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Full Length Research Paper

Effect of subtropical forests on water quality in Southwestern China

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The objective of the study was to investigate the effects of different components of typical forests on water quality during the process of rainfall to runoff. Three typical forests, a *Pinus massoniana* × *Gordonia acuminata Chang* mixed forest (I_1), a *Phyllostachys pubescens* forest (I_2), a shrub forest (I_3)) and a bare land (a clear-cut), cited as a control plot (CK), at Jinyun Mountain, were selected as experimental sites. Four runoff plots were established on each of the four sites. Field monitoring for continuous measurements of water quality (rainfall, through fall, surface runoff and interflow) was carried out over 31 rain events during 2007 to 2010, using manual sampling methods. The results show that the rain water, with an average pH value of 5.43 in this area, was acidic. The water pH was mainly buffered at the conflux phase of surface runoff and forest stands had a better acid-buffer capacity than bare land. The concentration of NO_3^- played a leading role in the acidification of surface runoff and interflow in the forests. The amount of SO_4^{2-} was the dominant factor of acidification in throughfall. The main buffer elements in surface runoff were Mg^{2+} and Al^{3+}; those of the interflow were Ca^{2+} and Al^{3+}. An aluminum buffer system was present in I_1, I_3 and CK. During the four years of our study, the ions were mostly intercepted at the phase of the surface conflux and at soil level. Forests have better decontamination than bare land. I_1 and I_2 were better at interception with a large cut range of NO_3^-, SO_4^{2-}, K^+, Na^+, Mg^{2+} and Al^{3+}.

Key words: forest, components, water quality, subtropics.

INTRODUCTION

Rapid development of agriculture, industry and motor vehicles with sharply increased emission of pollutants (e.g. industrial waste water, exhaust from fossil fuels, sediments, pesticide and fertilizer runoff from agricultural use and solid waste) has placed heavy pressure on environmental protection all over the world. Given these conditions, massive pollutants are transported across land surfaces by runoff and through the soil by percolating water (Yoon et al., 2010). Thus, underground water and surface water such as streams, rivers, lakes and reservoirs have become contaminated by these sources of toxic waste. The quality of available fresh water, accounting for only 0.007% of the entire global water supply, is becoming increasingly worse. Various projects, to control pollution, are carried out in many countries. However, these efforts are still far from sufficient to slow down the degradation of the water environment. Worldwide water supply crises are continuously on the increase and those in China are no exceptions. With freshwater resources of 2.8 × 10^{12} m^3, which account for 6% of global water resources, China still has a significant water shortage. The per amount of water per person is 2200 m^3 which is only 1/4 of that of the world, while the proportion of polluted rivers in China is up to 40.6% (Zhang et al., 2009; Xia et al., 2008). Forests, occupying about 30% of the global land area, provide functions of soil and water conservation improve water quality and regulate runoff (Shigeru, 1996; Smith et al., 2008; Sebastian et al., 2000; Swank and Crossley, 1988). The relationship between forest ecosystems and water quality has become one of the most important issues in forest hydrology since the 1960s (Shi et al.,

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2000). That the Biochemical Oxygen Demand (BOD) in runoff of a clear-cut of a mixed fir and beech forest watershed in the former Soviet Union was 1.67 times greater than normal, suggests that the amount of organic pollutants is reduced by forests (Wang and Zhang, 1998). The studies in Hubbard brook, New Hampshire, USA, showed that forests can intercept NO_3^-, Ca^{2+}, Mg^{2+}, K^+ and Na^+ in water (Likens et al., 1970). This issue has also been investigated in a number of regions in China. Liu et al. (2003) carried out studies on the chemical properties of rainfall, throughfall, surface runoff and interflow of local forest stands at Dinghushan Mountain in Guangdong Province. Their results show that the rainfall was acidic (pH = 4.9), but that coniferous forests have a great soil buffering capacity. Studies on a *Quercus aliena var. acuteserrata* forest ecosystem at Qinling Mountain in Shaanxi Province showed that rain water was decontaminated after moving through different layers of the forest, with a purification rate of 88.4% (Lei and Lu, 2003).

