

Use of field measurement data to identify possible sources of major ions in a stream flowing through evergreen forests in the southern Kyushu Mountains

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The present study was conducted to verify our previous experimental results and to clarify the influence of leaf litter and stream geomorphology on stream water composition based on field measurements conducted from April 2012 to March 2016. Stream water samples were collected from four different environments (a) springs; (b) riffles; (c) pools; and, (d) side-pools. Samples were collected using a 250 ml polyethylene bottle and water temperature, EC, pH, and the concentrations of TC (total carbon), TN (total nitrogen), cations (Li^+ , Na^+ , NH_4^+ , K^+ , Mg^{2+} and Ca^{2+}) and anions (F^- , Cl^- , NO_2^- , Br^- , NO_3^- , PO_4^{3-} and SO_4^{2-}) were measured. It was revealed from two-way ANOVA and multiple regression analysis that the ion concentrations and physicochemical parameters of the stream water were affected by sampling season or stream environment, or both, and that ion concentrations might be related to each other, affecting physicochemical parameters.

Na^+ originates from the weathering of plagioclase in sedimentary silicate rocks and Mg^{2+} and Ca^{2+} originate almost entirely from the weathering of calcite and/or dolomite in sedimentary carbonate rocks in the study area. However, the contribution of biomass to stream water composition, i.e. through leachate from leaf litter, can be pronounced for K^+ concentrations. The findings of the present study also demonstrated that anion and cation concentrations in the study area differed significantly among stream environments and seasons, likely due to the heterogeneous distribution of ions resulting from leachate from leaves. As the reason for this, it was inferred that the presence of *sabo* dams affected the retention times of leaf litter in the stream. Thus, comparative studies of litter decomposition rates in reaches with and without *sabo* dams are needed in the future.

Key words: stream water composition, ions, sources, leaf litter, Paleogene.

1. Introduction

Stream water is composed of water from precipitation, groundwater and the soil (surface and subsurface water). Precipitation contains atmospheric gases and aerosols, and groundwater contains numerous ionic components derived from rock weathering, such as silicate, carbonate and sulfide rocks⁵⁾. Soil can be defined as a complex matrix comprised of air, water, decomposing organic matter, living plants and animals, and the residues of rock weathering¹⁹⁾. Stream runoff transports nutrients derived from minerals, precipitation, and organic matter, directly downstream. Stream water composition is therefore largely influenced by the geochemistry of groundwater and soil water⁶⁾.

The amount of allochthonous material that enters lotic ecosystems annually from terrestrial riparian forests is considerable⁴⁾, and the compounds derived from the decomposition of leaf litter are thought to have an important effect on stream water quality. We have demonstrated experimentally that, although the primary source of ions is rock weathering, soil and plant materials also contribute

to ion loads. Specifically, leaf litter is one of the primary sources of ions, especially K^+ , Mg^{2+} and Ca^{2+} , in stream environments such as pools, rapids, springs and side-pools¹⁰⁻¹³⁾. In terms of the materials from which ions are leached, the order of release is leaves > soil > rock¹⁷⁾. Further, the influence of leaf litter on stream water composition can be accelerated in side-pools, which tend to retain leaves supplied from the riparian zone⁸⁾.

The present study was conducted to verify these experimental results and to clarify the influence of leaf litter and stream geomorphology on stream water composition based on field measurements conducted from April 2012 to March 2016 in Miyazaki Prefecture, Japan.

2. Site description

Experiments were conducted in the Takeo River in Saito City of Miyazaki Prefecture, Japan. The Takeo River, a tributary of the Hitotsuse River, ranges in elevation from 100 m to 600 m and originates in the southern Kyusyu Mountains. The Takeo River Basin overlays the Miyazaki Formation, which was formed during the Cretaceous

to middle Paleogene periods. The formation consists of black slate, sandstone and shale. Consequently, the geologic structure of the basin is characterized by the prevalence of weak and extensively folded rock strata with numerous faults that are susceptible to weathering. These geologic conditions have formed steep and unstable basin slopes where several mid-sized landslides have occurred in the last fifty years. To prevent landslides in the basin, seven 3- to 5 m-high *sabo* dams have been constructed along the river since 1965⁷⁾.

The study site consists of a section of river measuring approximately 1 km, between *sabo* dam No. 5 and a point approximately 50 m downstream of *sabo* dam No. 6 (Fig. 1). The stream is a first-order stream with a mean width of 10 m, mean depth (at modal flow) of 0.3 m, mean slope of 1/40, and mean current velocities ranging from 20–30 cm/sec. The stream bottom is composed primarily of gravel, pebbles and cobble substrates, and the riparian vegetation consists of evergreen trees such as *Symplocos theophrastifolia* Sieb. et Zucc., *Machilus japonica* Sieb. et Zucc., *Meliosma rigida* Sieb. et Zucc., and *Litsea acuminata* Kurata. Since the slope of the stream basin is steep, tree leaves supplied to the forest floor of the slope tend to be removed to the stream bed.

3. Methods

3-1 Stream water sampling and estimation of water physicochemical parameters

Stream water samples were collected from four different environments (streambed types) (Fig. 1): (a) springs arising from cracks on the vertical cliffs of the bedrock slope running along the side of the stream, approximately 150 cm above the stream margin (hereafter, denoted as S); (b) riffles (R); (c) pools (P); and, (d) side-pools (SP), which were defined as stagnant areas of water along the stream margin. Since these sampling points (spring, riffle, pool and side-pool) were not distributed continuously, the water quality measurements at each sampling point were

considered to be independent of each other.

Samples were collected using a 250 ml polyethylene bottle. Water from springs was collected from cracks in the bedrock, and water from riffles was collected 10 cm below the water surface. In pools and side-pools, samples were collected approximately 5 cm above the substrate using a 250 ml polyethylene bottle. A water sampler was used to collect water in pools that were deeper than 50 cm. At the time of sampling, water temperature, EC and pH of the water were measured with a water quality probe (WQC-20A, TOA Electronics Ltd., Japan). The collected water samples were transported to our laboratory and the concentration of total carbon (TC; including total organic carbon (TOC) and inorganic carbon (IC)) and total nitrogen (TN) were measured using an automatic total organic carbon analyzer (TNC-6000, Toray Engineering K.K., Japan). The concentrations of cations (Li^+ , Na^+ , NH_4^+ , K^+ , Mg^{2+} and Ca^{2+}) and anions (F^{3-} , Cl^- , NO_2^- , Br^- , NO_3^- , PO_4^{3-} and SO_4^{2-}) were measured by ion chromatography (DX-120, Nippon Dionex K.K., Japan).

Sampling of water was performed discretely and at random in the rainy season and during floods in summer, and in the non-rainy and dry season in winter, from July 2011 to January 2014, and monthly from April 2015 to March 2016.

3-2 Calculation of antecedent rainfall

A previous study showed that the release rates of cations differed according to the materials from which those cations were released as well as the specific cations involved¹⁷⁾. The author of that study proposed that one of the reasons for the observed differences in release rates may have been the amount of rainfall. In order to clarify the effect of rainfall on the release rates of these substances in a natural stream basin, antecedent rainfall was inferred 30 and 90 days before each measurement day (hereafter referred to as Rain30 and Rain90, respectively) using daily rainfall data collected by a Japan Meteorological Agency rainfall observation station in Saito City. The observation station was located 5 km away from the study stream.

3-3 Statistical analysis

In the present analysis, the sampling seasons were defined as follows: March–May was taken as spring, June–August as summer, September–November as autumn, and December–February as winter. The effects of these sampling seasons (spring, summer, autumn and winter) and the sampling-point environment (S, P, R and SP) on water physicochemical parameters (temperature, EC, pH) and TC, TN, anion and cation concentrations were analyzed by two-way ANOVA. Differences among individual physicochemical parameters were estimated using *Scheffe's* multiple range test. In this analysis, the seasons and sampling-point environments were regarded as independent variables and the measurement values of the water physicochemical parameters and ion concentrations were regarded as dependent variables. Furthermore, in order to estimate the relations among the water physicochemical parameters and the release rates of major ions (SO_4^{2-} , Na^+ , K^+ , Mg^{2+} and Ca^{2+}), partial correlation coefficients were calculated by multiple regression analysis, since the concentration of these major ions in stream water may be influenced through their interactions with the other water physicochemical components and ions. In the present analysis, partial regression coefficients corresponding to the stream environment (streambed types) were acquired

