL watershed covers an experimental area of 7.47 km^2, and is mainly composed of four subwatersheds which are Xiangsiyan (XSYs, 3.06 km^2), Huangbengliu (HBLs, 1.50 km^2), Madaogou(MDGs, 0.41 km^2) and Guanjingtai (GJTs, 1.05 km^2). Located in the watershed is the Huangbengliu River (5.06 km), which has four small tributary streams(Fig.1). In this study, the stream outlet of the watershed and three other subwatersheds (XSYs, HBLs and GJTs) were monitored for a comparative analysis of streamwater chemistry and flow dynamics along a succession gradient of the forest community. Stream flow in MDGs is short, and happens only during summer(Jun.—Jul.). Since study was carried out in late May, the MDGs stream outlet was not monitored.

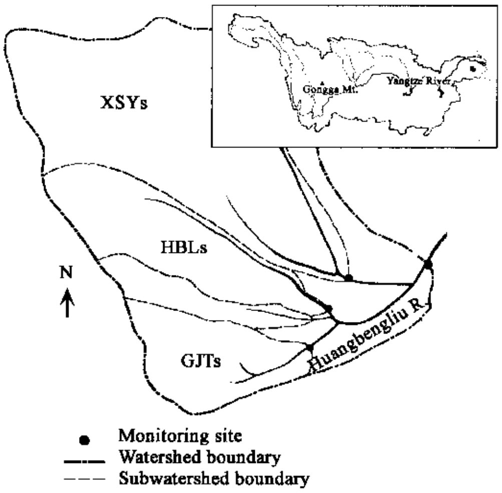

Fig.1 Location of the Huangbengliu (HBL) watershed and study sites within the Gongga Mountain, China
XSYs: Xiangsiyan subwatershed; HBLs: Huangbengliu subwatershed; GJTs: Guanjingtai subwatershed

The study area has a cold-wet mountain climate characterized by an annual mean precipitation of 1966 mm. Annual mean temperature is 4℃, with a mean temperatures -4.5℃ in January and 12.7℃ in July. Annual evaporation is 345 mm. Mean annual relative humidity in this area is high at 90%. Although it rains frequently, the total volume of precipitation events is low; storm events exceeding 30 mm are rare. Winter is long(late Oct. to early May) with an annual snowfall of 350 mm(Zhong, 1997).

1.2 Vegetation and soil

Subalpine dark coniferous forest is the dominant vegetation type in the Gongga Mountain Region and its altitude ranges from 2500 m to 3600 m on the east slope, and from 2800 m to 4000 m on the west slope. *Abies fabri* is one of the main dominant species. Since the region is located at the headwater region of the Yangtse River, subalpine dark forest has an important ecological function for hydrological control.

In the HBL watershed, virgin forest and shrub is 70% of the whole watershed area. The forest is located at the bottom and middle part of the watershed with the altitude ranging from 2800—4200 m. Alpine meadow appears in the watershed where the elevation exceeds 4200 m. It has a seasonal snow cover when the elevation exceeds 4000 m.

Abies fabri forest is the climax mature community in the HBL watershed. In the arborous layer there are *Abies fabri*, *Betula utilis*, *Populus purodmii*, *Salix* spp., and *Hippophae rhamnoides*. In the shrub layer, there are *Rhododendron calophytum*, *Rh. Maculiferum*, *Rh. lutescens*, *Rh. dendrocharis*, *Viburnum cordifolium*, and *Euonymus dasydictyon*. In the grass layer, there are *Ctenitis elarkei*, *Carex schneideri* and so on. The total biomass live-weight is approximately 350000 kg/hm^2. Among them, *Abies fabri* biomass live-weight is roughly 320000 kg/hm^2. The average age of a tree is 100—150 years. It is the important virgin forest species in this region(Luo, 1998).

The vegetation is developed from the debris flow slash in the HBL watershed. Beginning from the bottom part of the watershed, we observed a complete primary succession serial of community. Debris flow slash is a submarine bulge accumulated by debris flow. In slash, there are pioneer species like *Salix* spp., *Papulus purdomii*, *Hippophae rhamnoides* and other related species like *Betula* spp., and *Abies fabri*. In the high forest, there are more than ten kinds of azaleas. Folllowing the end of debris flow accumulations five years later, *Salix* spp., *Papulus purdomii*, and *Hippophae rhamnoides* seedlings association appeared. In 19 years it evolved into *Papulus purdomii* sapling and *Abies fabri* seedling association; in 47 years, the dominant species were *Papulus purdomii* medium-tree and *Abies fabri* sapling association; in 68 years, it was dominated by *Papulus purdomii* great trees and *Abies fabri* medium-tree association, 86 years *Abies fabri*, *Papulus purdomii* great tree association; and finally after 170 years, *Abies fabri* reached climax(Pan, 1994; Luo, 1998).

The succession stage is different in the three subwatersheds(Table 1). The forest area accounts for 30% of the whole area in the XSYs subwatershed; its succession serial of community is initial and middle stage and the dominant species are *Populus purdomii* and *Abies fabri*. The succession stage is mature-climax(aging 153 years) in HBLs and over-mature climax (age surpassing 400 years) GJTs subwatershed respectively; their dominant species is *Abies fabri*. In HBL watershed, the soil was characterized by a thin soil horizon, low horizon numbers, low pH value, high ratio of porosity and sand, and high organic matter content (Table 2).

