

THE ROLE OF SUBSURFACE FLOW DYNAMIC ON SPATIAL AND TEMPORAL VARIATION OF WATER CHEMISTRY IN A HEADWATER CATCHMENT

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ABSTRACT

Variation of water chemistry does not merely occur due to *in situ* chemical process, but also transport process. The study was carried out to address the role of subsurface flow dynamic on spatial and temporal variation of water chemistry in a headwater catchment. Hydrometric and hydrochemistry measurements were done in transect with nested piezometers, tensiometers, and suction samplers at different depths across hillslope and riparian zone in a 5.2 ha first-order drainage of the Kawakami experimental basin, Nagano, Central Japan from August 2000 to August 2001. Spatial variation of solute concentration was defined by the standard deviation and coefficient of variation of the seasonal observed concentrations. Autocorrelation analysis was performed to define temporal variation of solute concentration. The results showed that spatial variation of water chemistry was mainly influenced by the variation of subsurface flow through the hillslope and riparian zone. Solute concentration in the deep riparian groundwater was almost three times higher than that in the hillslope segment. A prominent downward flow in deep riparian groundwater zone provided transport of solutes to the deeper layer. Time series analysis showed that in the deep riparian groundwater, Ca^{2+} , Mg^{2+} , SO_4^{2-} and HCO_3^- concentrations underwent a random process, Na^+ concentration of a random process superimposed by a trend process, and SiO_2 of a random process superimposed by a periodic process. Near the riparian surface, SO_4^{2-} concentration was composed of a random process superimposed by a periodic process, whereas other solutes were mainly in a random process. In the hillslope soil water, there was no trend observed for the Na^+ concentration, but there were for Ca^{2+} and Mg^{2+} . The magnitude and direction of subsurface flow across hillslope and riparian zone created transport and deposition processes that changed solute concentration spatially and temporally.

[**Keywords:** Spatial variation, temporal variation, solutes concentration, sub-surface flow, headwater catchment]

INTRODUCTION

Understanding the linkage between runoff process and the hydrochemical behavior of the catchment should not be directed merely for the short-term process during the rainfall event, but treating the seasonal variations may also provide valuable insights into the pattern of hydrochemistry changes as a

function of the dynamic of hydrologic process. The reason has been mentioned by Jenkins *et al.* (1994), who reported that runoff generation mechanisms are difficult to be generalized from one basin to another and even from storm to storm within the same basin.

Stream flow generation varies spatially and temporally (Genereux *et al.* 1993), which gives a different influence on the hydrochemistry in the catchment. This is because the solute transport by flow causes the solutes to spread out in time and space. The variability of the flow governing the solute transport has become a factor determining the solute variability. de Rooij and Stagnitti (2002) reported that a stochastic-convective transport process occurred in the high flow area, while convection-dispersion was predominantly in the low flow area, the one that could give insight into a spatial variability in the characteristics of intrabasin flow that can create the spatial variation in water chemistry. Within a catchment, spatial and temporal variations in water chemistry may occur based on the specific characteristic of the catchment on which the various factors play a role.

The hydrometric-hydrochemistry interaction has been proved by many authors to be powerful to understand the flow path and chemical pathways in the headwater catchment (Pionke *et al.* 1988; Hill 1993; Eshelman *et al.* 1994; Cirno and McDonnell 1997; McDonnell *et al.* 1998; McGlynn *et al.* 1999). Not only the surface runoff has a contribution to stream flow generation and its chemistry, but the subsurface flow has also generated the major hydrologic process governing solute transport in a headwater catchment. The role of source areas (end-members) on stream chemistry through various flow pathways has been studied. SiO_2 concentration in the stream increased with the increase in near surface riparian contribution to runoff generation, but decreased with the increase in both deep riparian groundwater and hillslope soil water contributions

(Subagyono and Tanaka 2003). The near surface riparian contributed little on peak runoff, but it dominated baseflow (87%), early on-set rain (58%), storm end (66%), and poststorm (76%). This means that an intense flushing of high concentration of SiO_2 has occurred during those periods, which exponentially correlates with its contribution to runoff generation.

The relationship between flow and chemical concentration provided the conceptual model of stream flow and chemistry. Subagyono and Tanaka (2004) found that the change in NO_3^- concentration agreed well with the magnitude and direction of flow, where its concentration in deep riparian groundwater zone increased during low flow, and decreased during high flow.

Although the role of flow path and chemical pathways on stream flow and its chemistry had been intensively studied, the phenomenon on the variability of chemistry in a headwater catchment is rarely studied. The study on control of subsurface flow on the spatial and temporal variation of water chemistry in a headwater catchment will be valuable to conceptualize the dynamic behavior of water chemistry and form a basis for land management and environmental protection.

In agricultural management, soil fertility and fertilizer application status needs to be defined. The dynamic behavior of nutrients has often been discussed in terms of loss through erosion, uptake by crops and gain through fertilizer application, yet the dynamic behavior of nutrients through transport processes by flow of water has been paid less attention. In addition, intensive agricultural management has often come up with pollution due to over-fertilization and transport of solutes from adjacent areas by flow of water. Study on the dynamic of solute concentration as affected by the dynamic of subsurface flow becomes important for a better planning in fertilizer application and environmental protection. The objectives of the study were: (1) to elucidate how the subsurface flow affects the dynamic behavior of water chemistry spatially and temporally, (2) to understand which factors dominantly influence the variation of water chemistry, and (3) to analyze the long-term variation in hydrochemistry.

MATERIALS AND METHODS

Study Area

The study was conducted from August 2000 to August 2001 in Kawakami experimental basin,

Nagano Prefecture, Central Japan. This is a first order basin of 5.2 ha from the total area of 14 ha. The altitude of the catchment ranges from 1500 m to 1680 m asl with slightly steep slopes (about 20%) over the riparian zone and very steep slopes (>60%) over the hillslope area.

