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Effects of Forestry Activities on Streamwater Chemistry of a Small Mountainous Sub-Watershed at Serikawa River Basin on Shikoku Island, Japan

Abu Farah Md. Anisur RAHMAN[1], Hiromasa HIURA[2*] and Kazuo SHINO[2]

[1] The United Graduate School of Agricultural Sciences, Ehime University
(Tarumi, Matsuyama 790–8566, Japan)
[2] Faculty of Agriculture, Kochi University (Nankoku, Kochi 783–8502, Japan)

Abstract

Two small mountainous sub-watersheds, located at Serikawa river basin on Shikoku Island of Japan were studied for streamwater chemistry. The objective of this study was to determine the impacts of reforestation subsequent to partial logging on streamwater chemistry of the treated sub-watershed compared to the adjacent undisturbed one after several months of reforestation. Both of the sub-watersheds have similar geological and climatic conditions except they vary in size. We collected bulk precipitation and streamwater samples in the pair of sub-watersheds for a period of three years, and analyzed for 10 chemical components (pH, EC, Cl^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Ca^{2+}, and Mg^{2+}). Non-parametric statistical analyses were applied in this study. The pH, EC, SO_4^{2-}, and cation concentrations in the streamwater were almost unaffected by the reforestation subsequent to partial logging, whereas NO_3^- and Cl^- were sensitive to the forestry activities since their concentrations largely fluctuated in the streamwater of the treated sub-watershed. Results suggested that the increasing NO_3^- and Cl^- concentrations in streamwater caused by the partial logging may be recovered by subsequent reforestation within more or less two years.

Discipline: Forestry and forest products
Additional key words: flow-adjusted concentration, nonparametric statistics, partial logging, reforestation, streamwater chemistry

Introduction

The roles of mountain forests for the conservation of soil, water and ecosystem are of fundamental importance in Japan, where about 75% of the total land area is mountainous and of that 66.6% is forest[15]. Mountain forested watersheds supply downstream areas with good quality water for domestic, agricultural and industrial uses. The chemical composition of streamwater in a forested watershed is usually controlled by the interaction of hydrological factors with geological and biological materials. Water chemistry of a stream may be affected by a wide range of natural and anthropogenic influences. The anthropogenic influences are more intense since they usually affect both the quantity and quality of streamwater directly and rapidly.

Streams of forested watersheds are particularly good indicators of land use changes because their water chemistry can reflect changes in their watersheds. Monitoring of streamwater chemistry in forested watersheds is important for determining the impact of forestry practices as well as resolving issues related to the selection of best management practices. Many studies have shown higher concentrations of various ions in the streamwater of disturbed watersheds, than that of undisturbed watersheds[1,2,5].

Forestry activities such as timber harvest and thinning can affect the streamwater chemistry in different magnitudes based on the intensity of the operation. Good forestry practices minimize these impacts by preventing erosion and conserving soil nutrients. Since hydrochemical processes depend on site-specific conditions, it is difficult to generalize the impact of natural influences or forestry practices on streamwater quality.

The objective of this study was to determine the impacts of reforestation subsequent to partial logging on the streamwater chemistry of the treated sub-watershed compared to the adjacent undisturbed one after several months of reforestation.

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*Corresponding author: fax +81–88–864–5168; hiesando@ee.kochi-u.ac.jp

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Materials and methods

1. Study area

The study area is located at Serikawa river basin in the upstream region of Shimanto River on Shikoku Island, Japan, which is close to Kawai observation watershed studied by Rahman et al.[11]. The area is about 48 km from Nakamura City and 2 km from Yusuhara town of Kochi Prefecture (Fig. 1). The topography of the area is completely mountainous and highly dissected with very steep slopes. Serikawa river basin comprises an area of 470 ha, where two small sub-watersheds SW-1 and SW-2 draining through two small streams were selected for this study. SW-1 has an area of only 12.97 ha, while SW-2 covers a larger area of 36.02 ha. The elevation of SW-1 ranges from 710 m to 937 m, and that of SW-2 ranges from 600 m to 1,028 m. The distance between the mouths of the two sub-watersheds is about 700 m.

The area has a warm to temperate rainy climate. Snow falls occasionally and most of the precipitation is rain. According to the rainfall record of Yusuhara town office, the mean annual rainfall for 25 years since 1977 to 2001 was 2,470.2 mm. Average annual rainfalls recorded at the rain gauge installed near SW-2 outlet during the study period was 2,303.3 mm with the highest mean monthly rainfall in August (424.2 mm) and the lowest in February (89.2 mm). Storms by typhoons and frontal cyclones often attack this area during the months of June to September. The highest and the lowest average monthly temperatures during 1996–2003 at Yusuhara observation station of AMeDAS were 24.2ºC in August and 2.6ºC in January, respectively.