These previous studies have focused primarily on the impact of water quality of forest ecosystems, when taking the system as a whole, whereas few examined the impact of different components of the forest (canopy, litter and soil) on water quality (Zhang and Li, 2007). It is well known that the chemical content of water is changed by all three forest components when water moves through the forest ecosystem. In order to study the effect of water quality of the different forest components, studies should be conducted based on the spatial structure of forest ecosystems. In our present investigation, therefore, three types of forests were selected at Jinyun Mountain of Chongqing in the Three Gorges area and a bare land for control. The effect of these typical forests on water quality were studied for catching the dominant level of decontamination of forests and providing scientific evidence for the establishment and management of forests for the specific purpose of water conservation.

MATERIALS AND METHODS

Site description

This study was carried out in Jinyun Mountain, which covers an area of 7.6 km^2 and is located in the Three Gorges area, near Chongqing City, southwestern China. It is bounded by the two major river systems of the region, that is, the Yangtze and the Jialingjiang rivers. The elevation of this area is between 350 and 952 m. This region has a subtropical monsoon climate with long warm to hot humid summers and short cool to cold, dry and cloudy winters with the lowest total number of sunshine days (about 1000 h a year) in China. The mean annual temperature is 13.6℃ and the mean annual precipitation 1611.8 mm. The dominant soil types are yellow earth (natural) and paddy soils (cultivation). Jinyun Mountain has abundant typical subtropical forest species; its forest cover is about 97%.

For our study we selected three typical forest types, that is, a *Pinus massoniana* × *Gordonia acuminata Chang* mixed forest (I_1), a *Phyllostachys pubescens* forest (I_2) and a shrub forest (I_3), as well as a plot of bare land (clear cut in 2000) to be used as a control (CK). In addition, four runoff plots (5 m × 20 m) had already been established for all three typical forest stands and the clear-cut. Three sample plots (20 m × 20 m) of these typical forests near the corresponding runoff plots were established and surveyed in 2007, showing that the origin of these forests was natural and all were of middle age.

Sampling and chemical analyses

Rainfall (RF), throughfall (TF), surface runoff (SR) and interflow (IF) were monitored in the runoff plots studied. Since the main rainfall period is from April to August each year, the experiments were conducted during this period from 2007 to 2010. In total, 31 rainfall events were recorded and 403 samples collected. Rainfall was sampled at weekly intervals in plastic pots placed in open fields (ten pots were prepared and arranged in an S shape). Simultaneously, throughfall (TF), surface runoff (SR) and interflow (IF) were sampled. Throughfall samples were also collected in plastic pots located in the field (ten pots were prepared and arranged in the shape of an S in all three forest plots except for CK). Surface runoff and interflow samples were collected at the outlets of runoff plots (three replication of water were collected at each outlet). In addition, soil samples in the three forest stands and the clear-cut were collected at depths of 0 to 20, 20 to 40, 40 to 60 and 60 to 100 cm, at three randomly selected sampling points in each sample plot for chemical examination. Soil samples were numbered and mixed according to the plots and depth, air-dried at room temperature and transported to the laboratory for examination.

Water samples were analyzed within 24 h after being transported to the laboratory. Monitoring indicators, such as pH, NO_3^-, SO_4^{2-}, K^+, Na^+, Ca^{2+}, Mg^{2+} and Al^{3+}, were determined according to the Environmental Quality Standards for Surface Water (GB3838-2002) and local environmental conditions. All of these indicators were analyzed according to standard methods (Wang, 2002; Second Editorial of Standards Press of China, 2001). Soil tests were carried out for the following indices: pH, base saturation (BS), total nitrogen (N), exchangeable potassium (K), exchangeable sodium (Na), exchangeable calcium (Ca), exchangeable magnesium (Mg) and exchangeable aluminum (Al). The soil samples were analyzed according to the national standards of Soil and Agricultural Chemistry Analyses and the Physical and Chemical Analyses of Soils (Shi, 1983; ISSCAS, 1978). The quality of chemical analyses was checked by the methods of blank control and repeated internal measurements.

Calculations and statistics

The average concentrations of monitoring indicators in soil, rainfall, throughfall, surface runoff and interflow water were calculated. Relationships between pH and the concentrations of NO_3^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, K^+, Na^+ and Al^{3+} in throughfall, surface runoff and interflow water were established by means of correlation analyses. The differences of water quality between four sites and across different components within forest ecosystems were also analyzed by analyses of variance.

RESULTS

The variations of mean ion concentrations and water pH among the three different forest components were studied and, as well, we analyzed the relationships between the pH of water and ion concentrations. The chemical elements of the soil and pH values were tested

Table 1. Chemical properties of typical forest and CK soils.