This area was underlied by late Neogene of the Meshimoriyama volcanic rocks, which consists of lavas and pyroclass of olivine-hornblende-pyroxene andesites (Kawachi 1977). The upper soil mantle primarily consists of inceptisols with very narrow area of the riparian zone covered by 20-30 cm of peat. The A-horizon is rich in organic matter with rapid hydraulic conductivity ($K_s = 21.6-93.6 \text{ cm h}^{-1}$), while the B-horizon which has more clay has a very slow hydraulic conductivity ($K_s = 0.007-0.9 \text{ cm h}^{-1}$). Mean annual precipitation is about 1500-1600 mm, producing 853 mm of runoff (Matsutani *et al.* 1993). A natural deciduous forest of oak (*Quercus mongolica* Fisch), larch plantation (*Larix leptolepis* Gordon), and the bamboo grass (*Sasa nipponica*) are very common in this area.

Hydrometric Measurements

A transect across hillslope and riparian zone approximately along the flow line was nested with piezometers, tensiometers, and suction samplers with various depths to monitor the dynamic of subsurface flow and chemical pathways (Fig. 1). Discharge was continuously recorded with 30°V-notch gauging weir installed at upstream tributary of the northern valley of the catchment. Water level at weir was automatically recorded using a data logger that was set for every 10-minute interval recording. Rainfall was measured using a tipping bucket (recording) rain gauge placed at the climate station located near the main weir (about 150 m from the experimental site).

A partly perforated piezometer was used, which is a PVC tube with an inner diameter of 4 cm and the outer diameter of 4.8 cm and bottom perforation length of 10 cm. To be easily installed, a PVC cup was complemented at the top of piezometer for hammering. The rest of about 20-30 cm remains above the surface to avoid overland flow water (if any) from entering the piezometer. Since the groundwater samples are taken from the piezometer, it was covered by a PVC cup to avoid contamination from rain water. Soil water potential was measured using a mercury manometric tensiometer connected to a water column inside. The water column was a tube with inner diameter of 1.5 cm and outer diameter of 1.7 cm and the porous cup at the bottom of the tube.

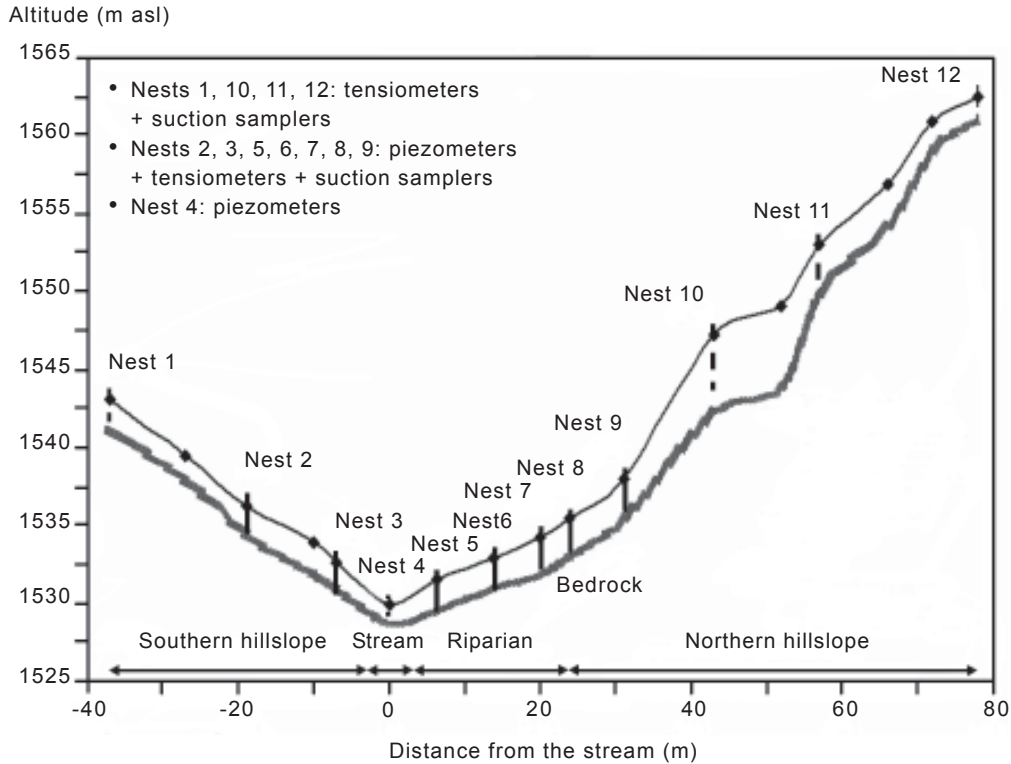


Fig. 1. The transect showing the nests of piezometers, tensiometers, and suction samplers at Kawakami experimental basin, Central Japan.

Flow line was determined across hillslope and riparian zone to define the spatial variation of subsurface flow based on this equipotential line. The equipotential line was defined using piezometer and tensiometer data. Monthly variation of vertical and lateral subsurface flows were defined by determining vertical and lateral head gradients of groundwater between two points at different depths in the riparian zone. The vertical head gradient ($\partial H/\partial z$) was determined as follows:

$$\frac{\partial H}{\partial z} = (H_2 - H_1)/(z_2 - z_1) \quad (1)$$

where H_1 and H_2 are hydraulic head at the shallowest (0.2 m) and deepest (2 m) depths, respectively, and z_1 and z_2 are the elevation of the observation points.

The lateral head gradient ($\partial H/\partial z$) was determined as follows:

$$\frac{\partial H}{\partial z} = (H_b - H_a)/(z_b - z_a) \quad (2)$$

where H_a and H_b are hydraulic heads at the nest 4 and 5, respectively, and z_a and z_b are elevation at the nest 4 and 5, respectively.

