SEASONAL CHANGE OF SOILWATER AND STREAMWATER CHEMISTRIES IN THE TSUKUBA EXPERIMENTAL FORESTED BASIN

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SYNOPSIS

The soilwater and streamwater chemistries in the Tsukuba experimental forest were examined using data sets monitored during the four-year period since 1985. The concentrations of nitrate nitrogen and potassium and so forth, classified into the major essential elements available for forest plant growth, rose in surface soilwater in summer due to the mineralization of organic substances accumulated in surface soil. Furthermore, the soilwater leaching during successive storm events raised those concentrations in streamwater through summer season. The rises of solute concentration and flowrate of streamwater in summer brought in heavy runoff loads for nitrate nitrogen and potassium, and resulted in the increase of the annual mean streamsolute concentration with increasing the annual runoff streamwater amount.

INTRODUCTION

The regular cycle of chemical constituents can be seen between forest plant and soil. A part of chemical constituents has moved within the forest ecosystem as the essential element inevitable for forest plant growth, and the cycling amount of such element rises to considerably large quantity, compared to that of less essential element. The element cycle through uptake by forest plant, reduction to the forest floor by litterfall and leaching from the plant body results in first changing the constituent of the forest soil, and second creating the chemical profile in soilwater unique to the forest ecosystem. With respect to the essential element (hereinafter referred to as Type II) it is likely that minerals like phosphorus and calcium, originating from soil and bedrock, become further enriched in surface forest soil. Even nitrogen and carbon, originally not contained in soil and bedrock, are gradually accumulated near surface soil. With respect to the minor or non-essential element (referred to as Type I) like dissolved silicate and sodium, the mixing process of the organic substances such as litterfall and plant root decease tends to reduce the element content in surface soil.

The chemical profile and concentration level of soilwater basically depend on the element content in soil. In this context the element content in forest soil makes near surface soilwater concentration lower in Type I and higher in Type II than the deeper soilwater and groundwater. The difference of the solute concentration between Type I and Type II substances in surface soilwater was confirmed by Hirata and Muraoka (3) to produce two patterns in the streamsolute behavior during storm events as displayed in Fig. 1. Namely, Type I recovers approximately the same concentrations around the end of runoff period as the baseflow level prior to the storm event, and Type II overshoots the baseflow level. As the

streamwater around the end of recession limb generally comprises groundwater and interflow, the difference in streamsolute behaviors may be totally attributed to the solute concentrations in groundwater and interflow.   In addition, the interflow running through the surface soil is flushing out the solutes accumulated in surface soil, therefore, *in-situ* investigation on the soilwater chemistry could successfully provide the interpretation for two patterns in streamsolute behavior during storm events.

The change of the streamsolute concentration accompanies the information about solute runoff source in the specified basin, therefore, the mechanism for soilwater chemistry and runoff behavior is expected to provide the migration path of rainwater to streamwater through the forest ecosystem as suggested in the studies by authors, Sklash and Farvolden (9), Hino and Hasebe (2), Takeuchi and Sakamoto (11), Muraoka and Hirata (7) and Sato and Sato (8). In addition to
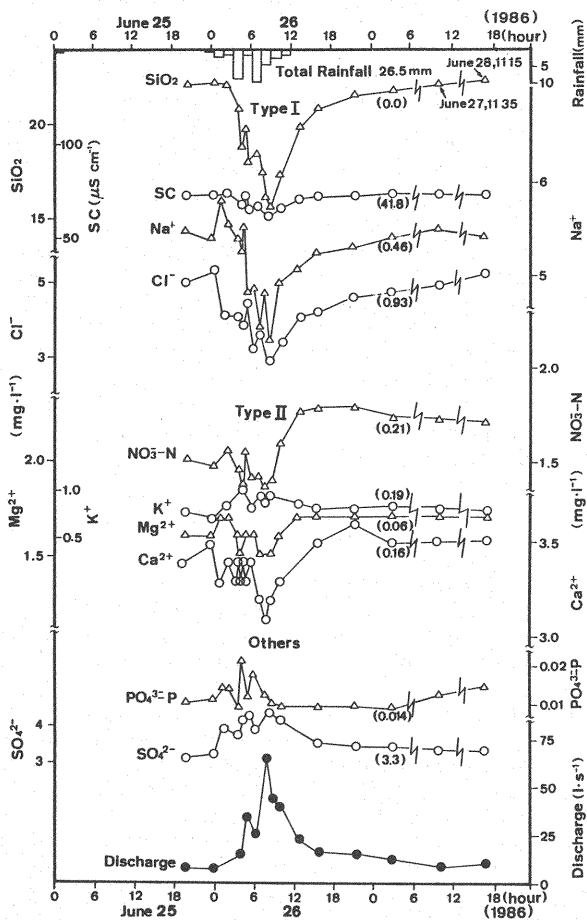