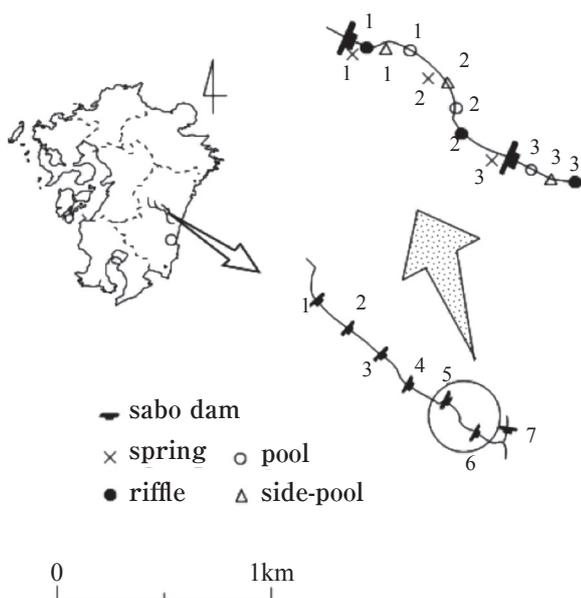


Fig 1. Map of the catchment, investigated stream, and sampling points

Table 1. Overall comparison of ranges, means and standard errors of measured physicochemical values in different stream environments

stream environment	temp. (°C)	EC ($\mu\text{S}/\text{cm}$)	pH	TC (mg/l)	TN (mg/l)	Cl ⁻ (mg/l)	NO ³⁻ (mg/l)	SO ₄ ²⁻ (mg/l)	Na ⁺ (mg/l)	NH ₄ ⁺ (mg/l)	K ⁺ (mg/l)	Mg ²⁺ (mg/l)	Ca ²⁺ (mg/l)	
P (pool)	min	8.1	38.3	6.6	0.10	0.00	2.908	1.482	2.154	2.156	0.000	0.325	1.041	1.660
	max	22.7	98.8	8.0	18.40	3.30	12.640	5.084	6.888	8.178	0.879	1.646	5.077	13.559
	mean	15.9	80.2	7.2	8.96	0.40	4.675	2.872	4.532	3.731	0.085	0.667	2.941	7.218
	standard error	0.6	1.5	0.0	0.45	0.08	0.242	0.126	0.132	0.189	0.019	0.029	0.105	0.360
R (rapid)	min	8.2	62.6	6.6	0.00	0.00	2.947	1.066	0.954	2.181	0.000	0.371	0.886	1.133
	max	22.7	99.2	8.0	14.10	3.00	9.538	5.230	6.530	7.198	0.592	1.958	5.133	13.839
	mean	15.4	82.9	7.3	8.37	0.41	4.303	2.676	4.693	3.844	0.068	0.687	3.098	7.590
	standard error	0.6	1.3	0.0	0.43	0.07	0.184	0.127	0.130	0.192	0.014	0.034	0.117	0.357
S (spring)	min	6.3	30.7	6.4	0.00	0.00	2.240	0.000	1.837	1.693	0.000	0.168	0.000	0.000
	max	23.6	79.3	8.1	37.40	2.00	8.177	5.644	6.954	7.735	0.648	1.339	4.066	10.765
	mean	16.6	70.6	7.3	6.48	0.18	4.573	1.550	4.042	3.853	0.106	0.500	1.484	3.032
	standard error	0.7	3.2	0.1	0.92	0.07	0.165	0.167	0.235	0.240	0.024	0.040	0.135	0.417
SP (side-pool)	min	6.7	34.3	6.5	0.20	0.00	0.251	0.089	0.194	0.603	0.000	0.042	0.159	0.229
	max	22.7	104.2	7.8	29.00	2.40	12.470	6.789	6.635	7.983	0.385	2.872	5.117	13.765
	mean	16.1	80.6	7.1	10.80	0.49	4.753	2.648	4.429	4.146	0.076	0.814	2.969	6.798
	standard error	0.5	1.6	0.0	0.66	0.07	0.249	0.147	0.137	0.184	0.010	0.057	0.119	0.331

with 9 measurements as explanatory variables (temp., pH, TN/TC (the ratio of TN concentration to TC concentration), Rain30, Rain90 and each major ion concentration) and one measurement as a target variable (major ion concentration).

4. Results

4-1 Stream water fluctuations

4-1-1 Overall comparisons of measured values in stream water

The ranges, means and standard errors of measured parameters, corresponding to the stream environments of the respective sampling sites are shown in Table 1. The mean water temperature in the spring was 0.5–1.2°C higher than that of the other stream environments sampled. The EC values in S were relatively lower than in R, P and SP. The highest pH value was observed in S and the mean pH value was lowest in SP. The range and mean of pH in R were almost the same as those in P, indicating the median value between S and P.

The measured TC concentration was the same as the TOC concentration, because no IC was detected in any samples. The values observed for TC were higher in S and SP than in R and P, except for mean TC value in S; however, those of TN were relatively higher in R and P than in S and SP, except for the mean TN value in SP.

The ranges and mean concentrations of each ion in the stream environments are also shown in Table 1. In the present study, Li⁺, NO₂⁻, Br⁻, PO₄³⁻ and F⁻ were not detected in the stream water. With the exception of Cl⁻, Na⁺ and NH₄⁺, mean ion concentrations were lowest in S and mean concentrations of Cl⁻, Na⁺ and K⁺ were highest in SP. Other than the three springs (S) that were sampled in the present study, no additional springs or tributaries flow into the river reach examined in this study, and there are no artificial sources of ions. Consequently, all of the ions in the river reach examined in this study were considered to be derived from natural sources.

Table 2. Date of sampling and study month. Time (months) indicates the number of months after the first measurement month

date of sampling	time (months)	seasons
2011.07.27	—	summer
2012.04.19	9	spring
2012.07.30	12	summer
2013.05.22	22	spring
2013.07.09	24	summer
2013.10.09	27	autumn
2014.01.22	30	winter
2015.04.09	45	spring
2015.05.12	46	spring
2015.06.16	47	summer
2015.07.14	48	summer
2015.09.02	49	autumn
2015.10.22	50	autumn
2015.11.27	51	autumn
2015.12.18	52	winter
2016.01.29	53	winter
2016.02.19	54	winter
2016.03.17	55	spring

4-1-2 Fluctuations of each parameter over the experimental period

The mean concentrations of EC, pH, TC, TN and the major ions at all of the sample sites are shown in Fig. 2. The sampling days and passage months which is the number of months since the first measurement month to each measurement month are shown in Table 2. Measurements conducted in September 2015 were disregarded due to

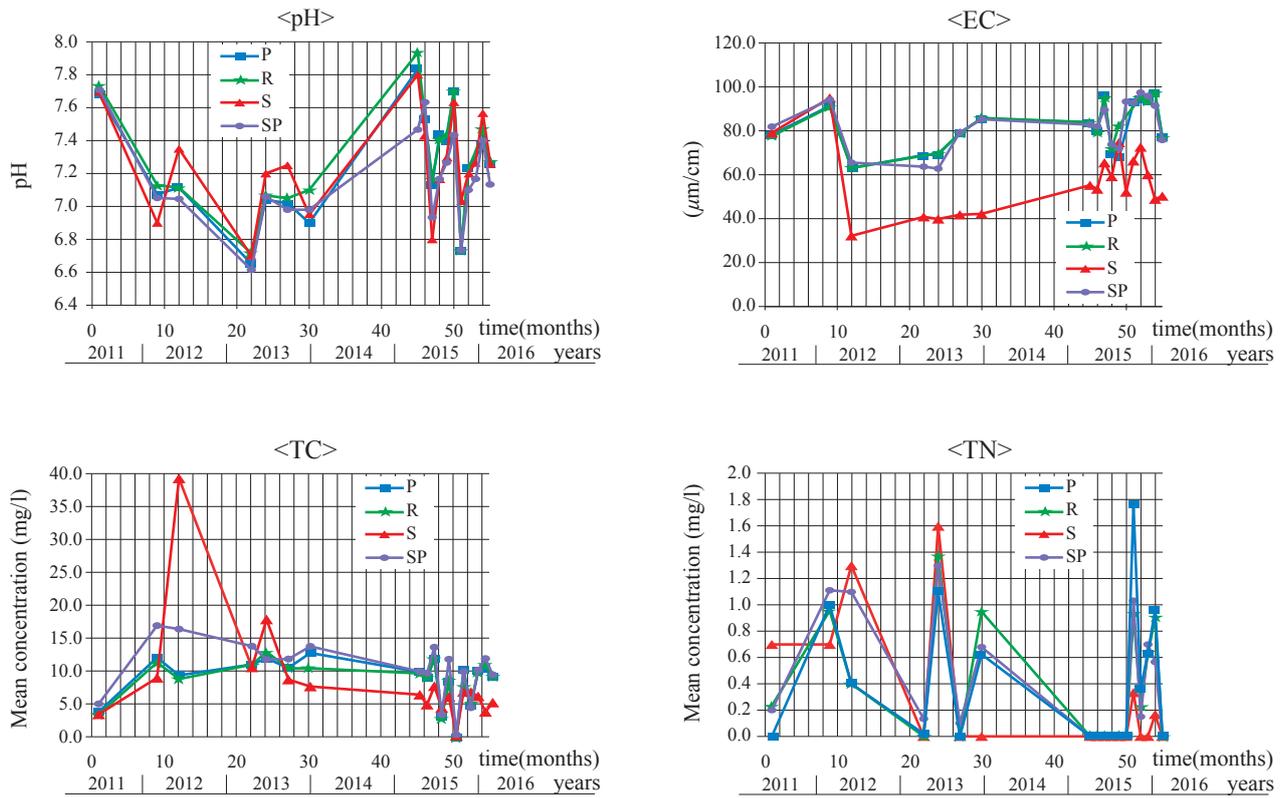


Fig 2(a). Fluctuations in mean physicochemical values in different stream environments. Time (months) on the horizontal axis indicates the number of months after the first measurement month