Hydrochemistry Measurements

Suction samplers were used for sampling soil water. These samplers were PVC tubes with diameter of 1.8

cm complemented with porous cups at the bottom of the tubes, which were connected to 100 ml flasks. To collect soil water, the flasks were vacuumed using a hand pump at a suction of about 80 bars. Depending upon the depths of bedrock, the thickness of soil mantle and the stratification of the soil horizon, samples were taken at various depths of 0.3, 0.4, 0.5, 0.6, 1.0, 1.1, 1.5, 2.0, 3.0, and 4.0 m.

Groundwater, soil water, and stream water samples were collected monthly. Groundwater samples were taken from the piezometers (perforated at the bottom of 10 cm), whereas soil water samples were collected from suction samplers installed at the same site with piezometer and tensiometer nests at depths of 0.3, 0.4, 0.5, 0.6, 1.0, 1.1, 1.5, 2.0, 3.0, and 4.0 m. The stream water samples were taken at the upstream, middle, transect site, and near the weir. Samples were collected using 100 ml polyethylene bottles. Before collecting the samples, the bottles were rinsed with the groundwater, soil water or stream water depending upon the sampling sites.

The water samples were filtered through 0.22 μm Millipore membrane filters to remove any suspended matters. Filtered solutions were, then, analyzed for Ca^{2+} , Mg^{2+} , Na^+ , SiO_2 , SO_4^{2-} , HCO_3^- , and dissolved organic carbon (DOC). Concentrations of Ca^{2+} , Mg^{2+} , Na^+ , and

SiO₂ were measured using Inductive Couple Argon Atomic Emission Spectrophotometer (ICAP-757V, Nippon Jarrel-Ash) at the Chemical Analysis Center of University of Tsukuba, whereas SO₄²⁻ concentration was measured using Ion Chromatographic Analyzer (Shimadzu PIA-1000). Concentration of HCO₃⁻ was measured only for the samples of fully filled bottles by titration with H₂SO₄ using 645 Multi Dosimat (Metrohn) at the Laboratory of Soil and Water, Institute of Geoscience, University of Tsukuba. DOC was measured using TOC analyzer at the National Institute for Agro-Environmental Sciences, Tsukuba.

Statistical Analysis

Spatial Variation of Water Chemistry

Three end-members contributing to stream flow generation and chemistry have been identified to be near surface riparian, deep riparian groundwater, and hillslope soil water (Subagyono 2003). These three end-members were assumed to have different chemical compositions. The variability of solute concentration of each end-member was defined by the standard deviation and coefficient of variation of the observed concentration. Since the dynamic of solute concentration change has not only been affected by the *in situ* process of solute reaction but also the hydrological process in the catchment, the spatial variation was described seasonally during the autumn, winter, spring, and summer. To understand the spatial variability in solute concentration across hillslope and riparian zone, mean of each chemical composition in each nest of piezometer and suction samplers was plotted in a graph.

Temporal Variation of Water Chemistry

To define the temporal variation of water chemistry, time series analysis was conducted. Since the change in time of hydrologic and hydrochemical processes is being the interest to understand their temporal variability, the autocorrelation analysis was performed using the method of Haan (1977) as follows:

$$\rho(\tau) = \text{Cov}(X_{(t)}, X_{(t+\tau)}) / \text{Var}(X_{(t)}) \quad (1)$$

where $\rho(\tau)$ is the autocorrelation function, $\text{Cov}(X_{(t)}, X_{(t+\tau)})$ is the autocovariance, and $\text{Var}(X_{(t)})$ is the variance. Since each source area of runoff composed of several realizations (single time series), the covariance was determined by:

$$\text{Cov}(X_{(t)}, X_{(t+\tau)}) = \frac{1}{m} \sum_{j=1}^m (X_j(t) - \overline{X(t)})(X_j(t+\tau) - \overline{X(t+\tau)}) \quad (2)$$

Because each time several observations were carried out, the variance ($X(t)$) of these group data is calculated as follows:

$$\text{Var}(X(t)) = \frac{1}{n-1} \sum_{i=1}^k (X_i - \overline{X})^2 \quad (3)$$

where $X_{(t)}$ represents a stochastic process, \overline{X} is the mean, k is the number of groups and n is the number of observations. The autocorrelation function was calculated using SPSS for windows release 10.0.1.

RESULTS AND DISCUSSION

Variation of Flow Gradient

Groundwater flow varied vertically and laterally with time. Data on hydraulic head gradients showed that downward flow and down slope flow to the stream channel (Fig. 2) during the base flow period varied with time. As the water flows downwardly, the solute concentration was transported deeper. The solutes may also be transported to the stream channel by lateral flow. Variation of solute concentration was strongly controlled by the dynamic of flow process.

The downward flow of groundwater promoted vertical variation of solute concentration, by which the solutes were transported to the deeper layer, whereas the flow to the stream channel provided contribution to the solute flushing. These flows strongly affected the dynamic behavior of solute concentration as well as their spatial variation.

Spatial variation of flow direction during base flow period is presented in Figure 3. Near the Fig. 3 riparian surface, the flows were lateral to the stream channel, whereas the deep riparian groundwater flows down-wardly. Meanwhile the flows in hillslope side were mainly downward except in the interface between bedrock and soil mantle, where the water flows laterally.