Typical forest	pH	N(g/kg)	BS (%)	K (g/kg)	Na (g/kg)	Ca (g/kg)	Mg (g/kg)	Al (g/kg)
I_1	4.10	1.1360	18.32	0.0440	0.0240	0.2259	0.1280	1.6184
I_2	4.70	0.8713	39.12	0.0249	0.0359	0.5587	0.1030	1.5644
I_3	4.27	1.1452	11.94	0.0262	0.0385	0.1735	0.1552	1.6615
CK	4.55	1.0174	16.73	0.0308	0.0300	0.4197	0.1027	1.2978

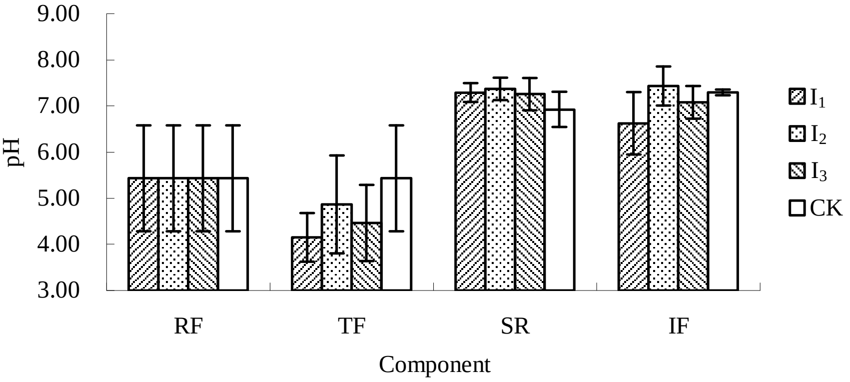

Figure 1. Variations in average pH for different components. Note: RF is rainfall, TF is throughfall, SR is surface runoff and IF is interflow.

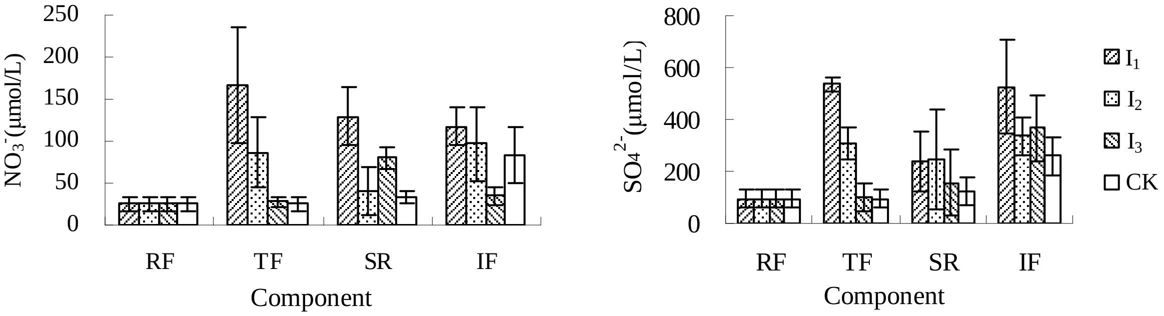

Figure 2. Concentrations of SO_4^{2-} and NO_3^- for different components.

in order to explain the variations of ions and pH in the water (Table 1).

Water pH

The variations of mean water pH among different components of the plots are presented in Figure 1. The average rainfall pH was 5.43, that is, acidic, while the pH of rain water decreased after moving through the forest canopy. The pH level of the throughfall of I_1 was, at 4.15, the lowest among the three forest plots. In contrast to throughfall, the mean pH values of surface runoff increased sharply. The pH of forest plot I_1 was 7.29, that of I_2 7.37 and of I_3 7.26. These values were larger than that of the clear-cut (6.92). It shows that forests have a better acid buffer capacity than bare land in the confluence of surface runoff. In interflow, pH values of I_2 (7.43) and CK (7.29) were higher than those of surface runoff; whereas, the pH values of interflow in I_1 (6.62) and I_3 (7.08) were lower.