Fig. 1 Time-varied changes of streamsolute concentration driven by the storm event with the rainfall amount of 26.5 mm observed during the period of 25th-26th June 1986.   The rainwater concentration of each chemical constituent staying in parentheses takes considerably less value than the baseflow level prior to the storm event, so direct rainwater runoff as overland flow is responsible for diluting the baseflow during the rising limb.   After the peak flowrate, streamsolutes recover the concentrations and exhibit two patterns of Type I and Type II around the end of the recession limb. (Hirata and Muraoka (3))

the element content in soil, the soilwater concentration is to some extent related to water contact time with soil, temperature, pH and microorganism activity, many of which depend on the meteorological factors, so the soilwater chemistry shows seasonal variation in concentration.

For the purpose of investigating the streamsolute origin and chemical change caused by water travel within forest ecosystem, rainfall, throughfall, stemflow, litterfall, soilwater and streamwater have been observed in the Tsukuba experimental forested basin of 67.5 ha. On the basis of the routine works conducted every two weeks, first the paper describes the seasonal change of soilwater and streamwater chemistries, which represents the effects of meteorological conditions. Second, annual input-output loading of each element within forest ecosystem is calculated from the data sets obtained during the four-year period since 1985. From the element budget point of view, the influences of rainwater amount and element cycling characteristics within forest ecosystem on streamwater chemistry are examined.

STUDY SITE DESCRIPTION

The experimental forested basin of 67.5 ha was established in the Tsukuba Mountains 60 km northeast from Tokyo Metropolitan. The altitude of the basin ranges between 200 and 380 m above the sea level. Three streams run through the basin, and get together at the just upstream of A1 site as illustrated in Fig. 2. Coniferous stands cover the whole basin, and the dominant plant species are Japanese cedar (Sugi, *Cryptomeria Japonica*), Japanese cypress (Hinoki, *Chamaecyparis obtsusa*) and burned pine, the areas of which account for 52.5, 17.7 and 13.2 % of the basin, respectively. In particular Sugi species extends along the streams, and there is no evidence of fire and fertilizer application in the history of these stands.

The experimental basin was designed to examine the chemical change with water migration through the forest ecosystem and evaluate the forest function of dominating water environment. The streamwater level has been measured by a float type level recorder at A1 site and turned into the streamwater flowrate. Rainfall intensity has been monitored with a tipping bucket rain gauge near A1 site, and also rainwater for chemical analysis was collected in a pot type rain gauge. The streamwater was sampled biweekly, and rainwater every week or after every rainfall.

In relation to the inner element cycle within the forest ecosystem, throughfall, stemflow, litterfall and soilwater were biweekly collected at the plot [2] of the
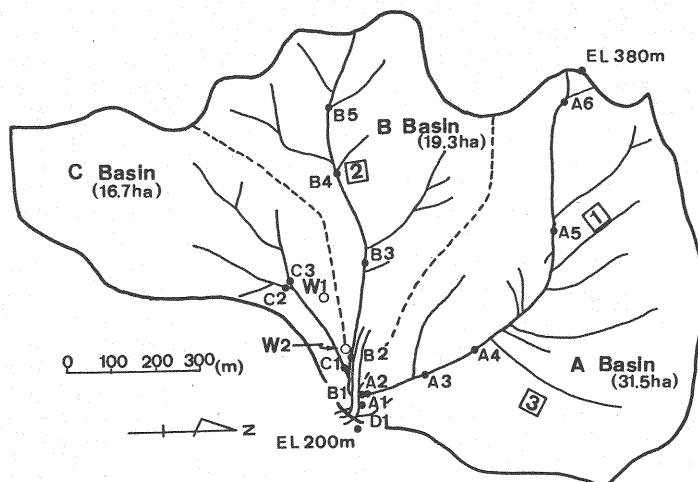

Fig. 2 Outline and measurement sites in the Tsukuba experimental forested basin

Sugi stand. Further details concerning the climate, vegetation and measurement are given in the manuscripts by Hirata and Muraoka (3 & 5).