Almost all parts of Serikawa river basin are underlain by sandstone rich mudstone and sandstone alternates of the Chichibu belt (Middle Triassic to Middle Jurassic). In the southern part of Serikawa river basin, limestone is distributed like an isolated island from east to west which is extended to the upper part of SW-2. Dry brown forest soil (B_B) or weakly dried brown forest soil (B_C) is distributed on the upper ridges of SW-1, while most other parts have moderately moist brown forest soil (B_D). In SW-2, weakly dried black soil (Bl_C) is distributed on the flat summit and gentle slopes, while other parts are occupied by moderately moist brown forest soil (B_D) similar to SW-1[8].

Both the sub-watersheds were artificially reforested in the 1960s with Japanese cedar (*Cryptomeria japonica* D. Don) and Japanese cypress (*Chamaecyparis obtusa* Endl.). There was no major silvicultural treatment in SW-1, while partial timber logging was carried out in SW-2 over 5.21 ha (14.4% of the total area) during December 1999. Trees were clearcut in fish-bone pattern strips as shown in Fig. 2. All of the timber was transported by mobile crane with a cable system. Twigs and branches were kept on the forest floor as logging residues. The harvested area was reforested with broad-leaved species (*Quercus serrata* Thunb. and *Zelkova serrata* Makino) in June–July of 2000. We considered the undisturbed sub-watershed SW-1 as a base or control for comparing the effects of reforestation subsequent to partial logging on the stream chemistry of SW-2.

2. Field Procedures

A V-notch weir and a rectangular weir were installed at the foot of SW-1 and SW-2, respectively to continuously register the water level by automatic data-logger at 10-minute intervals, which was later converted to the hourly and daily discharge data. Streamwater samples were collected at the weirs during May 2001 to April 2004 (3 years). Bulk precipitation samples were also col-

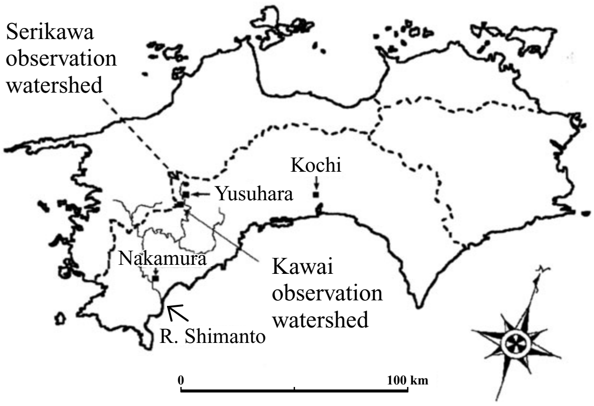

Fig. 1. Location map of Serikawa observation watershed

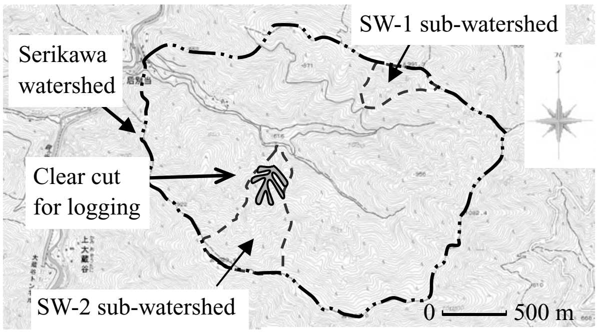

Fig. 2. Location map of SW-1 and SW-2 sub-watersheds in Serikawa river basin

lected during the same period in two bulk precipitation collectors located near open areas adjacent to the V-notch weirs of the sub-watersheds. Samples were collected in clean polyethylene bottles. Sampling frequency varied from weekly to monthly in different months based on the availability of resources. No sampling could be done in a few months (January 2002, March 2003 and April 2003).

3. Laboratory procedures

The pH and electrical conductivity (EC) were measured for non-filtered samples of bulk precipitation and streamwater usually within 24 h after each sampling. The remaining sample materials were stored at 4ºC after filtration until they were analyzed for dissolved ion concentrations. The concentrations of Cl^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Ca^{2+}, and Mg^{2+} were measured by an ion chromatograph (DIONEX: DX-320J). At the beginning of the study, NH_4^+ was not measured for streamwater. We measured NH_4^+ concentrations in streamwater from January 2002 to April 2004. The concentrations of H^+ were calculated from the pH values.