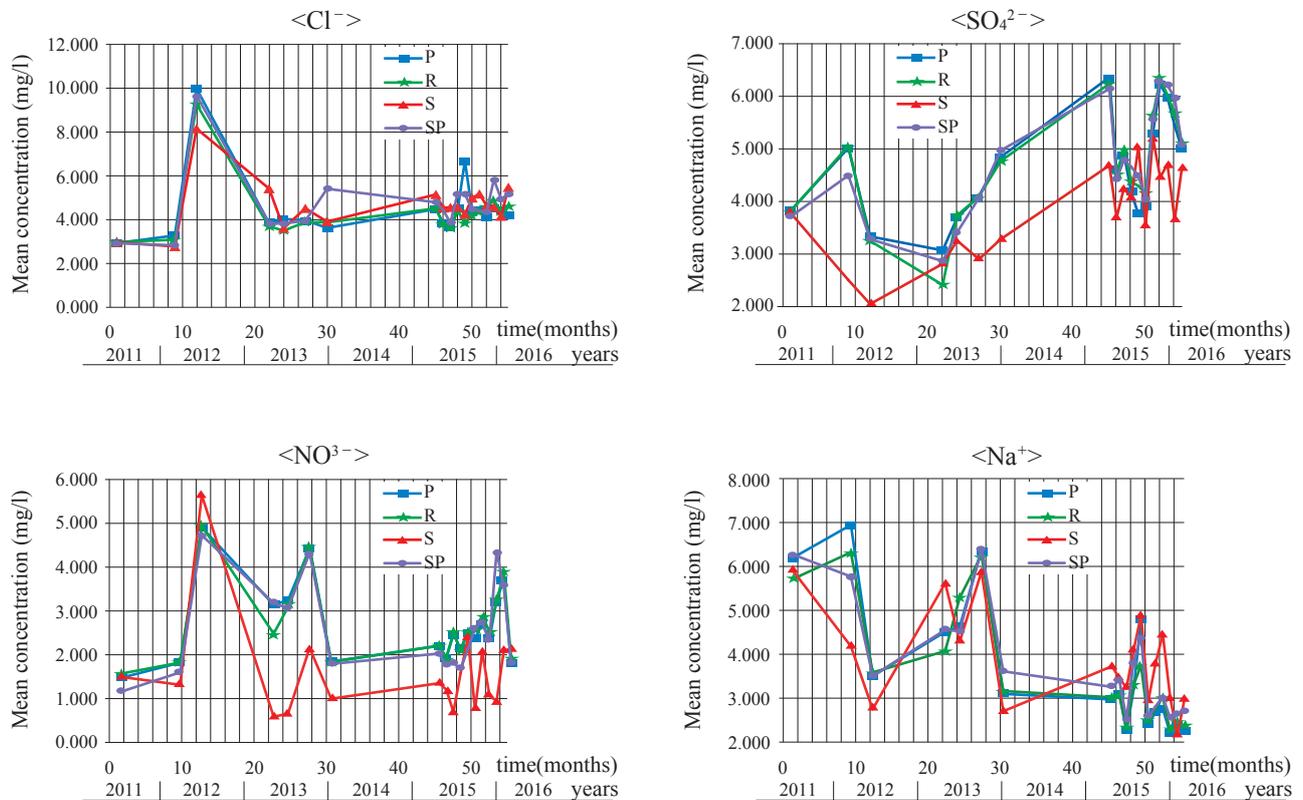


Fig 2(b). Fluctuations in mean physicochemical values in different stream environments. Time (months) on the horizontal axis indicates the number of months after the first measurement month

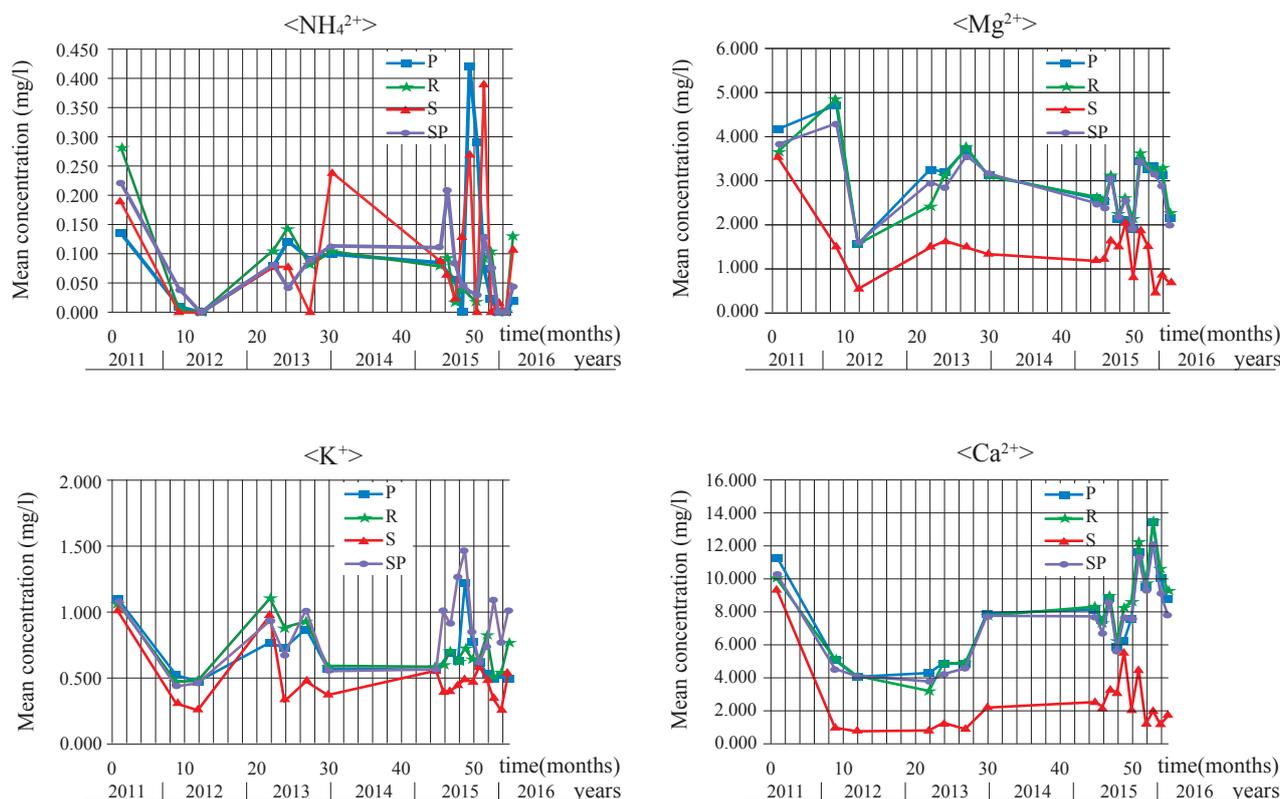


Fig 2(c). Fluctuations in mean physicochemical values in different stream environments. Time (months) on the horizontal axis indicates the number of months after the first measurement month

Table 3. Calculation results of antecedent rainfall 30 (Rain30) and 90 (Rain90) days before each measurement day

date of sampling	Rain30	Rain90
2011.07.27	184	957
2012.04.19	166	300
2012.07.30	349	825
2013.05.22	298	788
2013.07.09	535	1401
2013.10.09	246	686
2014.01.22	37	217
2015.04.09	160	238
2015.05.12	192	393
2015.06.16	188	567
2015.07.14	190	617
2015.09.02	540	833
2015.10.22	508	1081
2015.11.27	302	1414
2015.12.18	111	1048
2016.01.29	64	443
2016.02.19	178	328
2016.03.17	93	280

problems with the experimental apparatus. EC measurements in S were considerably lower than EC measurements in the other stream environments for most of the sampling period. Mean concentrations of NH_4^+ and K^+ , while considerably lower than those for the other ions, also fluctuated markedly in all of the stream environments over the course of the study. The mean concentrations of Mg^{2+} and Ca^{2+} were lowest in S during the study. The mean K^+ concentrations generally tended to be highest in SP, except for the 5th to 7th measurements, and lowest in S throughout the experimental period. The mean K^+ concentrations of the SP and P environments increased during the warm period from May to August 2015. The concentrations of K^+ in S fluctuated slightly, from a minimum value of 0.27 mg/l in February 2015 to a maximum value of 1.49 mg/l in September 2015.