SEASONAL CHANGES IN SOILWATER CHEMISTRY

Soilwater has been collected every two weeks since February 1986 from a slope with an average angle of 18 degrees, 9 m away from the stream B in the Sugi stand. Soilwater was collected at eight different depths: 10, 20, 30, 50, 75, 95, 125 and 175 cm below the groundsurface. The vertical profile of the forest soil proved that the A_0 horizon is less than 1 cm thick as usually in coniferous stands, and the A horizon containing a large amount of organic substances extends 30 cm deep, underlain by the B horizon. The soilwater suction and the ground-water level were also measured in this plot. The soilwater sampled from 125 cm and 175 cm depths was recognized to be groundwater since the groundwater level did not drop lower than 1 m depth over the observation period.

Seasonal Changes in Type I Substances

Taking the typical examples on dissolved silicate, sodium, nitrate nitrogen and potassium, Fig. 3 shows the seasonal changes in the soilwater chemistry and rainfall amount during a five-day basis since April 1986. Time-dependent solute concentrations are illustrated according to Type I and Type II.

The streamsolutes belonging to Type I hold the feature that their concentra-tions around the end of the recession limb almost returned to the baseflow level prior to the storm event. Such substances are represented by SiO_2, Na^+ and Cl^-, all of which are classified as minor or non-essential element circulated in the forest ecosystem to a small extent. Of much significance is the fact denoted by Hirata and Muraoka (4) that the element content of Type I becomes lower in the surface soil than that in the deeper layers.

Silicon constitutes 50% of the soil in weight. Sodium is in principle consid-ered to originate in the soil although it is also contained in rainwater. Accordingly, the longer the water has contact with the soil or the higher the temperature, the more the soilwater concentration of these substances increases. As reasoned from the streamsolute behavior during storm events and element content in the forest soil, the concentration of both substances shows larger value in the groundwater taken from 125 cm and 175 cm depths than in the surface soilwater at the depths of 10 cm and 30 cm. Seasonal variations were also discovered from each other. For example, the concentration of SiO_2 in the surface soilwater started rising in April and reached the peak in August. Despite a temporary drop in the concen-tration as a result of storm runoff leaching, the rise in temperature still lasted during this period and promoted the dissolution of new substances from the soil. Therefore, the concentration tended to keep increasing. After September, howev-er, due to the temperature drop, dissolution rate from the soil seems to decline. In addition, the storm runoff leaching resulted in further reduction of the concen-tration toward the winter, removing the solutes from the surface soil zone. This is also the case for Na^+.

On the other hand, surface soilwater percolates downward to meet ground-water. In the meantime, solute supplied from the soil is intermixed into the soil-water, thereby raising the SiO_2 and Na^+ concentrations in groundwater. In contrast with the case of surface soilwater, the concentration of SiO_2 in ground-water took its peak around November, approximately three months later than that in the surface soilwater.

In this paper the water year is defined to be from April to March of the following year. The annual rainfall amount was 1,552.5 mm in 1986, 1,293 mm in 1987 and 1,927 mm in 1988. The seasonal change of Type II soilwater concentration was found remarkable in 1987 when the effect of storm runoff was insignificant due to less rainwater amount. In 1988, however, seasonal changes in surface soil-water did not indicate regular patterns in both Type I and Type II because of successive storm runoff leaching. In 1988, rainfall amount was up to 956 mm recorded during only the four-month period from July to September when the substances in surface soilwater should rise in concentration naturally.

Seasonal Changes in Type II Substances

Type II substances keep the streamsolute concentration higher around the end of the recession limb than the baseflow level prior to the storm event. Such substances comprise NO_3^--N, K^+, Ca^{2+} and Mg^{2+}, which cycle extensively as major essential elements for the forest plant within the forest ecosystem, and often highly accumulate in the surface soil.