Table 1 Vegetation characteristics of three subwatersheds in the Huangbengliu(HBL) watershed

Subwatershed*		Community characteristics			Species number					Dominant species			
Name	Area, km^2	Type	Age, yrs	Succession stage	Tree	Shrub	Herb	Total	Tree coverage, %	Name	Mean height, m	Mean age, yrs	Basal area, m^2/hm^2
XSYs	3.06	*Populus-Salix* forest	34	Initial	8	23	25	56	90	*Populus purdomii*	10.8	23.4	6.48
		Populus-Abies forest	61	Medium	16	40	30	86	60	*Populus purdomii*	22.0	49.8	13.65
		Abies middle-aged forest	82	Medium	8	17	21	46	95	*Abies fabri*	26.6	56.3	29.79
HBLs	1.50	*Abies* mature forest	153	Climax (mature)	6	13	25	44	70	*Abies fabri*	37.0	139	41.86
GJTs	1.05	*Abies* over-mature forest	> 400	Climax(over-mature)	4	12	19	35	60	*Abies fabri*	48.0	> 170	37.73

Source: Adapted from Zhong *et al*., 1997. * XSYs-Xiangsiyan subwatershed, HBLs-Huangbengliu subwatershed, GJTs-Guanjingtai subwatershed (see Fig. 1)

Table 2 Soil chemical and physical parameters in the Huangbengliu watershed

Subwatershed	Soil development			Bulk density, g/cm^3	pH	Porosity	Texture**				Organic matter, g/kg	Kjeldahl-N, g/kg	TP, g/kg
							Clay	Silt	Sand				
	Age, yrs	Horizon*	Depth, cm				< 0.002	0.002—0.02	0.02—2	> 2			
XSYs	30—90	A_0 horizon	5	1.02	–	–	–	–	–	–	–	–	–
		A_1 horizon	10—15	1.12	5.8	20.2	2.8	12.0	21.7	63.5	103	3.74	1.4
HBLs	150	A_0 horizon	10—20	1.13	–	–	–	–	–	–	–	–	–
		A_1 horizon	15	1.20	4.9	27.3	4.4	14.7	27.4	53.5	189	5.38	1.2
		B horizon	20	1.01	5.3	38.5	2.2	9.4	28.3	60.1	45	1.94	1.7
GJTs	> 400	A_0 horizon	10—20	1.09	–	–	–	–	–	–	–	–	–
		A_1 horizon	20	1.22	5.2	26.9	4.2	14.9	29.7	51.2	182	5.14	1.3
		B horizon	30	0.99	5.2	43.1	2.6	12.1	27.0	58.3	80	2.87	1.6

Notes: * There are 2 or 3 horizons of soil layer in XSYs (A_0, AC or A_0, A_1, AC), 3 horizons in HBLs (A_0, A_1, B), and 4 horizons in GJTs (A_0, A_1, B, BC). ** International textural grade. A_0 horizon includes moss. – : No sample

1.3 Sampling and methods

Streamwater chemistry was conducted in late May 2001. Ice frozen in the surface soil thawed completely during this period. Discharge from the outlet mouth of the HBL watershed and three subwatersheds(XSYs, HBLs, GJTs) was monitored by an automatic-recording instrument at the gauging station. Daily precipitation data were obtained from the weather station located in the watershed.

At the mouth of the river and tributary streams, water samples were taken every 8 h and three times a day. Simultaneously, we collected rainwater and subsurface runoff in the soil(the subsurface runoff monitoring site located at the middle-part of GJTs) for comparison. Water samples were filled into acid-washed polyethylene bottles. Analyses for most indices followed the Chinese National Standards(Wei, 1997). Water temperature and pH were determined by a mercury thermometer and Rex pHB-4 acidometer in situ. The bottles were stored at 4℃ until ready for analyses. Analyses for Mg^{2+}, Ca^{2+}, Cl^-, and SO_4^{2-} were conducted by volumetry. Total alkalinity was measured by acid titrimetry. The contents of Na^+ and K^+ were calculated from the difference and subtraction method.

A general soil characterization of the three subwatersheds was made before water sampling was collected. The pH values of soil samples were determined by the electrometric method using a 2.5:1 water/soil solution. Bulk density obtained from the heat drying method and the corresponding porosity was calculated. Soil mechanical composition was taken by the hydrometer method. The soil organic matter content was acquired by the dilution heat method. Kjeldahl-nitrogen and total phosphorus were determined by the semimicro distillation method using a catalyzer of K_2SO_4-$CuSO_4$-Se and molybdate colorimetry with an oxidizing reagent of $HClO_4$-H_2SO_4(Lao, 1996).

The data set for the comparison of base ionic concentration in the stream water between different subwatersheds was subjected to analysis of variance (Duncan's Multiple Range Test for variable) using the statistical software SAS6.12 version. Significant differences between populations were determined at $p < 0.01$.

2 Results and discussion

2.1 Vegetation, soil and hydrological process

HBL is a small-scale watershed, and all the vegetation was completely developed at the base of the debris flow slash. A clear spatial variation of plant and community characteristics existed between subwatersheds in the HBL watershed(Table 1). From the XSYs to HBLs to the GJTs subwatershed, it showed a complete trend of community succession. The succession of community in the XSYs subwatershed is in its initial and medium stages with a year ranging from 30 to 80 years. The community types are dominated by the *Populus-Salix* forest, *Populus-Abies* forest and *Abies* middled-aged forest. The dominant species are *Populus purdomii* and *Abies fabri*. High coverage and species richness characterizes the community in the XSYs subwatershed. With the succession stage increasing, it gets to the climax and turns into a single dominant species *Abies fabri* forest community (HBLs and GJTs subwatershed). In these two stages, species and tree coverage declined substantially.