Similar fluctuations in SO_4^{2-} concentrations were observed in R, P, and SP, except in S, in which SO_4^{2-} concentrations were typically relatively smaller and ranged between 3.58 (mg/l) in October to 5.52 (mg/l) in November 2015.

4-2 Measurements of antecedent rainfall

The measurements of antecedent rainfall prior to each measurement day (i.e. Rain30 and Rain90) are shown in Table 3.

4-3 Results of statistical analysis

Table 4 shows the results of the two-way ANOVA, which was used to compare sampling seasons (spring, summer, autumn and winter) and the stream environments

Table 4. Results of two-way analysis of variance of physicochemical parameters and season

physico-chemical parameters	independent variables	n	mean square	F	P
EC	season	3	1318.233	7.859	< 0.0001
	stream environment	3	7051.635	42.038	< 0.0001
	interaction	9	527.020	3.142	< 0.001
	residual error	225	167.744		
pH	season	3	0.087	0.748	n.s.
	stream environment	3	0.367	3.164	< 0.05
	interaction	9	0.039	0.335	n.s.
	residual error	225	0.116		
TN/TC	season	3	0.013	2.908	< 0.05
	stream environment	3	0.006	1.390	n.s.
	interaction	9	0.004	0.941	n.s.
	residual error	225	0.004		
Cl ⁻	season	3	12.624	4.502	< 0.01
	stream environment	3	1.934	0.690	n.s.
	interaction	9	4.807	1.714	n.s.
	residual error	225	2.804		
NO ³⁻	season	3	9.253	8.387	< 0.0001
	stream environment	3	18.759	17.003	< 0.0001
	interaction	9	0.866	0.785	n.s.
	residual error	225	1.103		
SO ₄ ²⁻	season	3	16.166	13.857	< 0.0001
	stream environment	3	4.372	3.747	< 0.05
	interaction	9	1.631	1.398	n.s.
	residual error	225	1.167		
Na ⁺	season	3	20.452	9.380	< 0.0001
	stream environment	3	1.328	0.609	n.s.
	interaction	9	0.788	0.362	n.s.
	residual error	225	2.181		
NH ₄ ⁺	season	3	0.040	2.614	n.s.
	stream environment	3	0.013	0.853	n.s.
	interaction	9	0.008	0.508	n.s.
	residual error	225	0.015		
K ⁺	season	3	0.372	3.131	< 0.05
	stream environment	3	15.575	7.381	< 0.0001
	interaction	9	0.436	0.207	n.s.
	residual error	225	2.110		
Mg ²⁺	season	3	0.632	0.795	n.s.
	stream environment	3	30.475	38.327	< 0.0001
	interaction	9	2.297	2.889	< 0.01
	residual error	225	0.795		
Ca ²⁺	season	3	66.151	10.622	< 0.0001
	stream environment	3	250.276	40.189	< 0.0001
	interaction	9	25.748	4.134	< 0.0001
	residual error	225	6.228		

* n.s. is an abbreviation of not significant.

Table 5. Multiple regression analysis of major ions in stream environments

stream environments	components	multiple correlation coefficient r	coefficient of determination r ²	F	P
P (pool)	SO ₄ ²⁻	0.920	0.8460	27.515	0.000
	Na ⁺	0.941	0.8860	38.835	0.000
	K ⁺	0.724	0.5240	5.504	0.000
	Mg ²⁺	0.912	0.8310	24.642	0.000
	Ca ²⁺	0.932	0.8680	32.936	0.000
R (rapid)	SO ₄ ²⁻	0.920	0.8460	22.993	0.000
	Na ⁺	0.941	0.8860	52.375	0.000
	K ⁺	0.724	0.5240	3.497	0.001
	Mg ²⁺	0.912	0.8310	41.895	0.000
	Ca ²⁺	0.932	0.8680	27.089	0.000
S (spring)	SO ₄ ²⁻	0.617	0.3800	2.025	n.s.
	Na ⁺	0.879	0.7730	11.210	0.000
	K ⁺	0.831	0.6900	7.349	0.000
	Mg ²⁺	0.951	0.9040	31.248	0.000
	Ca ²⁺	0.922	0.8500	18.703	0.000
SP (side-pool)	SO ₄ ²⁻	0.827	0.6830	13.598	0.000
	Na ⁺	0.904	0.8180	28.299	0.000
	K ⁺	0.521	0.2710	2.344	0.020
	Mg ²⁺	0.904	0.8180	28.270	0.000
	Ca ²⁺	0.873	0.7620	20.181	0.000

* n.s. is an abbreviation of not significant.

of sampling points (P, R, S and SP), which were regarded as independent variables, against each measurement value, which was regarded as a dependent variable. Significant differences ($P < 0.05$) were observed in the sampling seasons and the stream environments in EC, NO³⁻, SO₄²⁻, K⁺ and Ca²⁺. In TN/TC, Cl⁻ and Na⁺, only the sampling seasons were significant independent variable ($P < 0.05$). In pH and Mg²⁺, only the stream environments were significant independent variable ($P < 0.05$). No significant differences were observed in either independent and dependent variables in NH₄⁺. Differences among individual variables were estimated using *Scheffe's* multiple range test (Fig. 3 and Fig. 4). In sampling seasons, significant differences ($P < 0.05$) were observed between winter and the other seasons, except for NO³⁻ (Fig. 3). Significant differences ($P < 0.05$) were observed between S and/or SP and the other stream environments (Fig. 4).

The results of the multiple regression analysis are shown in Table 5 and Table 6. Correlation coefficients are high, indicating that the concentrations of major ions are influenced significantly by the physicochemical parameters and the other major ions, except for SO₄²⁻ in S (Table 5). The standardized partial regression coefficients, significance probabilities (P value) and variance inflation factors of each independent value corresponding to treatment are shown in Table 6. Generally, the higher the standardized partial regression coefficient of an independent value is, the stronger the influence of the independent value on the dependent value in each treatment is. Several independent

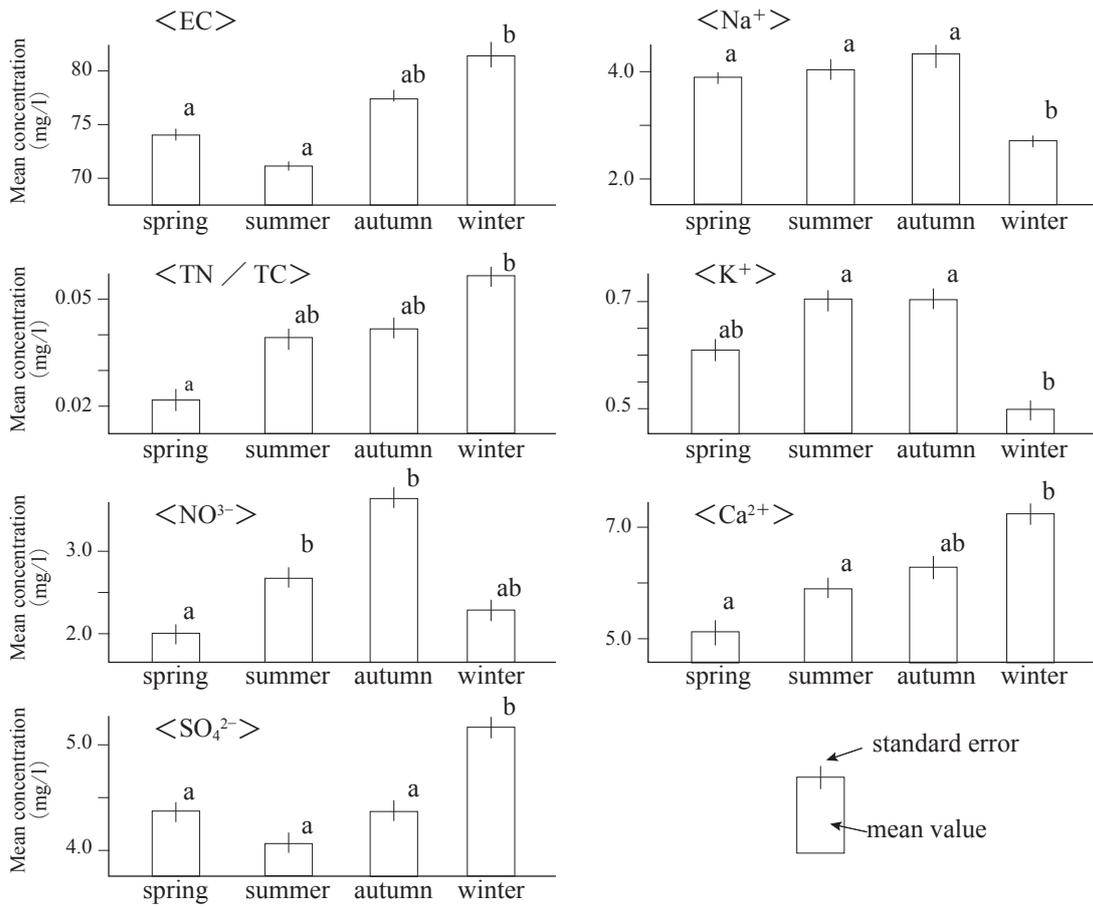


Fig 3. Results of *Sheffe's* multiple range test for changes in physicochemical parameters in different sampling seasons. Different letters above columns indicate statistical differences ($P < 0.05$).