4. Statistical analysis

Since water chemistry data possess unique characteristics of non-normal distribution and positive skewness, mostly nonparametric statistical analyses were used in this study. We applied descriptive statistics, Spearman's rank correlation coefficient (r_s), locally weighted scatterplot smoothing (LOWESS) and Mann-Whitney-Wilcoxon rank-sum test (Rank-sum test) in data analysis as suggested by Helsel and Hirsch[6]. Non-parametric Spearman's rank correlation coefficients (r_s) were computed to measure the strength of non-linear monotonic relationships. However, Pearson's product moment correlation coefficient (r_p) was calculated in a few cases where the relationship between the two variables was linear.

The variance in streamwater quality variables is often influenced by discharge due to the effect of dilution or wash-off of the solutes. We modeled the variation of streamwater chemical components due to discharge by LOWESS regression method[4] to minimize the influence of outliers. LOWESS is a robust locally weighted nonparametric regression and involves smoothing a scatterplot, (x_i, y_i), $i = 1 \dots n$, in which a fitted value at x_i is the value of a polynomial fit to the data using weighted least squares, where the weight for (x_i, y_i) is large if x_i is close to x_k and small if it is not. The weight function used by LOWESS is "tri-cube":

$$\omega(x) = \begin{cases} (1-|x|^3)^3 \; for \; |x| < 1 & (1) \\ 0 \qquad\qquad for \; |x| \geq 1 & (2) \end{cases}$$

LOWESS is computationally intensive since it is an iterative procedure. It does not produce a regression function that is easily represented by a mathematical formula. The residuals from the LOWESS regression relationship between mean hourly discharge (m^3/h) and solute concentration at the days of streamwater sampling were calculated. The i th residual, denoted by e_i, is the difference between the observed value Y_i and the corresponding LOWESS fitted value $\hat{Y}_i$:

$$e_i = Y_i - \hat{Y}_i \qquad (3)$$

The residuals were considered as the flow-adjusted concentrations in streamwater[7].

We also generated plots of LOWESS smoothing lines to illustrate the nonlinear temporal trends of solute concentrations for the study period[9]. The temporal trends of the treated sub-watershed (SW-2) were then compared to that of the control sub-watershed (SW-1) to observe any fluctuation of solute concentrations in streamwater. We used XL Statistics computer software developed by Carr[3] for LOWESS regression, residual analysis and smoothing curves.

We calculated the time series in number of days since January 1, 2001 because the time-scale of observed data was not equally spaced due to existence of missing data and variation in sampling frequency. The Rank-sum test was conducted to statistically determine whether the discharge, bulk precipitation chemistry and streamwater chemistry data of SW-2 were significantly different from that of SW-1.

Results and discussion

1. Bulk precipitation chemistry

During the study period, median pH of bulk precipitation was 5.1 in SW-1 and 4.9 in SW-2 (Table 1). Among the measured ions, Cl^- and SO_4^{2-} were dominant anions in SW-1 and SW-2 respectively, whereas Na^+ was the dominant cation in both sub-watersheds. Concentrations of NH_4^+ and Ca^{2+} were also rich in both SW-1 and SW-2. Highly significant correlation ($p<0.001$) among Cl^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, and Mg^{2+} concentrations revealed that they originated from similar sources. The bulk precipitation chemistry was probably affected by the wet and dry deposition of marine sources to a great extent, because the area is only 35 km away from the Pacific Ocean. Concentrations of SO_4^{2-} in precipitation might also be slightly influenced by the local deposition of SO_2 gas exhausted from the vehicles and equipments used for mechanical slope stabilization and road construction activities in the adjacent areas throughout the

Table 1. Descriptive statistics of the chemical constituents in bulk precipitation

Constituent	Sub-watershed	N	Minimum	Percentile			Maximum
				25	50 (Median)	75	
pH	SW-1	42	6.18	6.79	6.92	7.16	7.70
	SW-2		6.05	6.69	6.88	7.10	7.70
EC, μScm^{-1}	SW-1	41	20.30	39.80	43.40	45.30	49.90
	SW-2		17.40	34.10	36.10	38.20	42.60
Cl^-, μcqL^{-1}	SW-1	49	41.97	64.53	67.66	71.87	90.17
	SW-2		45.39	64.68	68.78	75.26	91.88
NO_3^-, μeqL^{-1}	SW-1	49	0.00	5.60	7.17	9.26	12.32
	SW-2		0.00	12.99	17.58	19.99	36.74
SO_4^{2-}, μeqL^{-1}	SW-1	49	29.48	67.39	75.74	89.35	106.10
	SW-2		18.84	29.77	33.64	38.29	93.10
Na^+, μeqL^{-1}	SW-1	49	76.88	124.70	131.50	151.10	178.90
	SW-2		87.06	99.03	104.60	123.30	162.40
NH_4^+, μeqL^{-1}	SW-1	32	0.00	0.86	1.95	2.85	17.92
	SW-2		0.00	1.23	1.54	2.76	10.39
K^+, μeqL^{-1}	SW-1	49	4.63	8.75	10.89	12.09	19.38
	SW-2		3.15	7.07	8.72	9.17	13.69
Ca^{2+}, μeqL^{-1}	SW-1	49	81.37	141.60	167.70	186.90	237.00
	SW-2		96.96	123.90	143.80	164.80	225.00
Mg^{2+}, μeqL^{-1}	SW-1	49	36.80	65.37	70.70	76.35	86.18
	SW-2		43.23	53.65	57.71	61.61	75.29