NO_3^- and SO_4^{2-}

The concentrations of NO_3^- in throughfall of the three typical forests (I_1=166.55 μmol/L, I_2=86.65 μmol/L, I_3=27.60 μmol/L) were greater than that of rain water (25.65 μmol/L), while these concentrations in surface runoff in I_1 (129.48 μmol/L) and I_2 (40.67 μmol/L) were lower than for throughfall (Figure 2). This shows that NO_3^- was intercepted by these two forest types in the conflux

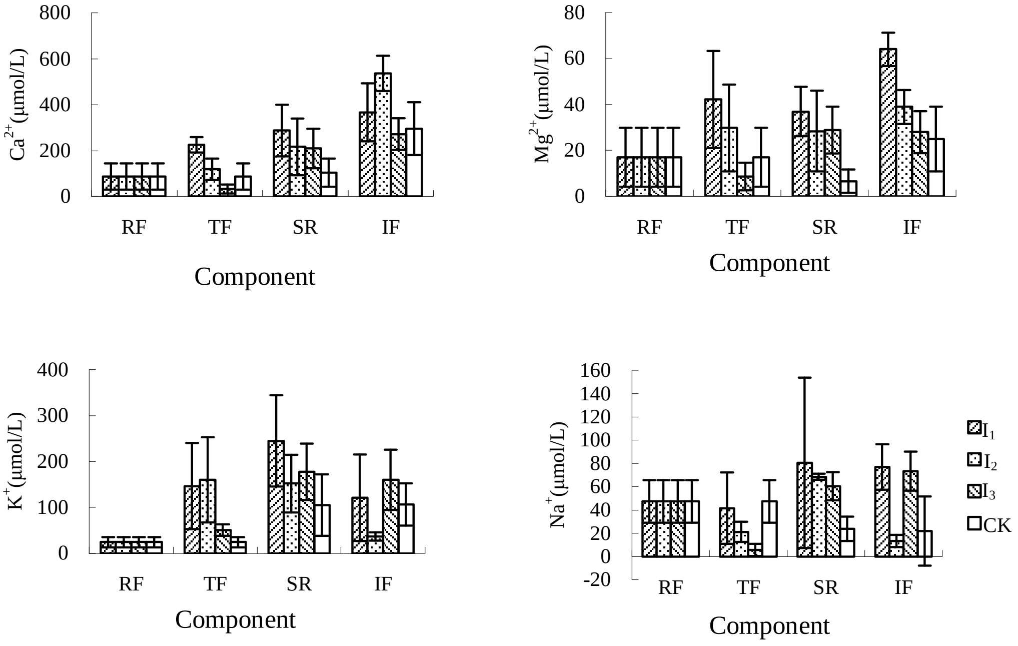

Figure 3. Concentrations of base cations for different components.

phase of surface runoff. The amounts of NO$_3^-$ in the interflow of I$_1$ (117.20 μmol/L) and I$_3$ (35.07 μmol/L) indicate that the soil layers under these two forests have an effect on reducing ion concentrations. Instead of interception, NO$_3^-$ was released with surface runoff and interflow from the CK. The pH values of throughfall are negatively correlated with concentrations of NO$_3^-$, with correlation coefficients of -0.6014 (I$_1$, p <0.001, n = 31), -0.1453 (I$_2$, p <0.5, n = 31) and -0.3002 (I$_3$, p <0.1, n = 31). The correlation coefficient of pH of surface runoff with its NO$_3^-$ concentration in I$_1$ was -0.2470 (p <0.2, n = 31), for I$_2$ -0.1799 (p <0.5, n = 31) and for I$_3$ -0.4836 (p <0.005, n = 31). Negative correlation coefficients between interflow water pH and NO$_3^-$ concentrations were only found in I$_1$ (-0.7250, p <0.001, n = 31) and I$_3$ (-0.2898, p <0.2, n = 31). This may be due to the greater amounts of N in the soil layers of I$_1$ and I$_3$ (see Table 1). These results demonstrate that an increase in water acidity is related to NO$_3^-$.