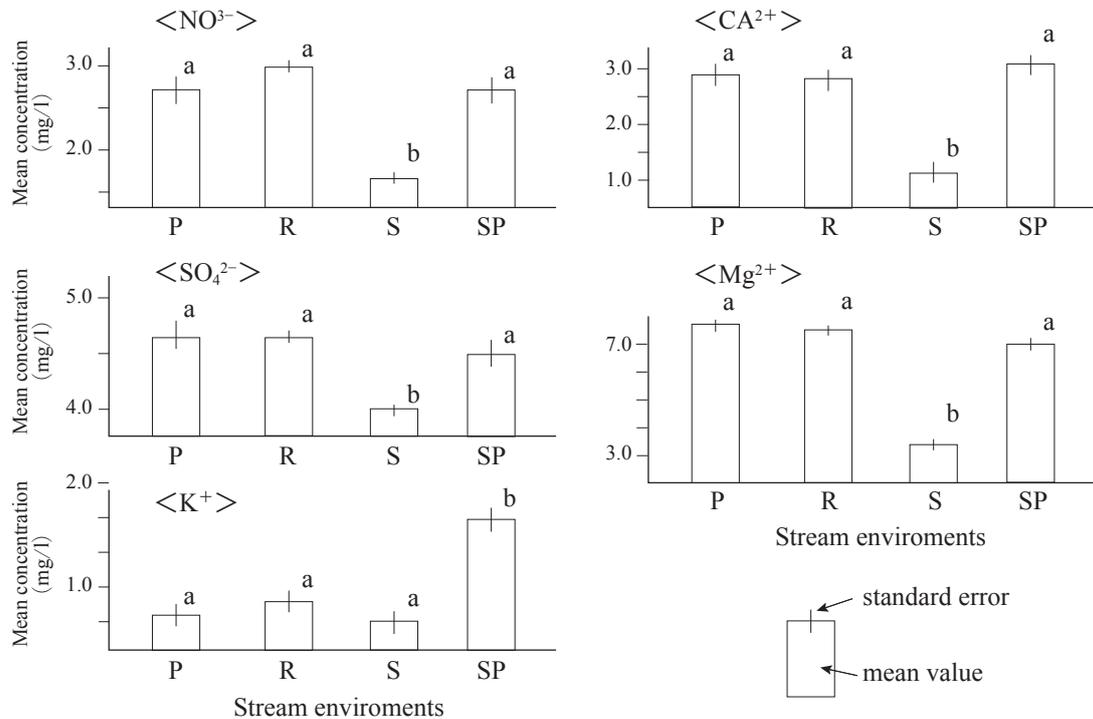


Fig 4. Results of *Sheffe's* multiple range test for changes in physicochemical parameters in different stream environments. Different letters above columns indicate statistical differences ($P < 0.05$).

Table 6(a). Standardized partial regression coefficient, probability (*P* value) and variance inflation factor of each independent value corresponding to treatment. * indicate that variance factor is ≥ 5.0 .

dependent variables	independent variables	P (pool)					
		partial regression coefficient	standardized partial regression coefficient	t	<i>P</i>	partial correlation coefficient	Variance Inflation Factor
SO ₄ ²⁻	temp.	-0.075	-0.339	-2.949	0.005	-0.385	4.301
	pH	1.281	0.414	4.926	0.000	0.572	2.297
	TN/TC	2.151	0.133	1.625	n.s.	0.224	2.172
	Na ⁺	-0.044	-0.063	-0.385	n.s.	-0.054	8.741*
	K ⁺	-0.276	-0.061	-0.768	n.s.	-0.108	2.076
	Mg ²⁺	0.294	0.236	1.802	n.s.	0.247	5.567*
	Ca ²⁺	0.088	0.242	1.624	n.s.	0.224	7.207*
	R30	-0.001	-0.190	-1.477	n.s.	-0.204	5.381*
R90	0.000	0.068	0.528	n.s.	0.075	5.350*	
Na ⁺	temp.	0.077	0.243	2.386	0.021	0.320	4.534
	pH	0.911	0.205	2.460	0.017	0.329	3.043
	TN/TC	3.133	0.135	1.932	n.s.	0.264	2.127
	SO ₄ ²⁻	-0.067	-0.047	-0.385	n.s.	-0.054	6.484*
	K ⁺	1.520	0.235	3.868	0.000	0.480	1.617
	Mg ²⁺	1.253	0.698	11.354	0.000	0.849	1.657
	Ca ²⁺	-0.371	-0.708	-8.300	0.000	-0.761	3.191
	R30	-0.001	-0.119	-1.066	n.s.	-0.149	5.491
R90	0.001	0.216	3.166	0.003	0.409	2.037	
K ⁺	temp.	-0.004	-0.089	-0.409	n.s.	-0.058	5.033*
	pH	-0.155	-0.226	-1.276	n.s.	-0.178	3.304
	TN/TC	-1.161	-0.323	-2.299	0.026	-0.309	2.068
	SO ₄ ²⁻	-0.042	-0.190	-0.768	n.s.	-0.108	6.427*
	Na ⁺	0.152	0.980	3.868	0.000	0.480	6.748*
	Mg ²⁺	-0.128	-0.460	-2.015	0.049	-0.274	5.483*
	Ca ²⁺	0.074	0.912	3.865	0.000	0.480	5.841*
	R30	0.001	0.458	2.062	0.044	0.280	5.176*
R90	0.000	0.060	0.263	n.s.	0.037	5.372*	
Mg ²⁺	temp.	-0.034	-0.192	-1.501	n.s.	-0.208	4.832
	pH	-0.883	-0.356	-3.764	0.000	-0.470	2.658
	TN/TC	-1.467	-0.113	-1.309	n.s.	-0.182	2.210
	SO ₄ ²⁻	0.207	0.259	1.802	n.s.	0.247	6.106*
	Na ⁺	0.575	1.032	11.354	0.000	0.849	2.450
	K ⁺	-0.588	-0.163	-2.015	0.049	-0.274	1.943
	Ca ²⁺	0.204	0.698	5.545	0.000	0.617	4.698
	R30	0.000	0.079	0.576	n.s.	0.081	5.578*
R90	0.000	-0.211	-2.459	0.017	-0.328	2.182	
Ca ²⁺	temp.	0.084	0.139	1.219	n.s.	0.170	4.904
	pH	2.117	0.250	2.837	0.007	0.372	2.938
	TN/TC	6.793	0.153	2.052	0.045	0.279	2.109
	SO ₄ ²⁻	0.568	0.207	1.624	n.s.	0.224	6.177*
	Na ⁺	-1.560	-0.818	-8.300	0.000	-0.761	3.687
	K ⁺	3.114	0.252	3.865	0.000	0.480	1.618
	Mg ²⁺	1.867	0.545	5.545	0.000	0.617	3.671
	R30	-0.004	-0.227	-1.936	n.s.	-0.264	5.224*
R90	0.001	0.225	3.050	0.004	0.396	2.062	

* n.s. is an abbreviation of not significant.