The vegetation succession had a significant effect on soil development, a high spatial variation of soil chemical and physical parameters was observed along *Abies fabri* succession (Table 2). For example, soil horizon and organic matter were low in XSYs(initial and midium succession stage) than that in HBLs and GJTs (the climax stage; Table 2). In addition, a general trend of a thin soil horizon(15—30 cm), low horizon numbers(only 1 or 2 horizons), low pH value, high ratio of porosity and sand, high humus horizon (including moss layer), and high organic matter content can be found in this region (Table 2). This phenomenon is characterized by the alpine environment with its long cold-wet conditions.

Surface runoff was not observed in our study. Others studies have reported that surface runoff never exists even during storm events in this region(Zhong, 1997). A high response of stream discharge to daily precipitation observed also confirmed our analyses(Fig.2). From Fig.2, we found the stream discharge volume showed a large spatial variation. In the three subwatersheds monitored, the volume in XSYs was larger than that in HBLs and GJTs, this was relative to its catchment areas; but all three showed the same change trend with daily precipitation. In addition, as the stream discharge increased or declined with precipitation quickly, this implied that the water content was constant in the soil system in *Abies fabri* forest. Generally, water exported from the forest watershed is stored in soils which prevent water being replaced by the new rainwater during precipitation events; this need long time(Baumler, 1999). But, in the HBL watershed, extended humid conditions caused saturation of the soil porosity, this made water cycle in the soil system was rapidly. We suggest that the special physical characteristics of the soil, such as high sand content (exceeding 80% in all subwatershed) and porosity in the soil (exceeding 20% in A horizon and 35% in B horizon), as well as a thick humus layer on the soil surface(Table 2), leaded the water to be filtered quickly. Most water was exported from the groundwater and soil saturated layer. This lead to a rapid stream discharge response.

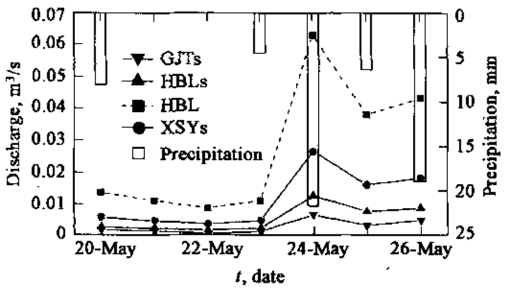

Fig. 2 Temporal trends of the stream discharge with precipitation in the Huangbengliu watershed

2.2 Temporal and spatial variation of streamwater chemistry

2.2.1 pH

The temporal variation of pH in the streamwater with precipitation and the stream discharge from the three subwatersheds and HBL watershed is given in Fig.3a. During low and absence of precipitation events, pH between sites was not different. But, during medium rainfall (24 May, precipitation volume 21.6 mm), a significant difference existed between sites. The change in pH in the HBLs subwatershed was similar with that of the GJTs subwatershed, but different with the XSYs subwatershed. pH declined with increasing stream discharge, but the duration of the decline in the HBLs and GJTs subwatersheds was longer than the XSYs subwatershed. In addition, the change in pH for the whole watershed was similar with the XSYs subwatershed. The water volume exported from XSYs accounted for roughly 45% of the whole watershed. This suggests pH variations are determined by the water contributed from the subwatersheds.

The thicker humus horizon and higher organic matter content in the HBLs and GJTs subwatershed may have lead to a time-lag phenomenon. The dynamic of leaf organic contribution and the decomposition and subsequent bioelement release played a fundamental role in the biogeochemical cycle of organic matter and mineral elements; the effect of organic residues is important for determining pH change in the streamwater(Keenan, 1996; Martin, 1996; Park, 1998). In HBLs, soil pH levels increased from 4.9 at the surface layer to 5.30 in the bottom layer, reflecting the increasing influence of slightly acidic rainfall from ground surface to bottom. When rainfall enters the primary forest soil, it reacts with the thick ground litter and loose subsurface layer where enriched organic matter has changed the composition of subsurface runoff. As rainfall increases, bicarbonates released from the organic material are elevated; this increases the buffering capacity of the streamwater. However, the relatively large precipitation levels over a short period can quickly wash out the minerals and weaken the buffering function of waters. This pH "lagging" phenomenon is the reflection of soil internal processes, controlled by the organic matter cycling and the succession stage of *Abies fabri* forest in cold-humid alpine conditions.

2.2.2 Cl^-, HCO_3^- and SO_4^{2-}

Two trends were observed for Cl^- in the stream water in the HBL watershed. First, Cl^- concentration was low at all four monitoring sites and ranged from 1 to 3 mg/L. Second, Cl^- was one of the least hydrologically variable element (hydrologically constant) in all-base ions in this study, there