Spatial Variation of Solute Concentration

Solute concentration showed a typical trend of low in the hillslope and high in the riparian zone (Fig. 4). This trend was strongly related with the flow process, where the prominent downward flows in the riparian zone caused an accumulation of solutes. Since the rapid flow obviously occurred in the hillslope segment especially during high storm event, high concentration of solutes may be leached out from this segment. The spatial variation in potential distribution and flow lines was responsible for the differences in solute concentration across the

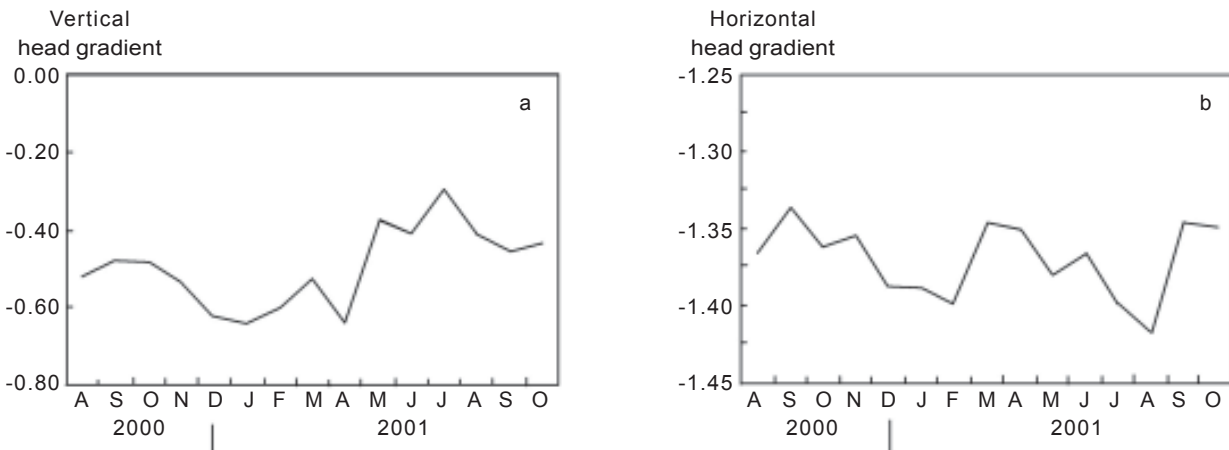


Fig. 2. Monthly variation of vertical (a) and lateral (b) head gradients of groundwater flow during base flow period, Kawakami experimental basin, Central Japan, August 2000-August 2001.

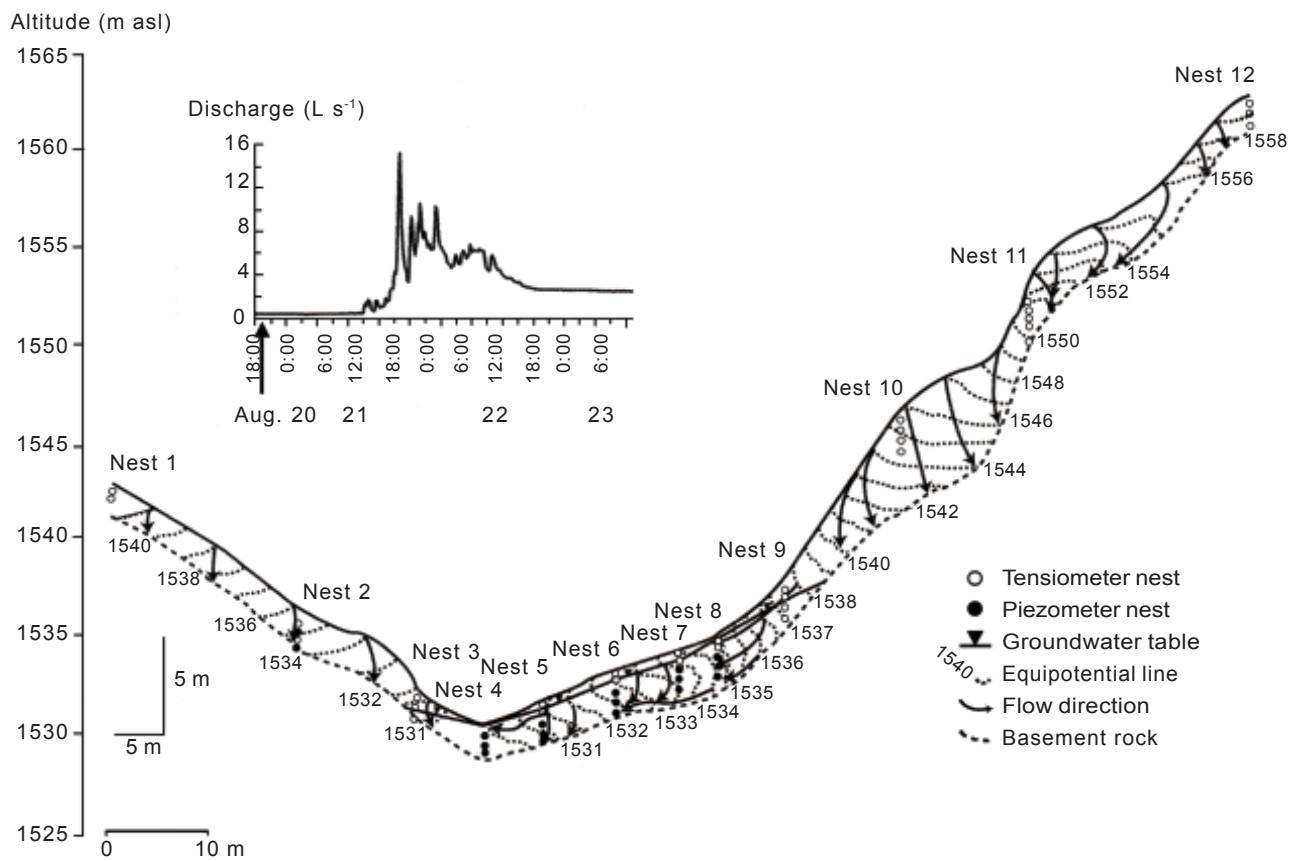


Fig. 3. Spatial variation of flow direction during base flow period across hillslope and riparian zone, Kawakami experimental basin, Central Japan, August 2000-August 2001.

hillslope segment and the riparian zone. In addition, the differences in residence time between the hillslope and the riparian zones may also influence the concentration (Subagyono 2006).