Table 6(b). Standardized partial regression coefficient, probability (*P* value) and variance inflation factor of each independent value corresponding to treatment. * indicate that variance factor is ≥ 5.0 .

dependent variables	independent variables	R (rapid)					
		partial regression coefficient	standardized partial regression coefficient	t	<i>P</i>	partial correlation coefficient	Variance Inflation Factor
SO ₄ ²⁻	temp.	-0.088	-0.397	-3.282	0.002	-0.418	4.104
	pH	0.853	0.269	3.310	0.002	0.421	1.855
	TN/TC	-0.531	-0.041	-0.556	n.s.	-0.078	1.524
	Na ⁺	-0.174	-0.256	-1.299	n.s.	-0.179	10.908*
	K ⁺	-0.737	-0.193	-2.661	0.010	-0.349	1.480
	Mg ²⁺	0.531	0.477	2.833	0.007	0.369	7.962*
	Ca ²⁺	0.086	0.237	1.622	n.s.	0.221	6.002*
	R30	0.000	-0.052	-0.453	n.s.	-0.063	3.692
	R90	0.000	0.116	0.925	n.s.	0.128	4.456
Na ⁺	temp.	0.088	0.271	3.192	0.002	0.408	4.143
	pH	0.893	0.191	3.374	0.001	0.427	1.843
	TN/TC	1.654	0.086	1.720	n.s.	0.234	1.449
	SO ₄ ²⁻	-0.185	-0.125	-1.299	n.s.	-0.179	5.332*
	K ⁺	0.622	0.111	2.131	0.038	0.286	1.548
	Mg ²⁺	1.345	0.819	15.210	0.000	0.905	1.665
	Ca ²⁺	-0.303	-0.564	-8.180	0.000	-0.753	2.730
	R30	-0.001	-0.113	-1.430	n.s.	-0.196	3.564
	R90	0.001	0.228	3.560	0.001	0.446	2.362
K ⁺	temp.	-0.022	-0.379	-1.615	n.s.	-0.221	4.729
	pH	0.027	0.032	0.199	n.s.	0.028	2.252
	TN/TC	-0.551	-0.162	-1.230	0.010	-0.170	1.489
	SO ₄ ²⁻	-0.165	-0.631	-2.661	0.010	-0.349	4.837
	Na ⁺	0.131	0.739	2.131	0.038	0.286	10.348*
	Mg ²⁺	-0.134	-0.458	-1.427	n.s.	-0.196	8.861*
	Ca ²⁺	0.053	0.555	2.138	0.037	0.287	5.793*
	R30	0.000	-0.257	-1.256	n.s.	-0.173	3.595
	R90	0.000	0.454	2.056	0.045	0.277	4.184
Mg ²⁺	temp.	-0.037	-0.184	-1.850	n.s.	-0.251	4.658
	pH	-0.724	-0.255	-4.287	0.000	-0.515	1.657
	TN/TC	-0.449	-0.039	-0.678	n.s.	-0.095	1.519
	SO ₄ ²⁻	0.256	0.285	2.833	0.007	0.369	4.759
	Na ⁺	0.609	1.001	15.210	0.000	0.905	2.036
	K ⁺	-0.287	-0.084	-1.427	n.s.	-0.196	1.621
	Ca ²⁺	0.167	0.512	5.616	0.000	0.618	3.900
	R30	0.001	0.087	0.992	n.s.	0.138	3.637
	R90	0.000	-0.233	-3.221	0.002	-0.411	2.450
Ca ²⁺	temp.	0.198	0.327	2.826	0.007	0.368	4.298
	pH	2.195	0.253	3.330	0.002	0.423	1.852
	TN/TC	4.354	0.122	1.829	n.s.	0.248	1.438
	SO ₄ ²⁻	0.567	0.207	1.622	n.s.	0.221	5.238*
	Na ⁺	-1.872	-1.007	-8.180	0.000	-0.753	4.874
	K ⁺	1.550	0.148	2.138	0.037	0.287	1.547
	Mg ²⁺	2.282	0.747	5.616	0.000	0.618	5.693*
	R30	-0.004	-0.213	-2.068	0.044	-0.278	3.420
	R90	0.002	0.333	3.977	0.000	0.486	2.251

* n.s. is an abbreviation of not significant.

Table 6(c). Standardized partial regression coefficient, probability (P value) and variance inflation factor of each independent value corresponding to treatment. * indicate that variance factor is ≥ 5.0 .

dependent variables	independent variables	S (spring)					
		partial regression coefficient	standardized partial regression coefficient	t	P	partial correlation coefficient	Variance Inflation Factor
SO ₄ ²⁻	temp.	-0.143	-0.406	-2.089	0.045	-0.342	2.012
	pH	0.649	0.149	0.988	n.s.	0.169	1.211
	TN/TC	-1.120	-0.063	-0.391	n.s.	-0.068	1.364
	Na ⁺	0.770	0.788	3.120	0.004	0.477	3.395
	K ⁺	-1.763	-0.298	-1.238	n.s.	-0.211	3.084
	Mg ²⁺	-1.138	-0.656	-1.531	n.s.	-0.258	9.774*
	Ca ²⁺	0.425	0.755	2.297	0.028	0.371	5.748*
	R30	0.000	0.022	0.095	n.s.	0.017	2.897
R90	0.001	0.168	0.576	n.s.	0.100	4.518	
Na ⁺	temp.	0.069	0.190	1.574	n.s.	0.264	2.118
	pH	-0.516	-0.116	-1.279	n.s.	-0.217	1.187
	TN/TC	-1.317	-0.072	-0.746	n.s.	-0.129	1.348
	SO ₄ ²⁻	0.296	0.289	3.120	0.004	0.477	1.246
	K ⁺	2.054	0.339	2.475	0.019	0.396	2.722
	Mg ²⁺	1.647	0.928	4.323	0.000	0.601	6.684*
	Ca ²⁺	-0.297	-0.516	-2.649	0.012	-0.419	5.498*
	R30	0.001	0.103	0.735	n.s.	0.127	2.852
R90	0.001	0.268	2.239	0.032	0.363	2.087	
K ⁺	temp.	-0.004	-0.065	-0.445	n.s.	-0.077	2.264
	pH	0.066	0.090	0.840	n.s.	0.145	1.220
	TN/TC	-0.408	-0.135	-1.216	0.020	-0.207	1.312
	SO ₄ ²⁻	-0.025	-0.149	-1.238	n.s.	-0.211	1.542
	Na ⁺	0.076	0.462	2.475	0.019	0.396	3.708
	Mg ²⁺	0.009	0.032	0.102	n.s.	0.018	10.466*
	Ca ²⁺	0.044	0.465	1.963	n.s.	0.323	5.971*
	R30	0.000	-0.194	-1.199	n.s.	-0.204	2.777
R90	0.000	0.234	1.155	n.s.	0.197	4.386	
Mg ²⁺	temp.	-0.003	-0.013	-0.160	n.s.	-0.028	2.276
	pH	0.068	0.027	0.451	n.s.	0.078	1.239
	TN/TC	0.681	0.066	1.066	n.s.	0.182	1.325
	SO ₄ ²⁻	-0.058	-0.101	-1.531	n.s.	-0.258	1.507
	Na ⁺	0.220	0.390	4.323	0.000	0.601	2.807
	K ⁺	0.034	0.010	0.102	n.s.	0.018	3.226
	Ca ²⁺	0.191	0.588	6.264	0.000	0.737	3.046
	R30	-0.001	-0.119	-1.332	n.s.	-0.226	2.750
R90	0.000	-0.191	-2.500	0.018	-0.399	2.021	
Ca ²⁺	temp.	0.077	0.123	1.233	n.s.	0.210	2.177
	pH	0.075	0.010	0.129	0.020	0.022	1.246
	TN/TC	0.492	0.015	0.196	n.s.	0.034	1.369
	SO ₄ ²⁻	0.324	0.183	2.297	0.028	0.371	1.391
	Na ⁺	-0.590	-0.340	-2.649	0.012	-0.419	3.626
	K ⁺	2.364	0.225	1.963	n.s.	0.323	2.890
	Mg ²⁺	2.844	0.923	6.264	0.000	0.737	4.783
	R30	0.001	0.062	0.540	n.s.	0.094	2.873
R90	-0.001	-0.180	-1.282	n.s.	-0.218	4.347	

· n.s. is an abbreviation of not significant.