Table 2. Descriptive statistics of the chemical constituents in streamwater

Constituent	Sub-watershed	N	Minimum	Percentile			Maximum
				25	50 (Median)	75	
pH	SW-1	40	4.00	4.64	5.13	5.67	6.60
	SW-2		3.70	4.53	4.89	5.41	6.60
EC, μScm^{-1}	SW-1	38	4.23	8.15	13.11	23.60	79.10
	SW-2		3.76	9.06	12.66	25.53	57.20
Cl^-, μeqL^{-1}	SW-1	47	1.61	16.25	33.91	58.07	917.70
	SW-2		2.01	12.89	24.73	67.12	957.50
NO_3^-, μeqL^{-1}	SW-1	47	0.00	1.04	4.53	19.92	205.60
	SW-2		0.00	1.40	5.26	18.66	174.10
SO_4^{2-}, μeqL^{-1}	SW-1	47	9.80	19.50	28.21	59.93	393.80
	SW-2		7.88	21.54	33.10	61.80	479.10
Na^+, μeqL^{-1}	SW-1	47	1.02	14.58	36.14	58.44	462.70
	SW-2		3.36	13.08	26.66	59.30	812.30
NH_4^+, μeqL^{-1}	SW-1	47	0.00	7.07	11.66	18.98	61.46
	SW-2		0.00	9.12	15.01	26.11	81.03
K^+, μeqL^{-1}	SW-1	47	0.44	3.06	5.23	8.13	35.56
	SW-2		0.60	3.47	5.39	7.36	46.37
Ca^{2+}, μeqL^{-1}	SW-1	47	1.02	5.53	11.48	24.66	306.50
	SW-2		1.28	5.70	11.83	22.88	251.70
Mg^{2+}, μeqL^{-1}	SW-1	47	0.96	2.92	5.04	10.54	201.50
	SW-2		1.15	2.92	5.63	12.01	225.80

study period. The Rank-sum test showed that bulk precipitation chemical parameters of SW-2 were statistically the same as SW-1. Therefore, precipitation chemistry did not significantly contribute to any variation of streamwater chemistry between the two sub-watersheds.

2. Streamwater chemistry

In streamwater of both sub-watersheds, SO_4^{2-} and Cl^- were major anions and Ca^{2+} and Na^+ were major cations (Table 2). Median EC and median concentrations of the major ions in streamwater were an order of magnitude higher than that in bulk precipitation, which suggested that streamwater chemistry was not predominantly controlled by precipitation chemistry, but by other factors of the catchment hydrochemical processes. The specific discharge at the days of streamwater sampling of the pair of sub-watersheds showed highly significant linear correlation (r_p = 0.99) and a similar temporal pattern (Fig. 3). However, Rank-sum test revealed that there was a highly significant ($p<0.001$) difference between the discharges of the two sub-watersheds at the days of streamwater sampling.

The streamwater H^+ concentration (calculated from pH) was not significantly correlated with discharge in both sub-watersheds (Table 3). The pair of temporal trend lines of H^+ concentrations in the two sub-watersheds almost overlapped on each other for both unadjusted and flow-adjusted data (Fig. 4). Rank-sum test