Nitrogen as discussed in this paper is directly derived from organic substances contained in the surface soil. Most of the nitrogen in the soil remains in organic form and is mineralized first to NH_4^+-N and NO_2^--N, and second to NO_3^--N through biodegradation. The NH_4^+-N compound is also contained in rainwater and takes the same way to NO_3^--N during the water migration in forest soil zone. It is well known that the nitrification rate depends on the temperature and accelerates by two times every time the temperature increases 10 °C. Therefore, NO_3^--N concentration in the surface soilwater increases during the summer season as
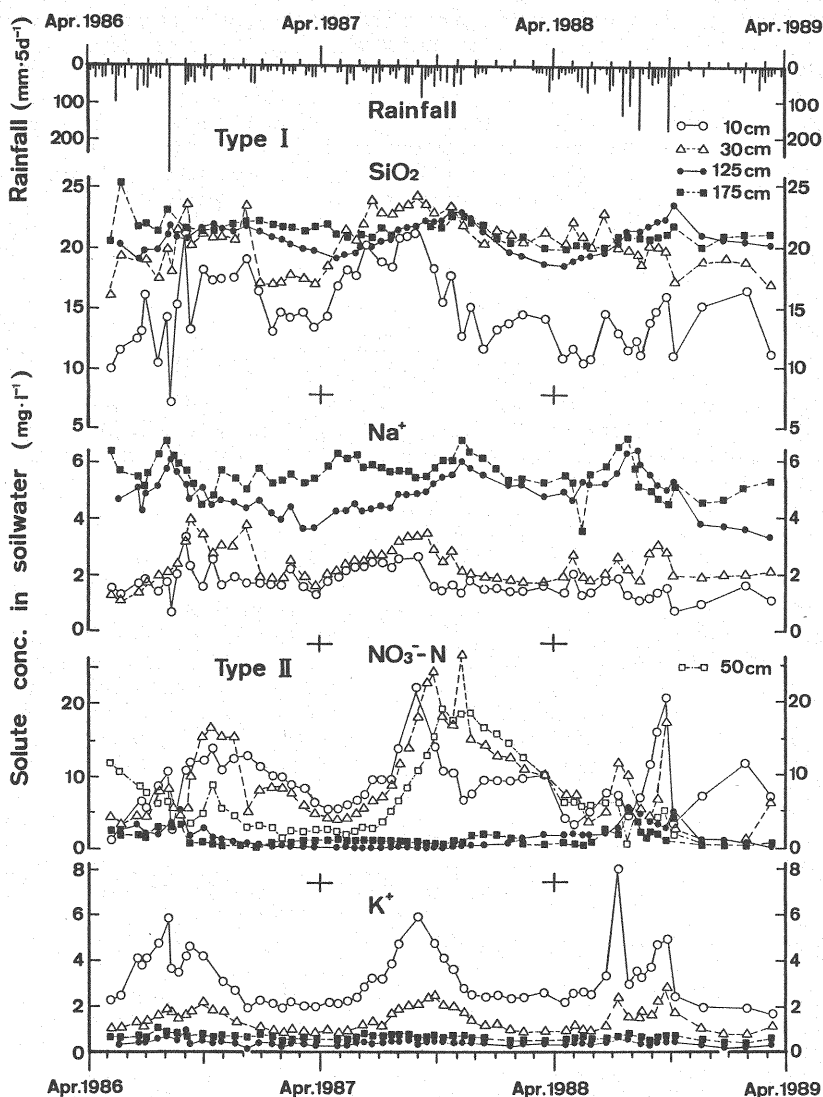

Fig. 3 Seasonal changes in soilwater chemistry observed in the Tsukuba experimental forest during a three-year period from April 1986 to March 1989

shown in Fig. 3. Biodegradation activity decelerates due to the temperature drop from autumn to winter. In addition, interflow running through surface soil zone during the storm run-off facilitates to wash off the solutes, and thereby decreases the solute concentration in soilwater in a way similar to the Type I substances.

Potassium, calcium and magnesium exist in organic form of plant body deceases, and also originate in the soil and bedrock. Similar to NO_3^--N, K^+ in the surface soil became more concentrated due to biodegradation during summer. In addition to this effect, the increased activity of microorganisms releases carbon dioxide gas, and creates carbonate in the soilwater. In the summer forest, since the surface soil is ready for acid-base reaction to replace H^+ discharged in the above process with K^+ in the soil, the dissolution of K^+ is likely to be prompted (Stumm and Morgan(10)).

On the other hand, the concentration of NO_3^--N and K^+ in the groundwater collected from 125 cm and 175 cm depths increased in August 1986 and June to August 1988 when there were heavy rainfall periods. In general, their variation ranges are small in contrast to seasonal changes in the concentration of Type I substances such as SiO_2 and Na^+. The variation range in this paper is defined to be the difference between annual maximum and minimum values. According to the record in 1986, the annual mean concentrations of NO_3^--N and K^+ in the surface soilwater at the depth of 10 cm were 8.65 mg/l and 3.19 mg/l respectively. However, both concentrations in the groundwater at the depth of 175 cm fell down to one sixth (1.41 mg/l) and one fifth (0.685 mg/l) respectively. As NO_3^--N is an anion, it is strongly resistant to adsorption into the negatively charged soil, and is easily mobile in the soil zone. The NO_3^--N diffusion with percolation possibly takes place. According to the continuous test of sludge applied to large-scale lysimeter (Goda et al. (1)), however, the peak concentration of NO_3^--N is cut down to only about a half when measured at the point of 155 cm depth. NO_3^--N is one of the major essential elements for plant growth, and is very likely to be uptaken into plants during percolation, thereby reducing its concentration.