For the whole depths of the riparian zone, Ca^{2+} concentration increased away from the stream and

decreased at the border between the hillslope and the riparian zone. It also progressively increased with depth. The change in Ca^{2+} concentration, compared with other solutes, has strongly related to the flow process. As the lateral flow in the hillslope was going deeper (Subagyono *et al.* 2005), Ca^{2+} concentration in

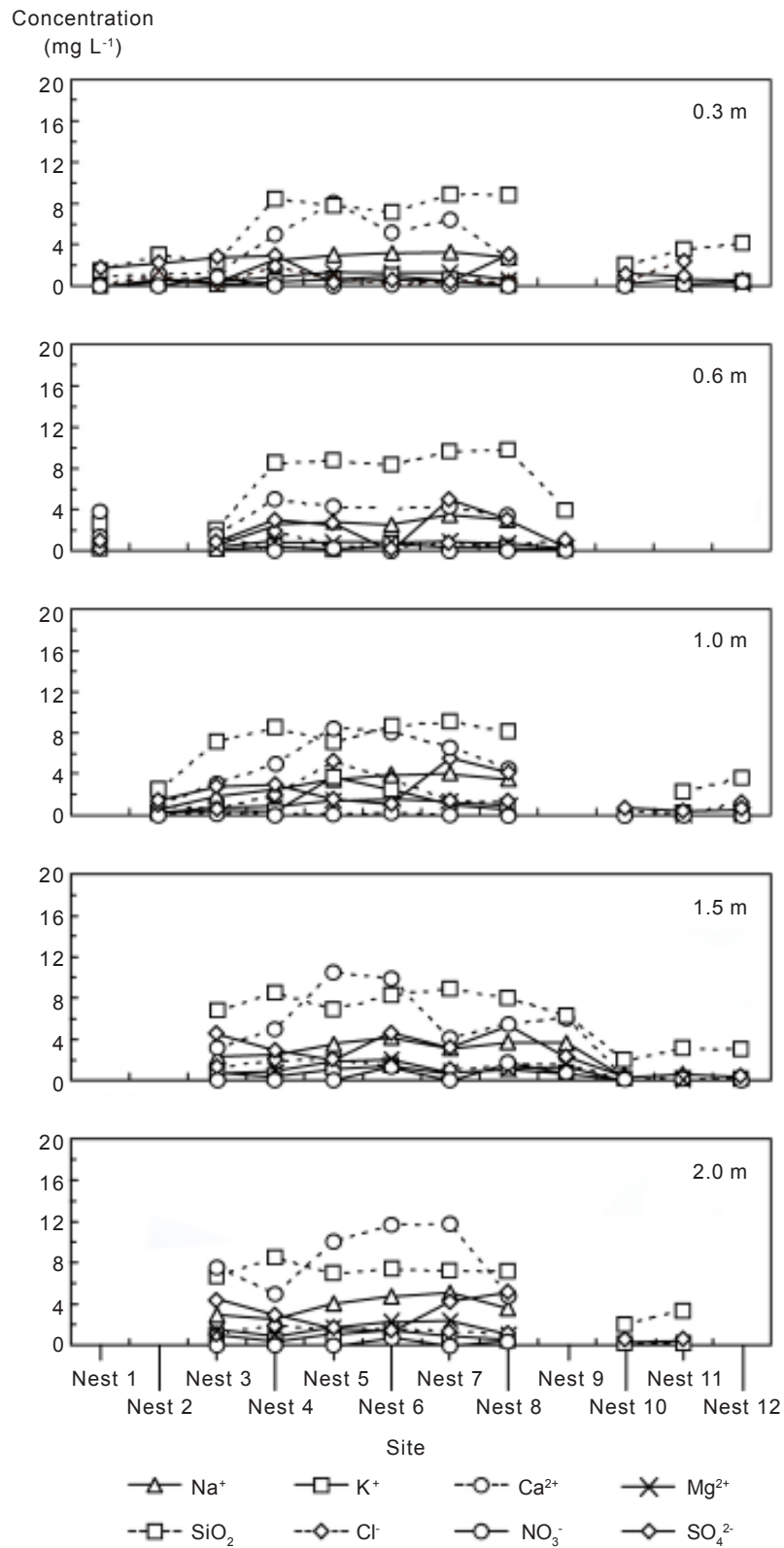


Fig. 4. Spatial variation of solute concentration measured at 0.3-2.0 m depths across the hillslope and riparian zone, Kawakami experimental basin, Central Japan, summer 2001.

the deep riparian groundwater increased. During summer, where this flowpath was shallow, the concentration of Ca^{2+} was lower compared with other seasons. The flow lines as depicted in Figure 3 and the dynamic behavior of Ca^{2+} concentration, where its concentration in hillslope was lower due to leaching process and this leached Ca^{2+} transported to the riparian before it reached the stream, could explain the linkage between hillslope and riparian zone during the runoff process. The flow at bedrock-soil interface may also play a role, because this flow was also prominently developed in the catchment studied.

Unlike Ca^{2+} , SiO_2 concentration had typical evidence at the hillslope, where it tend to increase with altitude in many nested sites. SiO_2 was the most dominant solute in the studied catchment, which was in accordance with the soil mineralogical data where quartz was dominant. The average concentration of SiO_2 in the hillslope soil water was 2.78 mg L^{-1} , which was almost three times lower than that of the deep riparian groundwater (8.26 mg L^{-1}). This finding was similar with that found by Shimada *et al.* (1993) for Kiryu experimental basin in Shiga Prefecture, Central Japan, where the average concentration of SiO_2 in unsaturated soil water was 2.6 mg L^{-1} , whereas that in the groundwater ranged from 3.1 to 22.5 mg L^{-1} . As SiO_2 concentration in the rain water was low while the soil was rich in quartz mineral, it suggested that SiO_2 was dissolved from the soil minerals. The flow affected the variability of solute concentration within the catchment.

As the second major solutes, Na^+ and Mg^{2+} showed similar trend with Ca^{2+} and SiO_2 across the riparian zone, where their concentration increased away from the stream and decreased at the border between the riparian zone and the hillslope. These solutes also appeared frequently in the stream channel.