Table 6(d). Standardized partial regression coefficient, probability (P value) and variance inflation factor of each independent value corresponding to treatment. * indicate that variance factor is ≥ 5.0 .

dependent variables	independent variables	SP (side-pool)					
		partial regression coefficient	standardized partial regression coefficient	t	P	partial correlation coefficient	Variance Inflation Factor
SO ₄ ²⁻	temp.	-0.136	-0.541	-3.789	0.000	-0.431	4.050
	pH	0.243	0.069	0.762	n.s.	0.096	1.635
	TN/TC	-0.906	-0.034	-0.398	n.s.	-0.050	1.447
	Na ⁺	-0.009	-0.012	-0.073	n.s.	-0.009	5.491*
	K ⁺	0.354	0.147	1.818	n.s.	0.223	1.304
	Mg ²⁺	0.236	0.205	1.248	n.s.	0.155	5.355*
	Ca ²⁺	0.188	0.452	3.383	0.001	0.392	3.557
	R30	0.002	0.295	2.140	0.036	0.260	3.791
R90	-0.001	-0.288	-1.841	n.s.	-0.226	4.853	
Na ⁺	temp.	0.158	0.469	4.499	0.000	0.493	3.764
	pH	0.322	0.069	1.002	n.s.	0.125	1.624
	TN/TC	0.061	0.002	0.026	n.s.	0.003	1.451
	SO ₄ ²⁻	-0.009	-0.007	-0.073	n.s.	-0.009	3.158
	K ⁺	0.215	0.067	1.071	n.s.	0.134	1.347
	Mg ²⁺	1.313	0.853	13.005	0.000	0.854	1.489
	Ca ²⁺	-0.276	-0.497	-5.487	0.000	-0.569	2.844
	R30	-0.003	-0.234	-2.244	0.028	-0.272	3.766
R90	0.001	0.203	2.498	0.015	0.300	2.284	
K ⁺	temp.	0.031	0.301	1.269	n.s.	0.158	4.849
	pH	-0.046	-0.031	-0.228	n.s.	-0.029	1.649
	TN/TC	-2.854	-0.257	-2.049	0.045	-0.250	1.360
	SO ₄ ²⁻	0.141	0.339	1.818	n.s.	0.223	3.001
	Na ⁺	0.083	0.268	1.071	n.s.	0.134	5.394*
	Mg ²⁺	-0.069	-0.144	-0.574	n.s.	-0.072	5.459*
	Ca ²⁺	0.032	0.184	0.837	n.s.	0.105	4.157
	R30	0.000	0.033	0.154	n.s.	0.019	4.065
R90	0.000	-0.077	-0.315	n.s.	-0.040	5.106*	
Mg ²⁺	temp.	-0.064	-0.295	-2.582	0.012	-0.309	4.497
	pH	-0.333	-0.109	-1.613	n.s.	-0.199	1.585
	TN/TC	2.064	0.089	1.395	n.s.	0.173	1.407
	SO ₄ ²⁻	0.102	0.118	1.248	n.s.	0.155	3.082
	Na ⁺	0.555	0.854	13.005	0.000	0.854	1.490
	K ⁺	-0.075	-0.036	-0.574	n.s.	-0.072	1.365
	Ca ²⁺	0.164	0.455	4.835	0.000	0.520	3.066
	R30	0.001	0.098	0.905	n.s.	0.113	4.015
R90	0.000	-0.223	-2.775	0.007	-0.330	2.237	
Ca ²⁺	temp.	0.173	0.285	2.156	0.035	0.262	4.631
	pH	2.216	0.262	3.658	0.001	0.419	1.361
	TN/TC	-1.755	-0.027	-0.369	n.s.	-0.046	1.448
	SO ₄ ²⁻	0.818	0.340	3.383	0.001	0.392	2.673
	Na ⁺	-1.170	-0.650	-5.487	0.000	-0.569	3.716
	K ⁺	0.347	0.060	0.837	n.s.	0.105	1.357
	Mg ²⁺	1.647	0.594	4.835	0.000	0.520	4.002
	R30	-0.009	-0.464	-4.242	0.000	-0.471	3.163
R90	0.002	0.295	2.201	0.031	0.267	4.749	

· n.s. is an abbreviation of not significant.

values were judged as significant ($P < 0.05$) in each treatment. However, distortion due to multicollinearity may exist in a calculated partial regression coefficient when the variance inflation factor is ≥ 5.0 ²²⁾. Thus, in the present analysis, a maximum of five independent values (in descending order of standardized partial regression coefficients with $P < 0.05$ and variance inflation factor < 5.0) were selected from the common independent values as significant independent values in each treatment in all the stream environments for temp., Rain90, N/C, Ca²⁺ and pH, in SO₄²⁻, Na⁺, K⁺, Mg²⁺ and Ca²⁺ (Table 7).

5. Discussion

The present analysis revealed that the ion concentrations and physicochemical parameters of the stream water were affected by sampling season or stream environment, or both, and that ion concentrations might be related to each other, affecting physicochemical parameters.

SO₄²⁻ was detected every month at all sampling sites in the stream water, but it was not detected in the leachates from evergreen tree species in our previous leaching experiments^{9, 10)}; it is therefore considered that sulfide rock weathering is the primary source of SO₄²⁻⁵⁾ and that Na⁺ and Ca²⁺ concentrations fluctuate in response to the SO₄²⁻ concentration in S and SP, respectively. While atmospheric gasses and aerosol dust may also contribute to SO₄²⁻

levels in stream water, the multiple regression analysis showed that the significant independent value affecting SO₄²⁻ concentration was water temperature. Thus, while the main sources of SO₄²⁻ in the study area are unknown, they are affected by water temperature, such as dissolved sulfate containing organic sulfur²⁾.

Na⁺ is commonly found bound to Cl⁻. Although weathering of NaCl-containing rocks accounts for most of the Na⁺ found in river water, the constant supply of Na⁺ and Cl⁻ through rainwater originating from sea water is considered to contribute markedly to ion supply along the coast¹⁾. However, in the present study, the concentrations of Na⁺ and Cl⁻ were inversely related on a seasonal basis (see Fig. 2). The independent variable that had a significant influence on the Na⁺ concentration in the stream water was Rain90 (see Table 7). Previous studies reported that daily Na⁺ release rates from bedrock by leaching are higher over 90 days than over 30 days of incubation, indicating a relatively strong relation with Rain90. Thus, it is possible that an appreciable fraction of Na⁺ in the stream water arises from silicate contained in the bedrock of the basin in which the study area is located. Sodium in silicate rocks is present mainly as the albite component of plagioclase, with the formation NaAlSi₃O₈ which contains no Cl⁻, weathering slowly. Since plagioclase is a major source of the Na⁺ in groundwater, it is also likely to be a major source of Na⁺ in stream water⁵⁾.

It has been reported that Ca²⁺ and Mg²⁺ in river wa-

Table 7. Significant independent variables corresponding to stream environments for major ions for which standardized partial regression coefficients are $P < 0.05$ and variance inflation factors are < 5.0

stream environments	P (pool)	R (rapid)	S (spring)	SP (side-pool)				
dependent variables	independent variables	standardized partial regression coefficient	independent variables	standardized partial regression coefficient	independent variables	standardized partial regression coefficient	independent variables	standardized partial regression coefficient
SO ₄ ²⁻	pH	0.414	temp.	-0.397	Na ⁺	0.788	Ca ²⁺	0.452
	temp.	-0.339	pH	0.269	temp.	-0.406	R30	0.295
			K ⁺	-0.193			temp.	-0.541
Na ⁺	Mg ²⁺	0.698	Mg ²⁺	0.819	K ⁺	0.339	Mg ²⁺	0.853
	temp.	0.243	temp.	0.271	SO ₄ ²⁻	0.289	temp.	0.469
	K ⁺	0.235	Rain90	0.228	Rain90	0.268	Rain90	0.203
	Rain90	0.216	pH	0.191			Rain30	-0.234
	pH	0.205	K ⁺	0.111			Ca ²⁺	-0.497
K ⁺	TN/TC	-0.323	Rain90	0.454	Na ⁺	0.462	TN/TC	-0.257
			TN/TC	-0.162	TN/TC	-0.135		
			SO ₄ ²⁻	-0.631				
Mg ²⁺	Na ⁺	1.032	Na ⁺	1.001	Ca ²⁺	0.588	Na ⁺	0.854
	Ca ²⁺	0.698	Ca ²⁺	0.512	Na ⁺	0.390	Ca ²⁺	0.455
	K ⁺	-0.163	SO ₄ ²⁻	0.285	Rain90	-0.191	Rain90	-0.223
	Rain90	-0.211	Rain90	-0.233			temp.	-0.295
	pH	-0.356	pH	-0.255				
Ca ²⁺	Mg ²⁺	0.545	Rain90	0.333	Mg ²⁺	0.923	Mg ²⁺	0.594
	K ⁺	0.252	temp.	0.327	SO ₄ ²⁻	0.183	SO ₄ ²⁻	0.340
	pH	0.250	pH	0.253	pH	0.010	Rain90	0.295
	Rain90	0.225	K ⁺	0.148	Na ⁺	-0.340	temp.	0.285
	TN/TC	0.153	Rain30	-0.213			pH	0.262

ter are almost entirely derived from rock weathering¹⁾. Ca^{2+} sources consist mainly of carbonate rock containing calcite, CaCO_3 , and dolomite, $\text{CaMg}(\text{CO}_3)_2$, with small quantities of CaSO_4 minerals⁵⁾. Mg-silicate minerals, chiefly amphiboles, pyroxenes, olivine, biotite, as well as dolomite, constitute the main sources of Mg^{2+} . Thus, it is possible that the release of Ca^{2+} from carbonate rock is accompanied by the release of Mg^{2+} . This hypothesis is supported by the results of the multiple regression analysis in this study which showed that the most significant independent variable affecting the Mg^{2+} concentration is the Ca^{2+} concentration (see Table 7). The Mg^{2+} concentration was significantly and positively related to the Na^+ concentration of the water in Table 7. The reason for this may be that Ca^{2+} was absorbed by clay minerals (montmorillonite) in the weathered sedimentary rock, Na^+ being released from the rock¹⁸⁾.