The cations such as Na^+ and K^+ are easily adsorbed into the negatively charged soil. However, in particular Na^+ has a weaker ionic bonding force than K^+ or Ca^{2+}. Therefore, it is released from the soil after being replaced by other cations, and travels easily in the soil zone. On the other hand, the K^+ concentration varies to a small extent in the groundwater due to uptake and adsorption into plant bodies and soil during percolation.

SEASONAL CHANGES IN STREAMWATER CHEMISTRY

With respect to the streamwater, biweekly water collection and continuous monitoring of flowrate using a float-type recorder have been continued since September 1984. The time-varied changes of streamwater chemistry consist of data sets taken biweekly, and definitely include fluctuations affected by storm runoffs. However, the large amount of data is much enough to see the seasonal change in the streamwater chemistry. Fig. 4 displays the time-varied patterns of the streamwater chemistry, rainfall and flowrate as observed on a five-day basis since April 1985.

Streamwater flowrate was sharply raised due to typhoons 8506 (total rainfall amount=136.5 mm) in June 1985 and 8610 (total rainfall amount=291 mm) in August 1986. Another clear rise in flowrate occurred during the period from July to September 1988, corresponding to the successive rainfall of 956 mm.

Seasonal Changes in Type I Substances

The SiO_2 concentration declined extremely during storm runoffs resulting from typhoons due to the dilution effect of surface runoff, and was apt to increase from summer to autumn because of seasonal changes in solute concentration in the groundwater as shown in Fig. 3. However, changes in the concentration are generally not marked. The time-varied patterns for Na^+ and Cl^- also depicted their stable trends around averaged concentration throughout a year and often dilution during periods of storm runoffs.

Seasonal Changes in Type II Substances

Among the Type II substances, NO_3^--N exhibited the most distinctive seasonal changes in concentration. As shown in Fig. 4, a rise in the concentration is conspicuous in summer, which is strongly associated with flowrate increase caused by two typhoons in 1985 and 1986. In addition, the time-varied pattern for the NO_3^--N concentration holds a positive relationship with the streamwater flowrate throughout a year. Such positive correlation between the NO_3^--N concentration and flowrate is common, having been discovered by Likens et al.(6), Tsutsumi and Fukushima (12) and Webb and Walling (13). When the annual variation range of concentration in 1986 is compared with that in 1987, the former is 1.66 mg/l, and the latter 0.845 mg/l. Thus, both of the annual variation range and the peak concentration become higher with increasing the annual runoff streamwater from the forested basin. The concentrations of K^+ and Ca^{2+} also showed the pattern
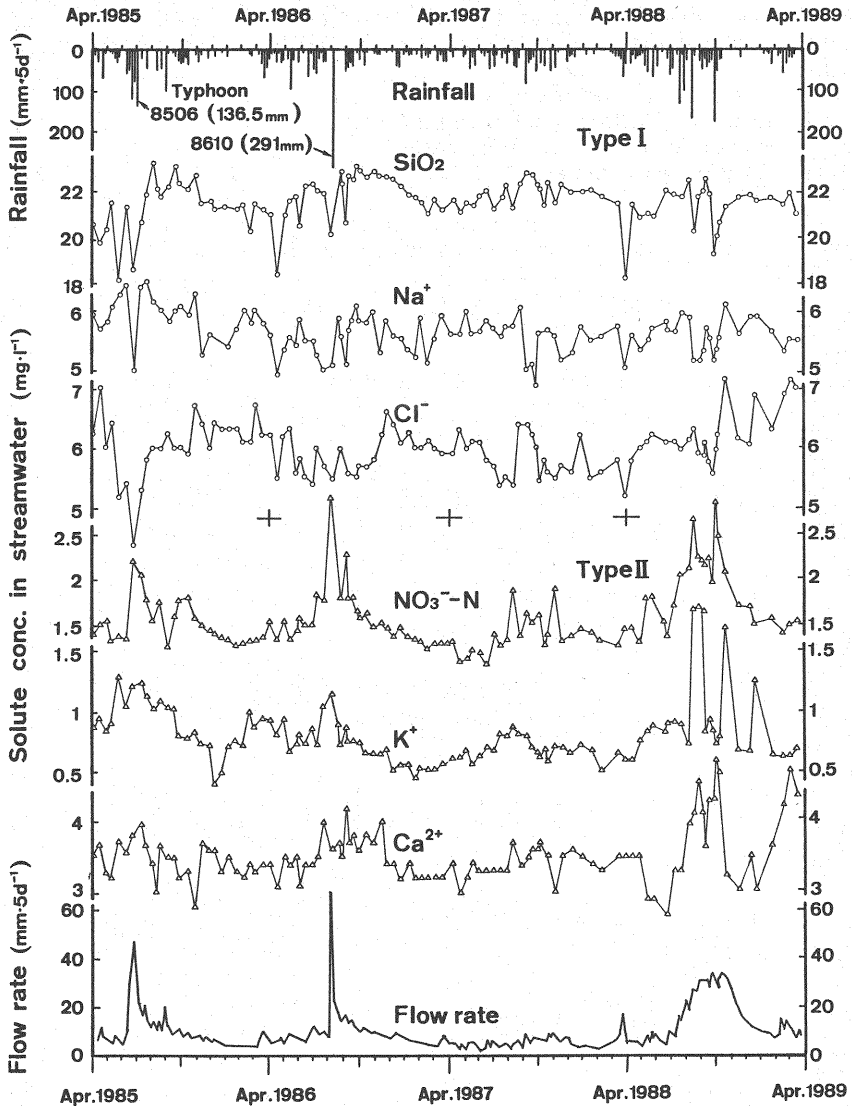