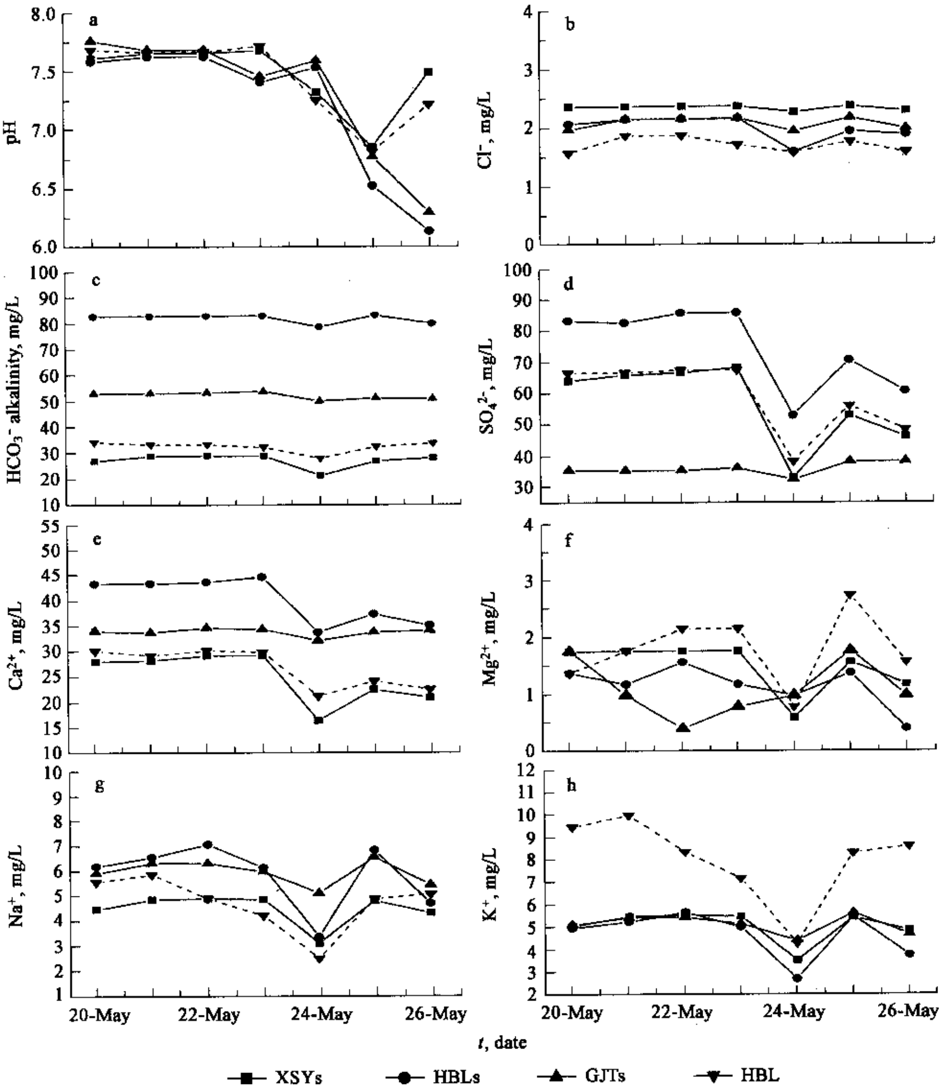

Fig.3 Temporal trends of streamwater chemistry in the Huangbengliu watershed

was almost no temporal change of flow dynamic in ionic concentration with precipitation and the stream discharge (Fig. 3b). This phenomenon may be related to the high mobile capacity of Cl^-. Chlorine ion is one of the most diluted and transported elements by water in the soil(Grieve, 2001; Salmon, 2001). This result suggested that the *Abies fabri* forest soil system can provide a good condition for Cl^- transport, due to high soil porosity, more rainy climate and long-term saturation of soil. Long-term export has caused decreasing Cl^- concentrations in the *Abies fabri* forest system.

HCO_3^- and SO_4^{2-} were the dominant anions in the stream water. Similar to the observed decreases in pH during periods of high flow, the concentrations of HCO_3^- and SO_4^{2-} also decreased sharply (Fig. 3c, 3d). The concentrations of HCO_3^- alkalinity and SO_4^{2-} showed a high temporal synchronous change in HBL watershed with precipitation-discharge. In addition to a similar temporal trend, ionic concentrations in the streamwaters showed a high spatial variation. For example, in Fig.3c, HCO_3^- concentration was the highest in HBLs, followed by GJTs and XSYs. This is correlated with the organic matter content in soil and vegetation stage(Table 2).

Except for the spatial variation along the *Abies fabri* forest-soil system, all the SO_4^{2-} concentration in rainwater, subsurface water and groundwater(Fig.4) were lower than in the streamwater. According to one of the most widespread hydro-chemical classifications (Alekin, 1970), the rainfall type belongs to class C-Na (hydrocarbonate-sodium) of the first type ($HCO_3^- > Ca^{2+} + Mg^{2+}$); this is not significantly different from other regions (Zhong, 1997). As rainfall passes through primary forest soil, the resulting subsurface runoff changes to class C-Ca(hydrocarbonate-calcium) of the second type($HCO_3^- < Ca^{2+} + Mg^{2+} < HCO_3^- + SO_4^{2-}$). The increased calcium concentrations in the subsurface runoff appear to come from the soil. Streamwater was classified as S-Ca(sulfate-calcium) of the second type, with sulfate being the dominant anion. For example, in GJTs, mean sulfate concentration in the streamwater was 36.2 mg/L, while subsurface runoff and groundwater showed sulfate concentration levels at 3.2 mg/L and 4.4 mg/L respectively (Fig. 4). Surface water receives sulfur from rainfall and weathering of sedimentary rocks such as dolomite and pyrite. Precipitation in this region showed sulfate levels(3.0 mg/L) as low as those observed in the groundwater. Input from aerosols and dust in humid and cold regions is not likely due to the atmospheric circulation determined by the Qinghai-

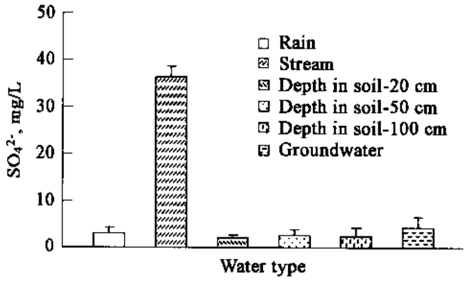

Fig.4 Sulfate concentration in different water types along the soil profile in the Guanjingtai subwatershed

Tibet Plateau. Thus, we can conclude that sulfates appear to not come from the primary forest soil but from the parent rock in the stream watershed. The changes in spatial export of SO_4^{2-} concentration in streamwaters may be related to stream history and soil pH (at the storm rainfall events). Further study is required to confirm this process.