The correlation coefficient of pH values of throughfall with SO$_4^{2-}$ concentrations in I$_1$ was -0.8302 (p < 0.001, n = 31), for I$_2$ -0.4755, (p < 0.01, n = 31) and for I$_3$ -0.5728 (p < 0.001, n = 31), each negative but significant at least at the level of $p \leq 0.01$. SO$_4^{2-}$ was dominant in the acidification of throughfall, as indicated by correlation coefficients higher than for NO$_3^-$. The pH of surface runoff in the CK was negatively correlated with the SO$_4^{2-}$ concentration with a correlation coefficient of -0.4608 (p < 0.01, n = 31). There was no evident correlation between the pH of surface runoff and SO$_4^{2-}$ concentration in forest plots. Moreover, no correlations were found in interflow. Thus, NO$_3^-$ concentrations played a leading role in the acidification of surface runoff and interflow in the forests. In surface runoff, SO$_4^{2-}$ concentrations in I$_1$ and I$_2$ decreased (Figure 2), while I$_1$ had a greater capacity of interception with a rejection rate of 55.6%. However, its ion concentration in the soil layer was not reduced in the CK during this period. We conclude that, once a forest ecosystem is destroyed, the discharge of SO$_4^{2-}$ increases with period.

Base cations

From our study we conclude that, among base cations, only the pH of surface runoff was significantly correlated with the concentrations of Mg^{2+}, with correlation coefficients of 0.7728 for I$_1$ (p < 0.001, n = 31), 0.4573 for I$_2$ (p < 0.01, n = 31), 0.4871 for I$_3$ (p < 0.005, n = 31) and 0.6287 for CK (p < 0.001, n = 31). The interflow water pH of all plots was correlated with the concentrations of Ca^{2+} with correlation coefficients of 0.6569 for I$_1$ (p < 0.001, n = 31), 0.1835 for I$_3$ (p < 0.5, n = 31) and 0.5243 for CK (p < 0.002, n = 31) except for I$_2$. Moreover, there was no evident correlation between the pH of throughfall water and base cations. In the surface runoff confluence phase, the capacity of the acid-buffer of I$_1$ was the greatest due to its greater amount of Mg^{2+} in the surface runoff. It stands to reason that the CK should have the least capacity because of its minimum amount of Mg^{2+}. The soil of I$_2$, with its large amounts of BS and exchangeable Ca (Table 1), had the best effect on buffering acidification of the interflow. The amount of Ca^{2+} in its interflow water and pH value were also the largest.

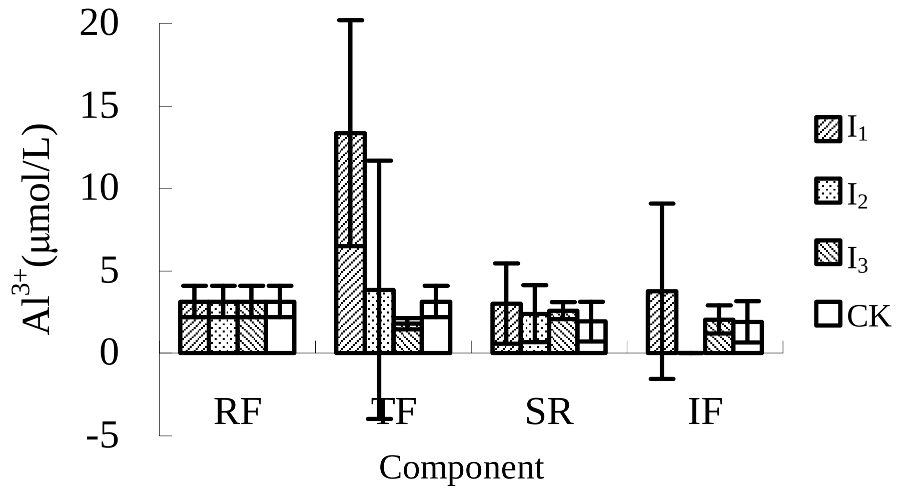

Figure 4. Concentrations of Al^{3+} for different components.

Figure 3 shows the concentrations of base cations among different components. Na^+ was intercepted by the canopies of all three typical forest plots, while Ca^{2+}, Mg^{2+} and K^+ were leached into the throughfall. Base cations were released into the surface runoff in the forest stands. Similar conditions were found in studies in the Qinling and Dinghushan mountains (Zhang and Li, 2007; Liu et al., 2003). While the amounts of Mg^{2+} and Na^+ in the CK decreased during the stage of surface conflux, these were even lower than the Mg^{2+} and Na^+ concentrations for rainwater. After moving through the soil layer, the concentrations of K^+ and Na^+ decreased except for Na^+ in the interflow water of I_3. In contrast, the concentrations of Ca^{2+} and Mg^{2+} rose. Studies in the Qinling Mountain indicated that K^+ and Na^+ concentrations in water from soil layers were less than those from surface runoff, but concentrations of Ca^{2+} and Mg^{2+} had increased (Zhang and Li, 2007). However, the pH of interflow water did not obviously increase. That of I_1 was even lower. It may be related to low soil pH and BS (Table 1).