Fig. 4 Seasonal changes in streamwater chemistry observed in the Tsukuba experimental forest during a four-year period from April 1985 to March 1989

similar to NO₃⁻-N during summer although the variation ranges were smaller than that identified in the NO₃⁻-N concentration.

Type II substances show the higher concentration in the recession limb during the storm event than in the baseflow level. When a new storm event takes place within such situation, Type II substances may progressively raise their concentrations during successive storm runoffs. This is the mechanism for the concentration rise in Type II substances in summer. As shown in Fig. 3, the solute concentration in surface soilwater is also higher during the summer season when there is a heavy rainfall period. It is apparent from Figs. 3 and 4 that the runoff of surface soilwater as an interflow component causes the remarkable seasonal change in the NO₃⁻-N concentration of streamwater.

INPUT-OUTPUT OF CHEMICAL CONSTITUENTS IN TSUKUBA EXPERIMENTAL FOREST

Data sets of solute concentrations and water amount concerning rainwater and streamwater have been combined to calculate the input and output of chemical constituents in the experimental forest. On the basis of the each element budget and statistical data, the effect of the characteristics of element cycle and rainfall amount upon the streamwater chemistry is studied as follows.

Rainwater quality offers considerable fluctuation as arranged in Table 1. In the case of inorganic nitrogen, the variation range for the NH₄⁺-N and NO₃⁻-N concentrations takes the value of ten times as high as the annual mean in the

Table 1 Input-output of chemical constituents monitored in the Tsukuba experimental forest during a four-year period from April 1985 to March 1989