2.2.3 Ca^{2+}, Mg^{2+}, Na^+ and K^+

In the HBL watershed, Ca^{2+} was the dominant cation and accounted for a high rate in H_T concentration in the stream water (Fig. 3e). Similar to the temporal change in anion concentration with precipitation-discharge, Ca^{2+} concentration decreased sharply at the medium rainfall event (24 May). In the absence or low precipitation events, Ca^{2+} concentration was near constantly. In addition, Ca^{2+} levels were different between plot sites. The Ca^{2+} exported affected by the vegetation and soil gradient condition can be easily concluded (HBLs > GJTs > XSYs). Mg^{2+} levels showed an irregular pattern and we found no spatial differences between plot sites (Fig. 3f). This may be related to extremely low Mg^{2+} concentrations in the streamwaters, whose main source is rainfall.

Concentrations of Na^+ and K^+ were also low in the stream water of the HBL watershed (Fig. 3g, 3h). Although the export of Na^+ and K^+ can be related to the daily precipitation and the stream discharge change, there were no observable difference in spatial sites. As the change trend of Cl^-, we suggest that long time output has made Na^+ and K^+ concentration low due to their highly diluted and transported capacity in the soil water.

2.3 Process control analysis of streamwater chemistry

Gongga Mountain is located at the headwater of Yangtze River and on the southeastern fringe of the Qinghai-Tibet Plateau. The humid and cold climate in Gongga Mountain regions formed characteristic regional parent rock, soil type, and vegetation; these regional characteristics influences and determines the receiving water composition. The chemical composition of ground water and streamwater is determined primarily by the weathering of the parent rock (Meybeck, 1987; Drever, 1997). Generally, streamwater cation concentrations and stream discharge are usually negatively correlated. During low, base-flow conditions, fed primarily by ground water, Ca^{2+}, Mg^{2+}, and K^+ were largely derived from the weathering of primary minerals and showed the highest concentrations. As stream discharge increases, streamwater solute concentrations decrease because the stream becomes diluted by surface or lateral flow waters that enter during rain events or snowmelt (Likens, 1995). But, in the HBL watershed, Ca^{2+} and stream discharge showed a significantly negative correlation (R equals to -0.98, -0.99, -0.98 and -0.82 in HBL, XSYs, HBLs and GJTs, respectively), while Mg^{2+}, Na^+ and K^+ showed no correlation with stream discharge. Furthermore, Mg^{2+}, Na^+, K^+, and Cl^- also showed no correlation with HCO_3^- alkalinity in the streamwater.

Generally, in relatively young soils such as those occurring in most temperate ecosystems, dissolution of primary minerals by carbonic acid is the predominant weathering pathway that liberates Ca^{2+}, Mg^{2+}, Na^+ and K^+ and generates alkalinity in the hydrosphere (Stumm, 1996). The ratio of Na: (Na + Ca) has been used to infer whether streamwater cations were derived from precipitation inputs or mineral weathering (Drever, 1997). A ratio approaching one indicated little contribution from mineral weathering, while a smaller fraction indicates greater weathering inputs. In this cold-humid watershed, however, the Na: (Na + Ca) ratio was small in all four streamwaters (Fig. 5). This result suggested cation input from bedrock weathering was the primary process. This also implies cation in streamwaters come from internal source processes.

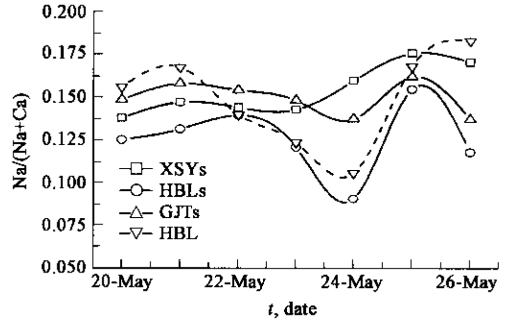

Fig.5 The mineral weathering index Na: (Na + Ca) for stream waters in the Huangbengliu watershed

A variance analysis between plot sites showed there were almost no significant differences between rainwater and streamwaters for Mg^{2+}, Na^+, K^+, and Cl^- concentrations (Fig.6a, b, c, d). This indicated that Mg^{2+}, Na^+, K^+, and Cl^- in the streamwaters come mainly from an external source; rainfall inputs likely determine their dynamics in the stream. This paradoxical result suggested the highly mobile capacity, rapid water exchange between precipitation and discharge, low weathered soil rate and cold-humid microclimate conditions (inhibiting the biological and biochemical processes) lead to this observed pattern. After an extended export period ions such as Na^+, K^+, Mg^{2+}, and Cl^-, originating from the soil parent, accounts for a small percentage. An insignificant correlation with HCO_3^- alkanility in the streamwater suggested the mineral weathering in the soil by carbonic acid have no or minimal influence on the concentration dynamics of Mg^{2+}, Na^+, K^+, and Cl^-. In the meantime, this implies a spatial effect along *Abies fabri* forest succession gradient does not exist. In contrast, change in Ca^{2+} levels were affected less by the precipitation events (Fig. 6e). A high correlative coefficient of Ca^{2+} with HCO_3^- was observed in HBLs (0.85) and GJTs (0.85), but no correlation was found in XSYs (0.65) and HBL (0.49). Internal weathering processes in the soil, and influences from the vegetation succession determined Ca^{2+} concentration in the streamwaters.