Al^{3+}

The concentrations of Al^{3+} in rain water, throughfall, surface runoff and interflow are shown in Figure 4. Aluminum was released to throughfall except in I_3. The concentration of I_1 sharply increased to 13.4 μmol/L, which was 4.3 times greater than that of rain water (3.14 μmol/L). But it then decreased dramatically to 3.01 μmol/L with a reduction rate of 77.4% in the phase of surface conflux. Similar to the process in I_1, the concentrations of Al^{3+} in the surface runoff of I_2 (2.41 μmol/L) and CK (1.93 μmol/L) were also reduced, but the reduction rates of I_2 at 37.6% and of CK at 38.5% were lower. In contrast, the aluminum concentration in the surface runoff of I_3 increased to 2.59 μmol/L. After moving through the soil layer, the aluminum concentrations of all plots, except for I_1, decreased. In I_2, the aluminum was completely intercepted. These results show that I_1 had the best effect on intercepting Al^{3+} in surface runoff, whereas I_2 had the strongest capacity to decontaminate Al^{3+} from the interflow. Forest soils have a greater cut rate of Al^{3+} than soils in CK.

The concentrations of Al^{3+} in surface runoff and interflow are related to the pH in water. Some correlation between aluminum concentrations and pH of surface runoff were evident with coefficients of 0.1713 for I_1 ($p < 0.5$, $n = 31$), 0.8955 for I_3 ($p < 0.001$, $n = 31$) and 0.6058 for CK ($p < 0.001$, $n = 31$). The amounts of Al^{3+} in interflow were significantly correlated with water pH with correlation coefficients of 0.9965 for I_1 ($p < 0.001$, $n = 31$), of 0.8246 for I_3, ($p < 0.001$, $n = 31$) and 0.3986 for CK ($p < 0.05$, $n = 31$). There was no clear correlation between these two factors in I_2.

Differences of water quality among plots and components within plots

According to Table 2, the differences of water quality of all four plots were significant among SO_4^{2-} of three forest plots for throughfall as well as NO_3^- and Al^{3+}, among NO_3^- of four plots for surface runoff as well as Ca^{2+} and Mg^{2+}, and only the difference among Al^{3+} of four plots for interflow was statistically significant. The results indicate that the following indicators SO_4^{2-}, NO_3^-, Ca^{2+}, Mg^{2+} and Al^{3+} showed differences with water quality in the four plots.

The three forest plots(except for CK) showed highly significant differences for pH values. But I_1 and I_2 had better capacity for changing water quality. The reason is that the two plots showed a significant difference on most of ions (Table 3).

Table 2. Probabilities of significant differences among water samples of experimental plots from variance analyses.

Indicators' P-value (n =31)	Throughfall	Surface runoff	Interflow
pH	0.5230	0.4441	0.7058
SO_4^{2-}	0.0061	0.6387	0.0899
NO_3^-	0.0048	0.0036	0.7198
Ca^{2+}	0.0592	0.0081	0.3197
Mg^{2+}	0.2636	0.0066	0.0704
K^+	0.2990	0.2411	0.4368
Na^+	0.3573	0.5768	0.6967
Al^{3+}	0.0088	0.9574	0.0078

p-values<0.05 show significant differences.

Table 3. Variance analysis among components among experimental plots.

Indicators' P-value(n=31)	I_1	I_2	I_3	CK
pH	$1.9×10^{-5}$	0.0005	$2.8×10^{-5}$	0.0111
SO_4^{2-}	0.0054	0.0007	0.0941	0.0991
NO_3^-	0.0004	0.0041	0.4363	0.4566
Ca^{2+}	0.0021	0.0991	0.0254	0.0025
Mg^{2+}	0.0035	0.0087	0.2158	0.3818
K^+	0.0685	0.0536	0.1052	0.1472
Na^+	0.1222	0.2474	0.6547	0.0852
Al^{3+}	0.0072	0.0008	0.0991	0.0773

p-values<0.05 show significant differences.