		NH_4^+-N	NO_2^--N	NO_3^--N	$PO_4^{3=}$P	SiO_2	Cl^-	SO_4^{2-}	Na^+	K^+	Mg^{2+}	Ca^{2+}	pH	SC(μS/cm)
Apr.1985-Mar.1986														
Rainfall														
Water amount (mm)	1576.5													
Mean conc. (mg·l⁻¹)		0.389	0.007	0.310	0.015	0.177	1.66	1.47	0.634	0.271	0.195	0.314	5.1	14.9
Conc. range (mg·l⁻¹)		4.57	0.110	3.04	0.955	2.20	10.1	6.45	3.65	3.58	1.08	1.80	2.8	67.1
Loading (kg·ha⁻¹)		6.13	0.113	4.89	0.241	2.79	26.2	23.2	10.0	4.28	3.08	4.93		
Streamwater														
Water amount (mm)	733.7													
Mean conc. (mg·l⁻¹)		0.037	0.003	1.67	0.010	21.1	5.79	3.76	5.89	1.01	1.67	3.59	7.0	73.2
Conc. range (mg·l⁻¹)		0.073	0.008	0.943	0.023	5.2	2.60	2.10	2.75	0.87	0.31	1.16	0.6	8.4
Loading (kg·ha⁻¹)		0.270	0.025	12.2	0.073	155	42.5	27.6	43.2	7.40	12.3	26.3		
Apr.1986-Mar.1987														
Rainfall														
Water amount (mm)	1552.5													
Mean conc. (mg·l⁻¹)		0.294	0.004	0.355	0.008	0.174	1.70	1.50	0.660	0.313	0.223	0.586	5.0	14.6
Conc. range (mg·l⁻¹)		1.53	0.035	1.77	0.130	2.00	4.19	5.00	2.70	2.34	0.70	1.80	3.5	57.9
Loading (kg·ha⁻¹)		4.56	0.067	5.51	0.116	2.70	26.2	22.7	10.2	4.87	3.46	9.09		
Streamwater														
Water amount (mm)	711.4													
Mean conc. (mg·l⁻¹)		0.034	0.003	1.77	0.007	21.7	5.83	3.38	5.50	0.788	1.66	3.60	6.7	74.4
Conc. range (mg·l⁻¹)		0.079	0.005	1.66	0.014	4.6	1.20	3.50	0.97	0.690	0.40	1.10	1.6	18.8
Loading (kg·ha⁻¹)		0.239	0.023	12.6	0.047	155	41.5	24.0	39.1	5.60	11.8	25.6		
Apr.1987-Mar.1988														
Rainfall														
Water amount (mm)	1293.0													
Mean conc. (mg·l⁻¹)		0.255	0.004	0.313	0.006	0.164	1.39	1.21	0.517	0.213	0.242	0.671	4.6	19.1
Conc. range (mg·l⁻¹)		1.63	0.018	0.971	0.029	0.40	3.70	3.60	3.39	0.640	0.410	3.26	2.2	58.5
Loading (kg·ha⁻¹)		2.64	0.042	4.04	0.075	2.11	18.0	15.6	6.68	2.75	3.13	8.67		
Streamwater														
Water amount (mm)	363.3													
Mean conc. (mg·l⁻¹)		0.025	0.003	1.40	0.008	21.7	5.78	3.12	5.53	0.676	1.62	3.39	6.6	79.2
Conc. range (mg·l⁻¹)		0.104	0.018	0.845	0.078	4.6	1.20	2.10	1.25	0.340	0.30	0.70	1.2	29.0
Loading (kg·ha⁻¹)		0.090	0.012	5.09	0.030	78.7	21.0	11.3	20.1	2.46	5.88	12.3		
Apr.1988-Mar.1989														
Rainfall														
Water amount (mm)	1927.0													
Mean conc. (mg·l⁻¹)		0.272	0.010	0.288	0.017	0.315	1.46	1.66	0.532	0.328	0.391	1.33	5.7	18.5
Conc. range (mg·l⁻¹)		3.68	0.105	1.64	0.210	1.0	4.44	6.32	2.48	1.63	0.750	2.27	2.4	70.0
Loading (kg·ha⁻¹)		5.25	0.191	5.55	0.334	6.08	28.2	32.0	10.2	6.31	7.54	25.7		
Streamwater														
Water amount (mm)	1075.4													
Mean conc. (mg·l⁻¹)		0.069	0.010	1.94	0.006	21.4	6.32	3.72	5.63	1.02	1.90	3.75	7.1	75.3
Conc. range (mg·l⁻¹)		0.205	0.014	1.54	0.027	3.2	1.59	2.10	0.93	1.26	0.74	2.12	0.9	48.4
Loading (kg·ha⁻¹)		0.745	0.104	20.9	0.061	231	67.9	40.0	60.5	10.9	20.4	40.3		

result in 1985. During passing through the forest ecosystem, however, rainwater quality is drastically changed and stabilized, which is totally attributed to the abundant buffer effect of forest ecosystem. For example, pH as a representative indicator is adjusted to be 6.6 to 7.1 in the streamwater, while the annual mean pH in rainwater is 4.6 to 5.7. It is real that some of the streamsolutes depict marked seasonal trends as illustrated in Fig. 4, however, from the annual fluctuation point of view, the streamwater chemistry is in general recognized to be relatively stable as a result of the magnificent buffer capability within the forest ecosystem. According to the total loads measured during the four-year period, NH_4^+-N and NO_3^--N existed at the ratio of 48:52 in rainwater, on the other hand, NO_3^--N predominated in the streamwater. This is because NH_4^+-N is easily adsorbed into the soil as a cation and nitrified into NO_3^--N by microorganism activity in the soil.