Solute concentration varied with space and seasons (Table 1). In general, solute concentration in the riparian zone was much higher than that in hillslope soil water. In the riparian zone, solutes were more concentrated in the deep riparian groundwater rather than near the surface (0.5 m). Ca^{2+} and SiO_2 were the most dominant solutes either in the deep riparian groundwater or near the riparian surface. In hillslope soil water, variation in solute concentration was also high as shown by the coefficient of variation (Table 1). The coefficient of variation of most solute concentration in hillslope soil water was higher than that in the deep riparian groundwater and near the riparian surface. For instance, in summer the coefficient of variation of Ca^{2+} concentration in hillslope soil water was 100%, which was higher than that near the

riparian surface (39%) and deep riparian groundwater (36%).

Temporal Variation of Solute Concentration

Temporal variation of solute concentration was affected by the dynamic of subsurface flow as represented by the vertical (Fig. 5) and the lateral (Fig. 6) head gradients. As the water flows downwardly, the Ca^{2+} , SiO_2 , Na^+ , Cl^- , NO_3^- , and SO_4^{2-} were transported to the deeper layer leading to an increase in solute concentration in the deep groundwater. For instance, during summer, where downward flow was dominant, Ca^{2+} concentration tended to increase in the deeper layer as described by the different values in near the riparian surface (3.949 mg L^{-1}) and deep riparian groundwater (8.205 mg L^{-1}) (Table 1). Those solutes decreased with the increase in flow gradient. The similar trend has been recorded for the solute concentration as affected by the lateral flow. This implies the solute flushing through lateral flow to the stream channel.

The time series of the solute concentration were mostly composed of a stochastic component allowing to the use of the autocorrelation function to describe the memory of the stochastic process. The plots of autocorrelation function against the lag number are presented in Figures 7, 8, and 9. In the deep riparian groundwater, Ca^{2+} , Mg^{2+} , SO_4^{2-} and HCO_3^- series underwent a random process, Na^+ series of the random process superimposed by a trend process, and SiO_2 seemed to be a random process superimposed by a periodic process (Fig. 7). Sodium (Na^+) being more mobile compared to bications, is flushable by water flow. Its concentration tended to decrease with time. This means that the rate of weathering was lower than that transported by water. Unlike the sodium, SiO_2 concentration periodically changed with time assuming that its concentration from weathered mineral in the soil is in balance with that transported by water. Near the riparian surface, SO_4^{2-} concentration underwent a random and periodic processes, whereas other solutes mainly a random process (Fig. 8). In the hillslope soil water, there was no trend observed on the Na^+ concentration, but there were for Ca^{2+} and Mg^{2+} (Fig. 9). The only solute that showed a negative autocorrelation function was HCO_3^- , which indicates that it was no memory for what occurred prior to time $t+\tau$ according to Haan (1977).

If the correlogram indicates a high correlation between $X(t)$ and $X(t+\tau)$, the observation cannot be assumed to be independent (Haan 1977). Compared with that of the riparian zone (the deep groundwater

Table 1. Spatial variation of solute concentration under the different seasons, Kawakami experimental basin, Central Japan, August 2000-August 2001.

Time	End-members		Solute concentration (mg L ⁻¹)								
			Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	SiO ₂	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	HCO ₃ ⁻
Autumn	NSR	Mean	2.657	0.368	4.329	0.927	8.265	0.694	0.086	1.881	0.375
		SD	0.443	0.171	1.327	0.254	0.949	0.198	0.128	1.623	0.126
		CV (%)	16.661	46.408	30.655	27.431	11.480	28.481	148.461	86.278	33.633
		n	24	24	24	24	24	24	24	24	23
	DRG	Mean	3.533	0.894	10.560	1.553	8.264	1.244	0.286	5.842	0.671
		SD	1.036	1.068	5.053	0.833	0.818	0.870	0.435	15.578	0.347
		CV (%)	29.333	119.535	47.852	53.519	9.892	69.958	152.062	266.646	51.674
		n	36	36	36	36	36	36	36	36	36
	HSW	Mean	0.730	0.216	0.987	0.293	2.955	0.742	0.284	1.159	0.070
SD		0.613	0.294	0.913	0.279	1.274	0.755	0.529	1.112	0.076	
CV (%)		83.947	136.119	92.504	95.353	43.131	101.804	186.384	95.978	108.584	
	n	54	54	54	54	54	49	49	49	14	
Winter	NRS	Mean	2.068	0.285	3.009	0.626	4.906	0.728	0.119	1.906	nd
		SD	0.593	0.218	0.931	0.198	2.188	0.245	0.096	1.613	nd
		CV (%)	28.690	76.633	30.931	31.693	44.604	33.717	80.712	84.630	nd
		n	7	7	7	7	7	7	7	7	7
	DRG	Mean	3.767	0.626	7.868	1.474	8.306	1.524	0.720	5.878	0.493
		SD	1.073	0.349	3.562	0.718	0.802	0.478	0.697	4.460	0.279
		CV (%)	28.492	55.788	45.264	48.691	9.658	31.362	96.802	75.877	56.630
		n	36	36	36	36	36	36	35	36	36
	HSW	Mean	0.729	0.125	0.649	0.169	1.071	0.766	0.351	0.661	nd
SD		0.241	0.181	0.506	0.114	0.609	0.553	0.567	0.250	nd	
CV (%)		33.109	144.423	77.928	67.502	56.871	72.213	161.472	37.845	nd	
	n	5	5	5	5	5	5	5	5	nd	
Spring	NRS	Mean	1.992	0.199	3.279	0.667	8.275	0.490	0.083	2.661	0.247
		SD	0.446	0.092	1.048	0.203	1.096	0.083	0.124	1.125	0.111
		CV (%)	22.409	46.353	31.968	30.394	13.245	16.914	149.257	42.260	45.144
		n	16	16	16	16	16	8	8	8	9
	DRG	Mean	3.129	0.778	8.118	1.522	8.166	1.429	0.490	5.010	0.552
		SD	0.556	0.954	3.070	0.611	0.770	1.393	0.662	4.664	0.255
		CV (%)	17.769	122.660	37.815	40.135	9.430	97.479	135.105	93.092	46.233
		n	36	36	36	36	36	24	24	24	36
	HSW	Mean	0.650	0.102	0.770	0.231	2.969	0.514	3.680	1.072	0.205
SD		0.479	0.164	0.751	0.186	1.736	0.442	15.318	1.050	nd	
CV (%)		73.779	160.761	97.576	80.660	58.482	85.959	416.221	97.905	nd	
	n	35	35	35	35	35	20	20	20	2.000	
Summer	NRS	Mean	2.489	0.331	3.949	1.054	9.124	0.687	0.074	1.313	0.314
		SD	0.915	0.368	1.546	1.084	1.042	0.262	0.208	1.499	0.116
		CV (%)	36.743	111.062	39.149	102.872	11.416	38.159	282.843	114.167	36.814
		n	24	24	24	24	23	8	8	8	7
	DRG	Mean	3.366	0.921	8.205	1.560	8.401	2.722	0.980	3.882	0.577
		SD	1.264	0.905	2.970	0.564	0.889	1.396	1.559	2.374	0.258
		CV (%)	37.552	98.258	36.200	36.155	10.583	51.296	158.997	61.157	44.663
		n	36	36	36	36	36	12	12	12	24
	HSW	Mean	1.131	0.258	0.773	0.222	3.354	0.933	0.046	1.599	nd
SD		0.965	0.315	0.772	0.182	1.964	0.936	0.128	1.902	nd	
CV (%)		85.377	122.171	99.836	81.923	58.544	100.380	280.268	118.913	nd	
	n	41	41	41	41	41	16	16	16	nd	