DISCUSSION

Water pH

In this study, the most serious water acidification was found in the canopy. The pH of water decreased sharply after moving through the canopy. Studies carried out at Nanshan Mountain in Chongqing also indicated that throughfall pH values decreased after moving through the canopies, where the pH values ranged from 3.43 to 3.58 (Zhou and Norio, 1996). The acid deposition is serious in Chongqing. Average rainfall pH was only 4.78 in this area (Zhou et al., 2003). Sulfur dioxide emission was 6.8×10^8 kg, while the number of vehicles had continuously increased in the last decade (Zhang, 2007). Therefore, massive amounts of acid material fell into the level of the canopy and adhered to it. When rain occurred, this material was dissolved in the throughfall and reduced its pH. In contrast to throughfall, the mean pH values of surface runoff had a sharp increase. Studies at the eastern mountain region in Heilongjiang Province of northern China and the Huitong forest watersheds in Hunan Province of southern China reached the same conclusions (Yan and Tian, 2003; Xin et al., 2006). However, pH values declined slightly while moving through the soil layers of I_1 and I_3. It may be caused by lower soil pH and BS. Because of these conditions, soil under these two plots had few base cations to meet the demand for ion exchange. More acidic material remained in the water. Thus, the pH of water is mainly buffered at the conflux phase of surface runoff.

NO_3^- and SO_4^{2-}

NO_3^- is one of the main factors of water acidification. It was intercepted by I_1 and I_2 in the conflux phase of surface runoff. Similar to this study, studies at Qinling Mountain and the Miyun reservoir watershed showed that forests have the capacity to intercept NO_3^- in surface runoff (Zhang and Li, 2007; Chen et al., 2007). A 6-year study which was conducted in the Johnstone River system in the wet tropics of north-eastern Australia also indicated that the median concentration of NO_3^- was only 0.006 mg/L in surface water of a rainforest area with a coverage of 95%, whereas its median concentration was as high as 0.64 mg/L in surface water of a sugar cane area without natural forests in the region (Heather and Richard, 2008). Robert (2000) conducted experimental clear-cut logging to test its effect on water quality in three forest watersheds in Ontario, Canada. By the second and third year after logging, the average volume-weighted concentration of dissolved total nitrogen had increased. After clear-cut logging, the function of forest for intercepting NO_3^- had decreased. Because of this, the risk level of runoff water acidification had increased. Thus, instead of interception, NO_3^- was released to surface runoff and interflow in CK in our study. Because of stronger interception of NO_3^-, forest ecosystems have the effect of improving water quality. But given that some correlation coefficients were not significant, other factors were clearly present affecting the relationships.

SO_4^{2-} can also lead to acidification in water. Given the correlation between water pH and SO_4^{2-} concentrations, SO_4^{2-} was dominant in the acidification of throughfall in our present study. It was also related to the amount of dry and wet deposition of these two elements. The proportion of SO_4^2 in rain water, accounted for 78.9%, which was far greater than that of NO_3^- (13.3%). The ratio of SO_2 to NO_x (nitrogen oxides) emissions was similar (Zhang, 2007). Because of this, the sulfur contained in dust (which fell into the canopy from the air) was more than the amount of nitrogen. Therefore, more SO_4^{2-} was released to throughfall in the canopy level when it rained. Moreover, this relationship was not found in surface runoff and interflow. In these two water regimes, NO_3^- played a leading role in acidification. Because sulfate precipitates easily in the water: Stream chemistry was monitored for eight mature hardwood ecosystems and 16 forest ecosystems in the mountains of North Carolina. All ecosystems showed very large accumulations of SO_4^{2-}, which demonstrated that the ion in surface runoff was intercepted by forest ecosystems (Swank and Douglass, 1977). Otherwise, according to a study in a forest area of southwestern China, the total amount of sulfur (Ning and Cheng, 1988) ranged from 0.0988 g/kg – 0.2593 g/kg, far less than the total nitrogen in soils (see Table 1). Therefore, the SO_4^{2-} released from soil to water may be less than NO_3^-, while its effect on changing pH was weaker.