Further, Ca^{2+} concentrations are also affected by pH, except in R. For example, a previous study showed that the release of Ca^{2+} increases markedly at higher temperatures and that low pH increases Ca^{2+} release even further¹⁰⁾. Previous experiments also showed that Ca^{2+} was released from leaves and rock at nearly the same rates at 90 days after submergence¹⁷⁾. Ca^{2+} release from bedrock and leaves is thus considered to be promoted through a combination of these factors. The Ca^{2+} content of leaves increases throughout the growing season and is retained until major structural breakdown of the leaf occurs²⁰⁾. Also, because Ca^{2+} occurs in an exchangeable form that is highly mobile and readily replaced by H^+ , Ca^{2+} can readily be leached from the surface organic layers²⁶⁾. In streams, minerals such as, Na^+ , Mg^{2+} and Ca^{2+} originate almost entirely from the weathering of sedimentary carbonate rocks¹⁾. However, based on the observed results, changes in water composition are also considered to occur in response to natural inputs and subsequent leaching of leaf litter. This hypothesis is supported by the field measurements in our previous studies⁹⁻¹¹⁾. Several sources of these minerals might be reflected as independent values in Table 7.

Potassium in river water comes predominantly (nearly 90%) from the weathering of silicate minerals, particularly potassium feldspar, as orthoclase and microcline (KAlSi_3O_8) and mica, as biotite ($\text{K}(\text{Mg}, \text{Fe})_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$)²¹⁾. However, we have showed that plant leaf litter supplied into stream water from the terrestrial ecosystem released K^+ due to leaching^{9, 10, 13, 17)}, indicating that leaf litter is also one of the major sources of K^+ in stream water.

The results of the two-way ANOVA showed that the K^+ concentration in the stream water is significantly higher in summer and autumn when leaf fall from evergreen trees is accelerated, and in side-pools where the leaves tend to accumulate for prolonged periods⁸⁾. The results showed that leaves from evergreen trees that entered the stream water in the study area are retained in side-pools where they release K^+ by leaching, which is the first stage of leaf decomposition^{11, 12)}, resulting in relatively high K^+ concentrations in the water. The main source of K^+ in the study area is therefore considered to be biological, such as leaf litter. Furthermore, the multiple regression analysis showed that TN/TC, which is the common significant-independent variable in all stream environments in this study area, significantly affected K^+ concentration. Because evergreen tree species are dominant in the study area (e.g. *Quercus glauca*), they constantly release carbon and nitrogen, as well as minerals, into the stream water^{11, 13)}; the TN/TC value can therefore be used as a biological index for leaf litter decomposition and subsequent mineral

release. The results of the multiple regression analysis (Table 7) also support the hypothesis that the main source of K^+ in the study area is plant material.

However, the reason for the relatively high concentrations of NO_3^- in SP remains unclear.

6. Conclusion

Minerals in stream water originate from a variety of sources. Based on the results of this study, it appears likely that Na^+ originates from the weathering of plagioclase in sedimentary silicate rocks and Mg^{2+} and Ca^{2+} originate almost entirely from the weathering of calcite and/or dolomite in sedimentary carbonate rocks in the study area. However, since Mg^{2+} and Ca^{2+} concentrations are lowest at S, it is possible that the water collected at these sites is subsurface water (soil water) and not groundwater. This hypothesis is supported by a previous study which demonstrated that the leaching rates of Mg^{2+} and Ca^{2+} from soil were markedly lower than from bedrock, likely because the study area is situated on an unstable alluvial plain and the soil used in the analysis lacked a humus layer¹⁷⁾.

It has been reported that approximately 90% of K^+ originates from the weathering of silicate materials, especially potassium feldspar and mica¹⁾ and biotite²¹⁾. However, it is not possible that the main source of K^+ in the study area is rock weathering because our previous leaching experiments, which used bedrock samples from the same study area, showed that only small amounts of K^+ , Mg^{2+} and SiO_2 in mica and dolomite were released from the bedrock samples¹⁷⁾. Indeed, previous studies have also shown that the contribution of biomass to stream water composition, i.e. through leachate from leaf litter, can be pronounced^{9-13, 17)}.

The findings of the present study also demonstrated that anion and cation concentrations in the study area differed significantly among stream environments and seasons, likely due to the heterogeneous distribution of ions resulting from leachate from leaves. In order for significant leaching to occur, leaves need to remain at a site for a sufficient period of time, which can be affected by factors such as channel morphology and riparian zone area³⁾; the hydrological and substrate characteristics along the stream margin²⁵⁾; the seasonal patterns of litter fall and the discharge characteristics of the stream²⁷⁾; the amount of leaf litter entering a stream²³⁾; and, biotic factors such as shredder density¹⁴⁻¹⁶⁾. Consequently, leaching is more commonly encountered in the side-pools because these sites satisfy the abovementioned conditions for promoting litter retention.

The stream environments in the investigated stream are characterized by uniform substrates consisting of similarly sized particles. Formation of side-pools along the stream margins was promoted by the uniform cross-sectional nature of the stream, low current velocity, and shallow water depth. Substrates along the stream margins are also more likely to trap leaves than the same substrates in the main stream channel. The presence of the *sabo* dams combined with the interactions between the hydrological and substrate characteristics along the stream margin further increase the potential for retention of litter²⁵⁾. Furthermore, given that the increased retention times attributed to the *sabo* dams also contribute to creating an environment suitable for colonization by shredder fauna²⁴⁾, litter decomposition in reaches with *sabo* dams is likely to be promoted. Thus, comparative studies of lit-

ter decomposition rates in reaches with and without *sabo* dams are needed in the future.

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要 旨

南九州第三紀層地域の山地溪流における主要イオンの起源と水質組成の支配要因の類推

渓流水質組成を規定する第一の要因は、流域を構成する基岩の岩種や地質構造等の地質的要因であるといわれてきたが、筆者は河畔域から溪流に供給されるリーフリターは膨大な量にのぼると推測されることから、その溶出成分も渓流水質の形成に重要な役割を果たすものであることを実験的に明らかにしてきた。これらの既往研究結果を踏まえ、本研究は5年間にわたり蓄積してきた現地溪流での水質測定結果をもとに、統計解析を交えながら、対象流域渓流水に含まれこれまで基岩風化起源とされてきた主要イオン(SO_4^{2-} , Na^+ , K^+ , Mg^{2+} , Ca^{2+})の流出に影響を及ぼす要因と起源の類推を試みたものである。

一ツ瀬川支流竹尾川(宮崎県)を対象溪流とし、湧水箇所(spring)、瀬(riffle)、淵(pool)、サイドプール(side-pool)の各3箇所の合計12箇所の採水ポイントから採水し、水温、電気伝導度(EC)、pH、全炭素濃度(TC)、全窒素濃度(TN)、陽イオン(Li^+ , Na^+ , NH_4^+ , K^+ , Ca^{2+} , Mg^{2+})、陰イオン(F^- , Cl^- , NO_2^- ,

Br^- , NO_3^- , PO_4^{3-} , SO_4^{2-})濃度を測定した。採水および測定は、2011年7月～2014年1月の期間では高温増水期(5～10月)、低温渇水期(11～4月)において無作為に選んだ日に行い、2015年4月～2016年3月の期間では、毎月1回の頻度で行った。

2元配置分散分析と多重比較結果から、EC、pH、 NO_3^- 、 SO_4^{2-} 、 Na^+ 、 K^+ 、 Ca^{2+} において、冬とそれ以外の季節との間に、また、 NO_3^- 、 SO_4^{2-} 、 K^+ 、 Ca^{2+} 、 Mg^{2+} において、湧水とそれ以外の流水環境との間に有意な差が認められた($P < 0.05$)。さらに重回帰分析結果から、 SO_4^{2-} 、 Na^+ 、 K^+ 、 Mg^{2+} 、 Ca^{2+} の流出に対しては、それぞれ水温、先行降雨量(90日間)、TN/TC、 Ca^{2+} イオン濃度と先行降雨量、pHがすべての流水環境に共通する支配要因であることがわかった($P < 0.05$)。

以上の結果から、 Mg^{2+} 、 Ca^{2+} は基岩(calcite(CaCO_3)もしくはdolomite($\text{CaMg}(\text{CO}_3)_2$))の機械的・化学的風化を主な起源とし、 K^+ はリター分解指標であるTN/TCとの関連が強くリターが滞留するside-poolにおいて濃度が高いことから、河畔域から溪流に供給されるリターの初期分解過程である溶出段階において放出される K^+ を起源とすることが、統計的にも裏付けられた。