SD: standard deviation; CV: coefficient of variation; n: number of samples; NRS: near the riparian surface; DRG: deep riparian groundwater; HSW: hillslope soil water.

and near the surface), it was a lower autocorrelation function values of the solute concentration in the hillslope soil water. This evidence indicated that the

temporal variability of solute concentration within the riparian zone differed with that in the hillslope segment, suggesting that the riparian zone and the

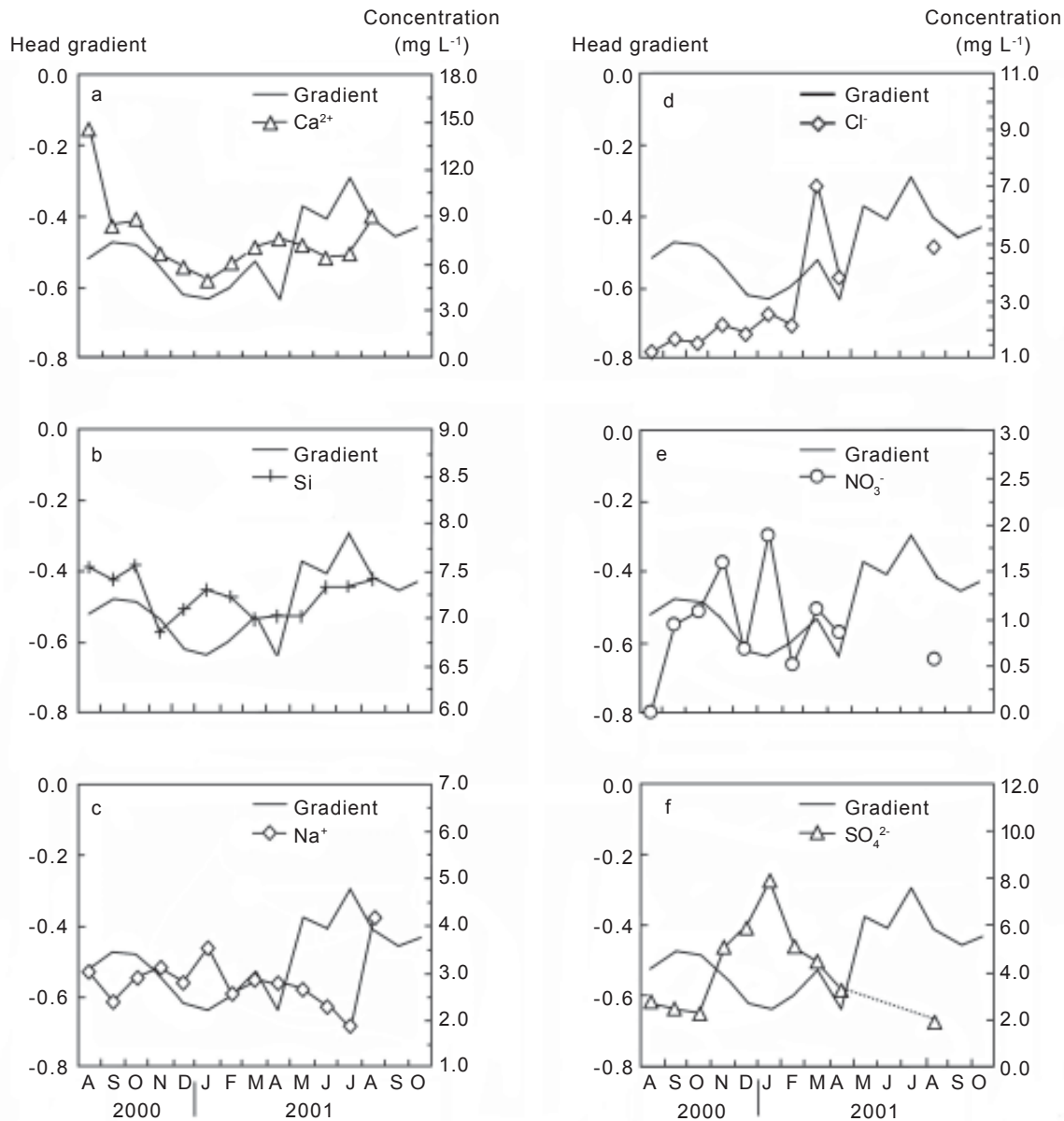


Fig. 5. Temporal variation of vertical head gradient and concentrations of (a) Ca^{2+} , (b) SiO_2 , (c) Na^+ , (d) Cl^- , (e) NO_3^- , and (f) SO_4^{2-} in groundwater (1 m depth) at K1 nest, Kawakami experimental basin, August 2000-August 2001.