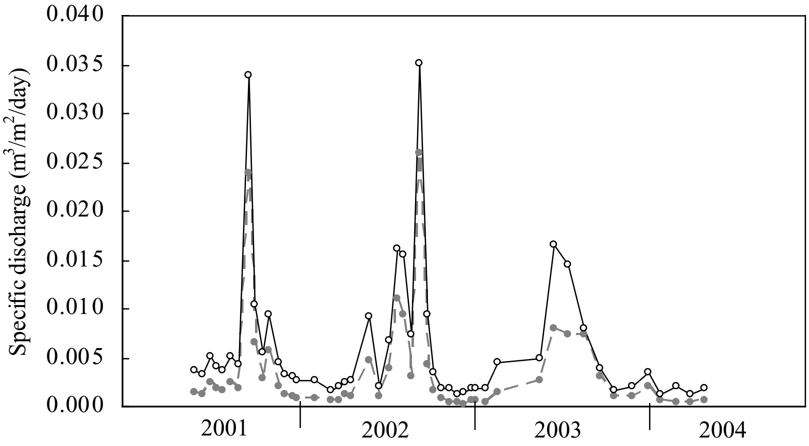

Fig. 3. Specific discharge at the days of streamwater sampling
---●---: SW-1, ——○——: SW-2.

Table 3. Results of (1) Spearman's rank correlation analysis between discharge and chemical constituents of streamwater and (2) Rank-sum test for difference of streamwater chemical constituents between two sub-watersheds

Constituent	(1) Spearman's rank correlation coefficient		(2) Rank-sum test results	
	SW-1	SW-2	Unadjusted concentration	Flow-adjusted concentration
pH	-0.17 (NS)	-0.17 (NS)	NS	NS
EC	-0.70 (S***)	-0.38 (S***)	S***	NS
Cl^-	-0.44 (S***)	-0.21 (NS)	NS	NS
NO_3^-	-0.14 (NS)	-0.14 (NS)	S***	NS
SO_4^{2-}	-0.76 (S***)	-0.68 (S***)	S***	NS
Na^+	-0.17 (NS)	-0.18 (NS)	S***	NS
NH_4^+	-0.03 (NS)	-0.10 (NS)	NS	NS
K^+	-0.08 (NS)	-0.23 (NS)	S***	NS
Ca^{2+}	-0.38 (S***)	-0.17 (NS)	S***	NS
Mg^{2+}	-0.54 (S***)	-0.37 (S***)	S***	NS

S***: Significant at $p<0.01$, NS: Not significant.

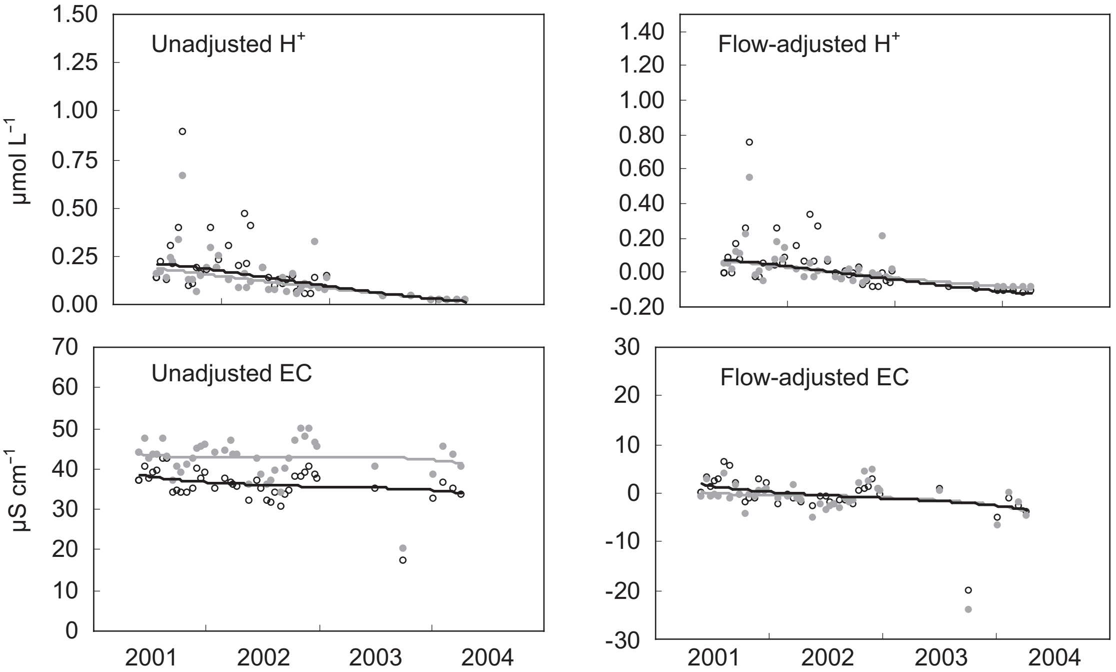

Fig. 4. Temporal trends of H+ (calculated from pH) and EC in streamwater of SW-1 and SW-2

—●— : SW-1, —○— : SW-2.