With respect to the streamwater chemistry monitored over the four-year period, the annual variation range of the SiO_2 concentration remains within 0.15 to 0.24 times the annual mean, and that of the NO_3^--N concentration takes somewhat larger value of 0.56 to 0.96 times the annual mean. These are the common characteristics of Type I and Type II substances. Fig. 5 displays the relationship between the annual run-off streamwater amount and the annual mean concentration of the streamsolutes. The annual mean concentrations of all the Type II substances including NO_3^--N are in proportion to the annual streamwater amount. On the other hand, there can be recognized no significant changes in the concentration of Type I substances except Cl^-. The result is totally attributable to the fact that the variation range of the Type I streamsolute concentration is relatively small, and in particular, is far below the variation range of the flowrate during storm events, which sometimes indicates a hundred times or more the baseflow level. As a result, the variation range of the streamsolute concentration belonging to Type I is likely to be buried in the flowrate change. With respect to the Type II substances, the streamsolute concentration possesses the positive relationship to the stream flowrate, and consequently the tremendous uprise in the summer runoff loads is presumed to be responsible for a linear relationship be-
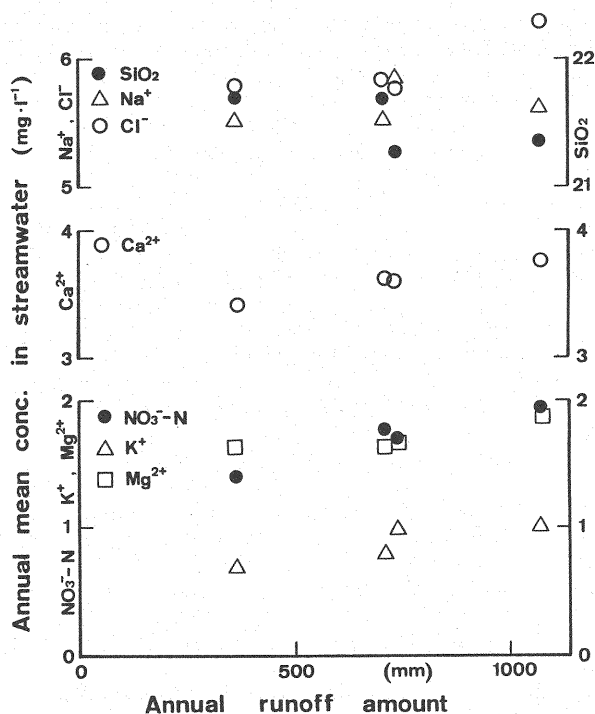

Fig. 5 Relationship between the annual mean concentration in streamwater and the annual run-off streamwater amount

tween the annual mean concentration and runoff streamwater amount. The long-term observations reveal that the element cycle characteristics, to some extent incorporated with the rainfall amount, do affect the annual mean concentration in the streamsolutes and even the effluent loads from the forested basin.

FINAL REMARKS

The element content in soil and the soilwater chemistry were unveiled to reflect the element cycle characteristics within the forest ecosystem. NO_3^--N and K^+, classified into Type II substances which are essential elements for the forest plant growth, have been regularly circulating in a large amount. The uprise in temperature in summer enhances mineralization and nitrification in soil, making the solute concentration of Type II substances higher in surface soilwater. In addition, in summer, mineralization and nitrification may be further accelerated under the wetted soil condition due to the successive rainfall. The results of the soilwater and streamwater chemistries monitored in the Tsukuba experimental forest reveal that the runoff of the soilwater, of which solute concentration of Type II keeps considerably higher than that of the streamwater baselevel, raises the streamsolute concentration in summer. A clear evidence in the seasonal trend can be seen in NO_3^--N concentration in streamwater. Furthermore, during summer, the streamsolute concentration for Type II rises with flowrate, which produces heavy runoff loads and consequently results in the positive correlation between the annual mean streamsolute concentration and the annual streamwater amount.

Annual budgets for rainwater input and streamwater output of dissolved chemical constituents were obtained in Table 1. The paper is concerned with the available form for plant growth, so the organic form of nitrogen and phosphorus is not taken into account. Among the nutrients, PO_4^{3-}-P despite a negative ion is specifically easily adsorbed into soil, so the more flux entered the forest ecosystem in rainwater than that was lost in streamwater every year over the four-year observation period. In this context the forest function of controlling the water environment fully operated. With respect to the total inorganic nitrogen (NH_4^+-N + NO_2^--N + NO_3^--N), only in the result in 1987 when the annual streamwater amount is the lowest among the four water years, the annual output is less than the input. Again this result emphasizes the significance of the soilwater leaching and annual streamwater amount in the formation of streamwater chemistry. In order to evaluate precisely the nitrogen behavior within the forest ecosystem, further long-term observation of chemical change with water migration is desired.

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