Base cations

Base cations, such as Ca^{2+}, Mg^{2+}, K^+ and Na^+, are necessary nutrients for plant growth and, as well, they also have an acid–buffer capacity. But in China, few studies show this aspect. Base cations are usually regarded as nutrients and investigators largely focused on transportation of these ions in geochemical cycles (Liu et al., 2003; Yan and Tian, 2003). However, given the correlation between pH values of water and concentrations of base cations, Ca^{2+} was the dominant factor of the acid–buffer in interflow, where Mg^{2+} was the main buffer ion in surface runoff. Studies on forest and aquatic ecosystems in New York found the same results. It indicated that surface water acidification was caused by a dilution of base cations (Driscoll et al., 2003).

Similar to our study, Zhang (2005) suggested that Ca^{2+}, Mg^{2+} and K^+ were leached into throughfall, except for Na^+. In our study we did examine the effect of Na^+. However, studies in Dinghushan Mountain showed that the concentration of Na^+ had increased, but the source of these Na^+ in the rain water is generally regarded as sea water (Liu et al., 2003). Both Chongqing and Qinling mountains are far from the coast, whereas Dinghushan Mountain is located in a coastal area. More Na^+ was supplied to rainfall and then throughfall by sea water. Therefore, different concentrations of Na^+ were due to different locations.

Al^{3+}

Al^{3+} is a toxic factor especially in areas with serious acid deposition. It is a harmful limitation on the growth of vegetation (Zhou and Norio, 1996; Riha et al., 1986; Liu and Tian, 1992; Cornan et al., 1989; Driscoll et al., 2001). Cornan and Schofield (1990) suggested that the highest concentrations of labile aluminum were found in watersheds characterized by soils with <10 to 15% BS, based on a survey of 14 forest watersheds in eastern North America and northern Europe. In our present study, the soils BS of the research plots were 18.3% (I_1), 39.12% (I_2), 11.94% (I_3) and 16.73% (CK) (Table 1). However, the Al^{3+} concentration in surface runoff and interflow from I_1 were the largest, instead of I_3 with soil BS (11.94%) between 10 to 15%. It may be related to the high import from throughfall and regional differences.

Acidic soils with pH between 3.5 and 4.5 also have an aluminum buffer system (Wang, 2009). Al is an important pH buffer (Driscoll, 1985) and the soil solution can be prevented from acidizing by the system. In our study, correlations between Al^{3+} concentrations and surface runoff pH were shown to exist, as well as interflow pH in all plots except in I_2. Studies on the leaching (leached by acid rain) of aluminum from several soil types in southwestern China indicated that the liberation of Al^{3+} was promoted by acid rain. The concentration of Al^{3+} was related to pH of soil, rain water and soil solution. Under the effect of acid rain, correlation was shown between runoff pH and Al^{3+} concentrations (Zhou and Norio, 1996; Kang and Pang, 1987; Fu et al., 1993; Cornan and Schofield, 1990). The soil pH values in the four plots were 4.10 (I_1), 4.70 (I_2), 4.27 (I_3) and 4.55 (CK) (Table 1). Thus, the existence of a soil aluminum buffer system in I_1, I_3 and CK may be confirmed by the correlation between Al^{3+} concentrations and water pH values. However, such a buffer system did not exist in I_2 due to its soil pH and the lack of correlation with water pH of surface runoff and interflow.

Relationships between water quality and forest ecosystems are complex. Longer periods of monitoring water quality in forest areas are necessary and important for the explanation of environmental effects of forests. In the future, surveys may be conducted throughout the entire year, during which the variations in runoff water quality between months or seasons can be investigated.

Conclusions

This study clearly demonstrates that the average pH value of rain water in Jinyun Mountain area is acidic (5.43) and it becomes more acidic after moving through the canopies of our three typical forests. The water pH is mainly buffered at the conflux phase of surface runoff and forests have clearly a much better acid–buffer capacity than bare land. NO_3^- concentrations play a leading role in the acidification of surface runoff and interflow from forest lands. The amount of SO_4^{2-} is the dominant factor of acidification in throughfall. The main buffer elements in surface runoff were Mg^{2+} and Al^{3+} and in the interflow Ca^{2+} and Al^{3+}. A soil aluminum buffer system may be present in I_1, I_3 and CK. During our investigations, ions were mostly intercepted in the phase of surface conflux and soil level. With less capacity of decontamination than forests, the concentrations of Al^{3+}, Mg^{2+} and Na^+ can only be reduced by CK. Among the four forest plots, I_1 and I_2 demonstrated the better interception with a larger cut range of NO_3^-, SO_4^{2-}, K^+, Na^+, Mg^{2+} and Al^{3+}.

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