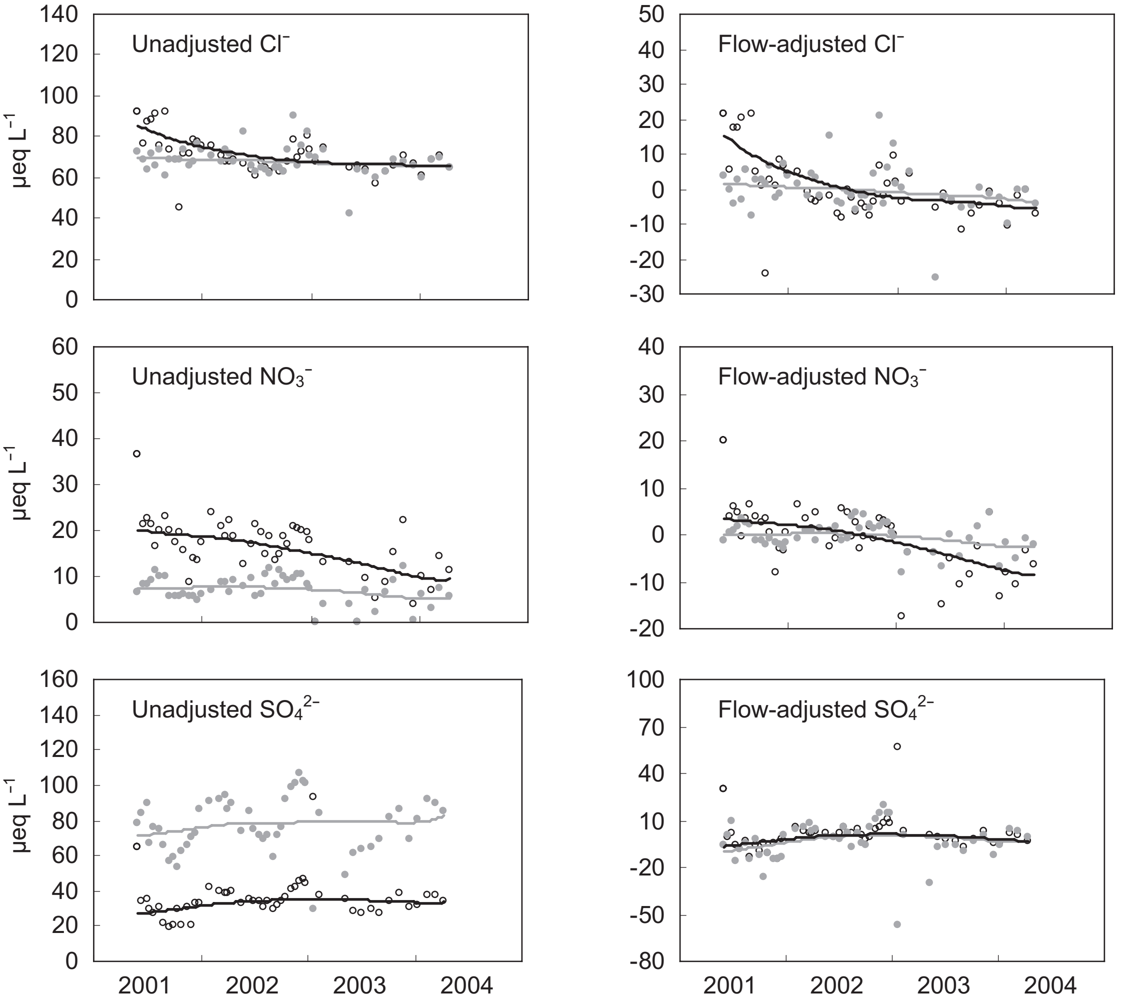

Fig. 5. Temporal trends of anion concentration in streamwater of SW-1 and SW-2

—●— : SW-1, —○— : SW-2.

also suggested that H^+ concentrations in the streamwater were statistically the same in both sub-watersheds (Table 3). Unadjusted EC of SW-1 was much higher than that of SW-2. This variation of EC is attributed to the variation of discharge between the two sub-watersheds since discharge and EC in both sub-watersheds were statistically correlated (Table 3). Temporal trend lines of flow-adjusted EC of the pair of sub-watersheds almost overlapped on each other. Rank-sum test also suggested that there was no statistical difference between the streamwater EC of the two sub-watersheds.