Ca^{2+}, SO_4^{2-} and HCO_3^- ions also showed a significant

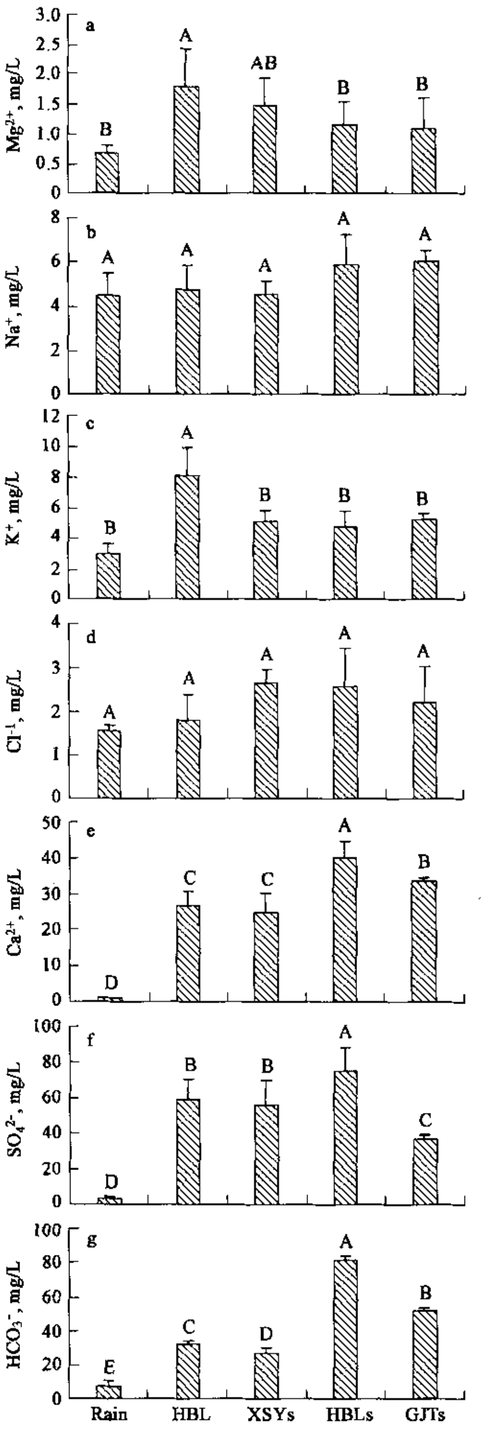

Fig. 6 Mean ionic concentrations in the streamwaters between watershed/subwatersheds

Variables with the same letter is not significantly different ($p > 0.01$)

negative correlation with discharge. Correlation coefficient of SO_4^{2-} was -0.99, -0.91, and -0.99 in HBLs, GJTS, and XSYs, respectively; correlation coefficient values of HCO_3^- were -0.87, -0.87 and -0.86 in HBLs, GJTS, and XSYs respectively. The variance analysis showed that SO_4^{2-} and HCO_3^- come mainly from internal source processes (i.e., diluted from the soil parent) (Fig.6f, 6g). In our study, SO_4^{2-} showed a positive correlative relationship with HCO_3^- in three subwatershed stream monitoring sites (XSYs 0.76, HBLs 0.86, GJTs 0.92). Along the gradient of vegetation and organic matter in the soil, there was a clear difference between subwatersheds. Due to low SO_4^{2-} concentrations in the soil water and groundwater (Fig.4), this may be related to stream history and soil pH. These patterns contrast with the seasonal patterns widely recognized in temperate ecosystems that had less strongly weathered soils (Likens, 1995). Because Ca^{2+}, SO_4^{2-} and HCO_3^- were the main ions in the streamwaters, and determined the basic trend of streamwater chemistry, we concluded that the streamwater chemistry in the HBL watershed was affected greatly by the vegetation and soil gradient.

3 Conclusions

Spatial variations in stream water chemical composition are interpreted in relation to the environmental chemistry of the major ions and controls such as bedrock geology, land-use, anthropogenic activities and atmospheric inputs. In our study, HBL is a small-scale watershed, located remotely at high altitude in the Qinghai-Tibet Plateau where anthropogenic effects on forest ecosystems are minimal. In the HBL watershed, vegetation developed at the base of the debris flow slash. XSYs, HBLs and GJTs subwatersheds showed a trend of complete primary community succession. Influenced by the climate and high mountain environmental conditions, soil development in the HBL watershed was low. We observed a general trend of thin soil horizon (15—30 cm), low horizon numbers (only 1 or 2 horizons), low pH, high ratio of porosity and sand, high humus horizon (including moss layer), and high organic matter content. Soil chemical and physical parameters showed a high spatial variation. Due to development on the same source of soil parent, the vegetation succession had a large effect on soil development.

The special vegetation and soil characteristics influenced the hydrological processes of the watershed. Due to high rainwater filtration capacity, there was no surface runoff even during storm events. Extensive humid environmental conditions saturated the soil and the groundwater level near the earth's surface. The water cycle is rapid, and stream discharge correlated with the precipitation process in all stream outlets monitored.

The temporal and spatial variations of base ions in the stream water were influenced by the complex interactions between vegetation, soil and hydrology processes. But, a large difference was observed between ions. In small precipitation events or lack of rain, there were no clear differences between events for base ions. In the medium rainfall (24 May, 21.6 mm) there was a significant trend difference among site. The pH declined as discharge increased, but the duration of decline in the HBLs and GJTs subwatersheds was longer than the XSYs subwatershed. A time-lag phenomenon existed in HBLs and GJTs.