Although there was no significant difference between Cl^- concentrations of the pair of sub-watersheds for both unadjusted and flow-adjusted data (Table 3), the fluctuation of flow-adjusted concentrations revealed Cl^- as sensitive to the forestry activities in SW-2 (Fig. 5). While the temporal trend of flow-adjusted Cl^- concentrations in SW-1 was almost constant, there were initial higher concentrations of Cl^- in SW-2 during 2001 which gradually decreased and became stable afterwards. Spearman's correlation analysis suggested that Cl^- concentration was significantly correlated with discharge in SW-1, but the correlation was not statistically significant in SW-2 (Table 3), which is attributed to the fluctuation of Cl^- concentrations in SW-2. The following processes are most likely to be associated with the fluctuation of Cl^- concentration in SW-2 followed by the forestry activities. The partial logging resulted in wetter and more hydrologically responsive soils caused by decreased evapotraspiration losses[13]. Less rainfall is required to recharge soil water under such a condition. Initially, a reduced canopy density allowed more rainfall to reach the wetter and more hydrologically responsive forest floor, resulting in more rainwater flowing to the stream through surface and subsurface flow and increasing the Cl^- concentration in the streamwater from rainwater. Later, the resilience process through reforestation of the logged over area caused Cl^- concentrations to gradually decrease and be stable with time.

We did not find any significant correlation between discharge and NO_3^- concentrations in either sub-watershed (Table 3). Flow-adjusted concentrations were considered better to explain the mobility of this nutrient, since a large variation of streamwater NO_3^- concentrations comes from the variation of discharge[12]. The NO_3^- concentrations in the streamwater of the undisturbed sub-watershed were more or less constant over the study period. We found large fluctuations of NO_3^- concentrations with the changing forest conditions in SW-2, which revealed NO_3^- to be very sensitive to the forestry activities in the treated sub-watershed. The initial higher concentrations of NO_3^- in SW-2 are attributed to be a consequence of the following two factors. Firstly, an increase in soil temperature on the logged over area caused an increased decomposition of logged residues and organic matter on the soil surface, which accelerated N mineralization and loss of NO_3^- to the stream[10]. Secondly, there was reduced uptake of NO_3^- because of fewer trees after the partial harvest, resulting in increased NO_3^- export to the stream[14]. The resilience process through reforestation of the logged over area and increased uptake of NO_3^- by the growing trees resulted in a gradual lower release of NO_3^- to the stream of SW-2. Rank-sum test showed that the difference between the flow-adjusted NO_3^- concentrations of the two sub-watersheds was insignificant, while the difference between the unadjusted NO_3^- concentrations was statistically significant.

The temporal trends of SO_4^{2-} and base cations in SW-2 closely resembled the respective trends of ion concentrations in SW-1. Spearman's correlation analysis showed that discharge was significantly correlated with SO_4^{2-} (both watershed), Ca (SW-1) and Mg (both watersheds) concentrations in streamwater (Table 3). Therefore, flow-adjusted concentrations of these solutes could be undoubtedly considered for comparison between the two sub-watersheds (Fig. 5, Fig. 6). Although discharge was not statistically correlated with Na^+ and K^+ concentrations in either sub-watershed, the pair of temporal trend lines showed that discharge was the most significant source of variation of these anion concentrations in the studied small sub-watersheds. Therefore, flow-adjusted concentrations were used for comparing these variables. The pair of temporal trend lines of the flow-adjusted concentrations of SO_4^{2-} and base cations almost overlapped on each other (Fig. 5, Fig. 6). Rank-sum test also showed that concentrations of these ions in SW-2 were statistically the same as SW-1. Therefore, reforestation subsequent to partial logging did not significantly affect the mobilization of these ions during the study period. Since we started our study after several months of reforestation, some of the immediate effects of partial logging on streamwater chemistry could not be detected. However, it is evident that the increasing NO_3^- and Cl^- concentrations in streamwater caused by the partial logging may be recovered by subsequent reforestation within more or less two years.

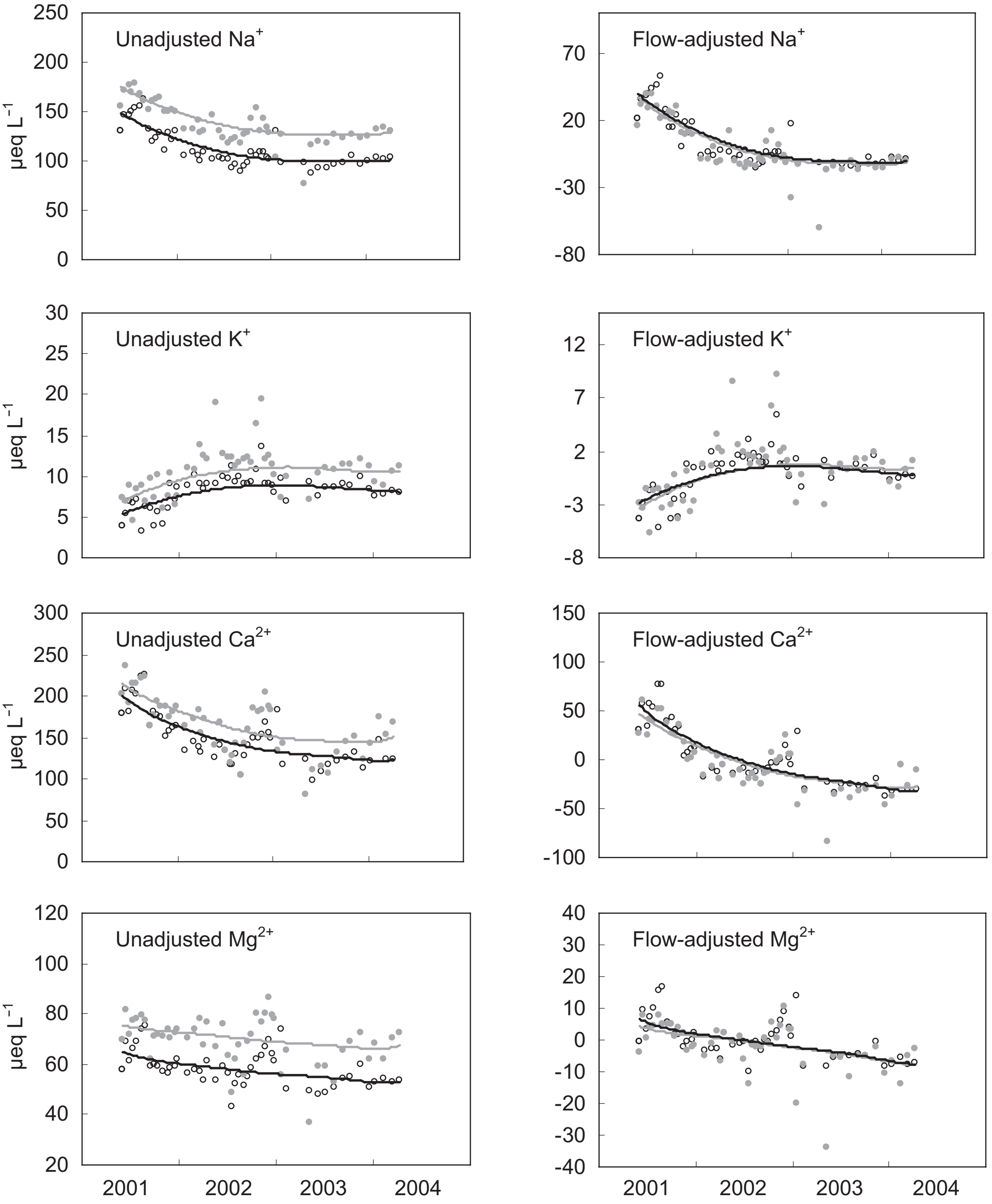

Fig. 6. Temporal trends of base cation concentration in streamwater of SW-1 and SW-2

—●— : SW-1, —○— : SW-2.

Conclusions

This study concludes that NO_3^- and Cl^- were sensitive to reforestation subsequent to partial logging in the treated sub-watershed of Serikawa river basin. The initial higher concentrations of NO_3^- in the streamwater are attributed to be a consequence of two factors; (1) accelerated N mineralization and (2) reduced NO_3^- uptake because of partial logging. Reduced interception allowed more rainfall to reach the wetter and more hydrologically responsive soils after partial logging, resulting in more rainwater flowing directly to the stream through surface and subsurface flow and increasing the Cl^- in the streamwater of the treated sub-watershed from rainwater. However, concentrations of NO_3^- and Cl^- gradually decreased in the streamwater due to the resilience process of the logged over area by reforestation with broad-leaved tree species. Streamwater pH, EC, SO_4^{2-}, and base cation concentrations in the treated sub-watershed were unaffected by the forestry activities. In this study, the comparison of temporal trend lines of flow-adjusted and unadjusted concentrations suggested that the chemical components in the streamwater largely vary with discharge. Therefore, although correlation between discharge and solute concentrations may not be sometimes statistically significant, flow-adjusted concentrations and trends should be used to detect the natural and human-induced changes affecting water quality within small watersheds. The results of this study revealed that the increasing NO_3^- and Cl^- concentrations in streamwater caused by the partial logging may be recovered by subsequent reforestation within more or less two years. Thus, reforestation followed by partial logging is an effective method for the ecosystem conservation and sustainable forestry.

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