Concentrations of Mg^{2+}, Na^{+}, K^{+}, and Cl^{-} were low in the streamwater in the HBL watershed. There were no observable differences among sites. Long-term export lead to low levels of Mg^{2+}, Na^{+}, K^{+}, and Cl^{-} concentration were low due to their highly diluted and transported capacity. This suggested that Mg^{2+}, Na^{+}, K^{+}, and Cl^{-} in the streamwater come mainly from external sources; rainfall inputs determined their change in the stream.

Ca^{2+}, HCO_3^- and SO_4^{2-} were the dominant anions in the streamwater and showed significantly negative correlation with stream discharge. We also observed there had high temporal synchronous change of Ca^{2+}, HCO_3^- and SO_4^{2-} with the daily precipitation and the stream discharge. Along the gradient of vegetation and organic matter in soil, a clear difference existed between the subwatersheds. Different soil characteristics due to varying succession stages and community compositions were the main reasons for leading this observation. Ca^{2+}, SO_4^{2-} and HCO_3^- were the main ions in the streamwater, we confirmed that streamwater chemistry was affected substantially by the vegetation and soil gradient due to its high correlative interactions.

Acknowledgements: The authors thank Professor Cheng G. W. for providing us data of the stream discharge and precipitation and Dr. Cindy Lin for reviewing the manuscript.

References:

Alekin O A, 1970. Basic hydrochemistry[M]. Leningrad: Gidrometeoizdat(in Russian).

Baumler R, Zech W G, 1999. Effects of forest thinning on the streamwater chemistry of two forest watersheds in the Bavarian Alps[J]. Forest Ecology and Management, 116 (1—3): 119—128.

Burdsoil R L, Emmins A B, 1935. Men against the clouds, the conquest of Minya Konga[M]. New York and London: Harper and Brothers.

Cassie D, Pollock T L, Cunjak R A, 1996. Variation in stream water chemistry and hydrograph separation in a small drainage basin[J]. J Hydrol, 178: 137—157.

Caldentey J, Ibarra M, Hernandez J, 2001. Litter fluxes and decomposition in Nothofagus pumillo stands in the region of Magallanes, Chile[J]. Forest Ecology and Management, 148: 145—157.

Chen F B, Li X, 1992. The evolution of the mountain environment in the east margin of the Qinghai-Tibet Plateau, Mountain Hazards and Environment in China[M]. Chongqing, China: Southwest Jiaotong University Press. 88—97.

Chen F B, 1995. The relation between Hengduan Mountain and Qinghai-Tibet Plateau Period and the boundary marks of neotectonic period[J]. Scientia Geologica Sinica(supplement), 1: 285.

Cheng G W, 1996. Exploration of precipitation features on extra-high zone of MT. Gongga[J]. Mountain Reasearch, 14(3): 177—182.

Chorley R J, Dunn A J, Beckinsale R P, 1964. The history of the study of landforms(Vol. 1), Geomorphology Before Davis[M]. London: Methuen.

Christmas M, Whitton B, 1998. Phosphorus and aquatic bryophytes in the Swale-Ouse River system, north-east England[J]. The Science of the Total Environment, 210—211: 389—399.

Christophersen N, Neal C, Hooper R P *et al.*, 1990. Modeling streamwater chemistry as a mixture of soil-water end-members—a step towards second-generation acidification models[J]. J Hydrol, 116: 307—320.

DeWalle D R O, Swisstock B R, Sharpe W E, 1988. Three components tracer model for storm flow on a small Appalachian forest catchment[J]. J Hydrol, 104: 301—310.

Drever J I, 1997. The geochemistry of natural waters: surface and groundwater environments[M]. 3rd edn. New Jersey: Upper Saddle River Prentice Hall. 138—196.

Editorial Committee of Monitoring and Analysis Methods for Water and Wastewater of Chinese EPA(Wei F S *et al.* ed.), 1997. Monitoring and analysis methods for water and wastewater[M]. Beijing: China Environmental Science Press. 221—326.

Eshleman K N, Pollard J S, O'Brien A K, 1993. Determination of contributing areas for saturation overland flow from chemical hydrograph separations[J]. Water Resour Res, 29(10): 3577—3587.

Gregory J W, Gregory C W, 1923. The Alps of Chinese Tibet and their geographical relation[J]. Geographical Journal, 61 (3).

Grieve I C, Marsden R L, 2001. Effects of forest cover and topographic factors on TOC and associated metals at various scales in western Scotland[J]. The Science of the Total Environment, 265(1—3): 143—151.

Havel M, Peters N E, Cerny J, 1999. Longitudinal patterns of stream chemistry in a catchment with forest dieback, Czech Republic[J]. Environmental Pollution, 104(1): 157—167.

Heim A, 1931. The structure of Minya Gongar[J]. Bulletin of the Geological Society of China, 11 (1): 36—44.

Heim A, 1936. The glaciation and solifuction of Minya Gongar[J]. Geographical Journal, 87 (5).

Hessling M, 1999. Hydrological modelling and a pair basin study of mediterranean catchments[J]. Phys Chem Earth(B), 24(1—2): 59—63.

Holloway J M, Dahlgren R A, 2001. Seasonal and event-scale variations in solute chemistry for four Sierra Nevada catchments[J]. Journal of Hydrology, 250 (1—4): 106—121.

Hudson R O, Golding D L, 1997. Controls on groundwater chemistry in subalpine catchments in the southern interior of British Columbia[J]. Journal of Hydrology, 201(1—4): 1—20.

Johnson N M, Likens G E, Bormann F H *et al.*, 1969. A working model for the variation of stream water chemistry at the Hubbard Brook Experiment Forest, New Hampshire[J]. Water Resour Res, 5: 1353—1363.

Keenan R J, Prescott C E, Kimmins J P *et al.*, 1996. Litter decomposition in western red cedar and western hemlock forest on northern Vancouver Island, British Columbia[J]. Can J Bot, 74: 1624—1634.

Kimmins J P, 1987. Forest ecology[M]. New York: Macmillan Publishing Company. 530.

Lao J C, 1996. Soil agrochemical analysis methods[M]. 2nd edition. Beijing: Agricultural Press.

Lee C S, 1931. The geological structure between Lengchi and Hisnmiaotze on the boundary of Hsikang and Szechuan[J]. Bull Geil Soc China, 11 (1): 45—50.

Li P, 1985. Seismic intensity zonation for the marginal region of the Qinghai-Tibet Plateau[M]. China Academic Publishers. 1—21.

Likens G E, Bormann F H, 1995. Biogeochemistry of a forested ecosystem[M]. 2nd edn. New York: Springer. 46—101.

Luo J, Zhong X H, Pan Z F, 1998. A preliminary study on the biomass of *Abies fabri* forest on the east slope of Gongga Mountain[M]. Research on the alpine forest ecosystem of Gongga Mountain(Chen F B, Luo J ed.). Beijing: China Meteorological Press. 10—14.

Luo J, 1998. Ordination of primary succession serial communities on the east slope of Gongga Mountain[M]. Research on the alpine forest ecosystem of Gongga Mountain(Chen F B, Luo J ed.). Beijing: China Meteorological Press. 23—27.

Mandernack K W, Lynch L, Krouse H R *et al.*, 2000. Sulfur cycling in wetland peat of the New Jersey Pinelands and its effect on stream water chemistry[J]. Geochimica et Cosmochimica Acta, 64(23): 3949—3964.

Markewitz D, Davidson E A, Figueiredo R *et al.*, 2001. Control of cation concentrations in stream waters by surface soil processes in an Amazonian watershed[J]. Nature, 410: 802—805.

Martin A, Gallardo J F, Santa R I, 1996. Aboveground litter production and bioelement potential return in an evergreen oak (*Quercus rotundifolia*) woodland near Salamanca(Spain)[J]. Ann Sci For, 53: 811—818.

Martin C W, Driscoll C T, Fahey T J, 2000. Changes in streamwater chemistry after 20 years from forested watersheds in New Hampshire, U.S.A[J]. Can J For Res, 30: 1206—1213.

Meybeck M, 1987. Global chemical weathering of surficial rocks estimated from river dissolved loads[J]. Am J Sci, 287: 401—428.

Pan Z F, 1994. A preliminary study on primary succession of *Abies fabri* forest ecosystem in Gongga Mountain[J]. Geography, 7(2): 34—39.

Park H, Hattori S, Tanaka T, 1998. Development of a numerical model for evaluating the effect of litter layer on evaporation[J]. J For Res, 3: 25—33.

Rock J F, 1930. The glacers of Minya Konka[M]. Washington D.C.: Nat Geogr Mog October.

Salmon C D, Walter M T, Hedin L O, 2001. Hydrological controls on chemical export from an undisturbed old-growth Chilean forest[J]. J Hydrol, 253(1—4): 69—80.

Sklash M G, Farvolden R N, Fritz P, 1976. A conceptual model of watershed response to rainfall, developed through the use of oxygen-18 as a natural tracer[J]. Can J Earth Sci, 13: 271—283.

Soulsby C, Malcolm R, Helliwell R *et al.*, 1999. Hydrogeochemistry of montane springs and their influence on streams in the Cairngorm Mountains, Scotland [J]. Hydrology & Earth System Sciences, 3(3): 409—419.

Stednick J D, 1996. Monitoring the effects of timber harvest on annual water yield [J]. J Hydrol, 176: 79—95.

Stumm W, Morgan J J, 1996. Aquatic chemistry: chemical equilibria and rates in natural waters[M]. 3rd. New York: Wiley. 872—932.

Toetz D, 1995. Water chemistry and periphyton in an alpine wetland[J]. Hydrobiologia, 312: 93—105.

Trinkler E, 1930. The ice-age on the Tibetan Plateau and in the adjacent regions [J]. Geographical Journal, 75 (3).

Wang L G, Li X M, Lin Z Y, 1995. A discussion on the soil below dark coniferous forests of the high mountains in southwest China[J]. Acta Geographica Sinica, 50 (6): 542—551.

Wu N, 1999. Dynamics of forest gaps in subalpine coniferous forests on the eastern slope of Gongga Mountain[J]. Acta Phytoecologia Sinica, 23 (3): 228—237.

Yi L Q, Miao R, Lin S Y, 2000. A study on the hydrological features of a small forested catchment on Mt. Gongga[J]. Journal of Sichuan University, 32 (1): 87—92.

Xie Z C, Su Z, Shen Y P *et al.*, 2001. Mass balance and water exchange of Hailuogou Glacier in Mount Gongga and their influence on Glacial melt runoff [J]. Journal of Glaciology and Geocryology, 23 (1): 7—15.

Zhen Y C, Zhang J P, Yin Y G, 1993. Characteristics of environmental background value of Hailuogou soil on MT. Gongga[J]. Mountain Reasearch, 11(1): 23—29.

Zhong X H, Zhang W J, Luo J, 1999. The characteristics of the mountain ecosystem and environment in the Gongga Mountain region[J]. Ambio, 28 (8): 648—654.

Zhong X H, Luo J, Wu N, 1997. Researches of the forest ecosystems on Gongga Mountain. Chengdu[M]. China: Chengdu Technological University Press. 8—19; 129—130.

(Received for review September 3, 2003. Accepted November 5, 2003)