hillslope segment are controlled by the different flow processes, and both interacts each other. For instance, during high storm event, preferential flow occurred in hillslope segment but not in the deep riparian groundwater. In many occasion of hydrological event, the flow at the interface between bed rock and soil mantle also occurred in hillslope segment but not in the deep riparian groundwater. In contrast, downward flow more frequently occurred in the riparian zone (especially in deep groundwater) rather than in hillslope segment. The preferential flow in hillslope segment is very potentially affecting the leaching of solute leading to the decrease in its concentration.

Meanwhile, the downward flow in the deep riparian groundwater caused accumulation of solutes.

The hydrological and hydrochemical phenomena in the catchment provided insight that solute concentration in the catchment can be depleted due to leaching by flow of water especially in the hillslope areas. The loss of solutes from the catchment can be reduced by implementation of conservation measures. Interception channel can be constructed in hillslope to reduce the flow and loss of nutrient through leaching. Land use management may be directed to increase interception and infiltration rate and reduce flow during hydrological event. This can be accomplished through

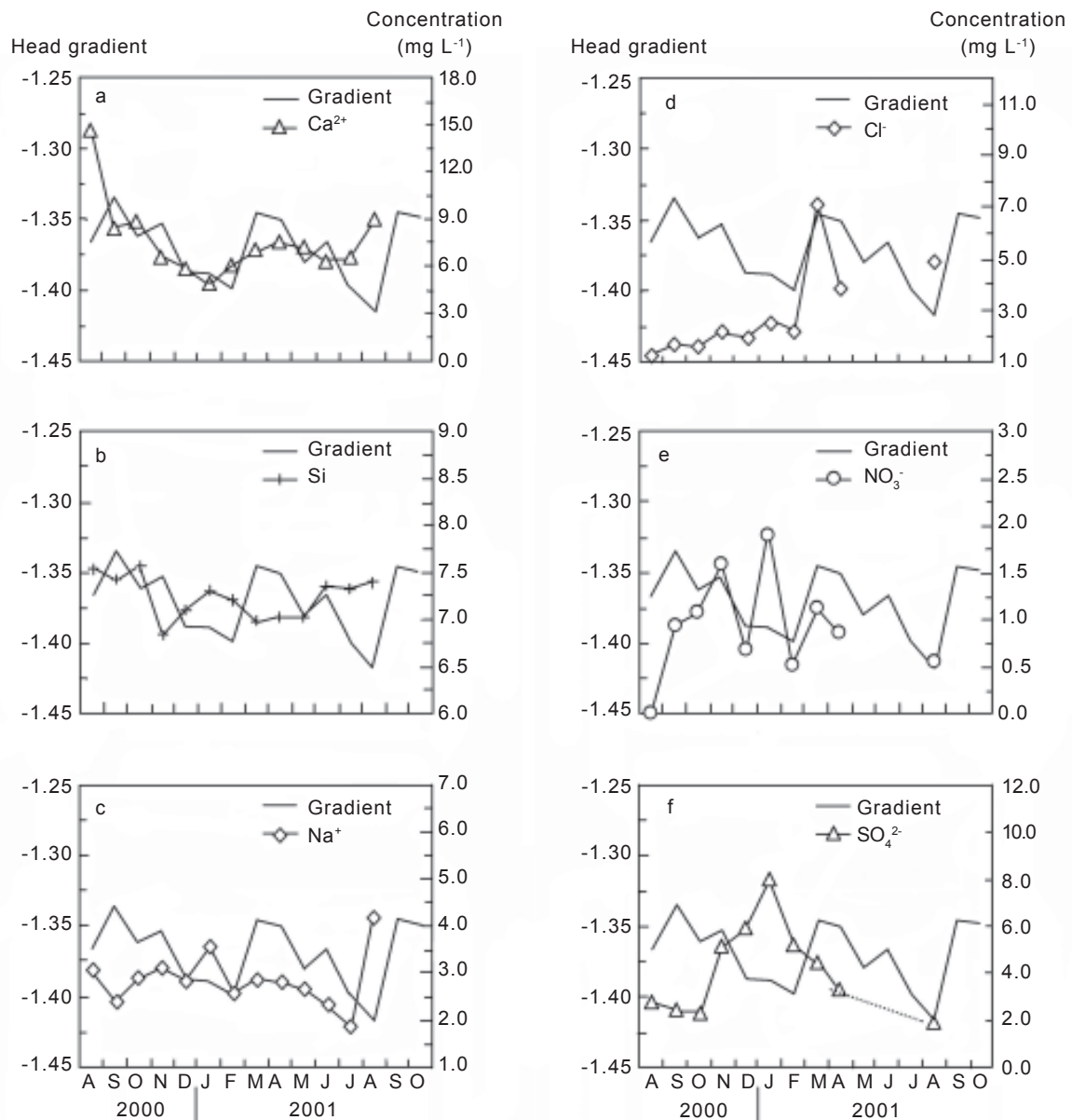


Fig. 6. Temporal variation of lateral head gradient and concentrations of (a) Ca^{2+} , (b) SiO_2 , (c) Na^+ , (d) Cl^- , (e) NO_3^- , and (f) SO_4^{2-} in groundwater (1 m depth) at K1 nest, Kawakami experimental basin, August 2000-August 2001.

introducing more tree crops rather than seasonal crops. Alley cropping may be applied to reduce subsurface preferential flow and solute leaching.

In Indonesia, slopping land is dominant while the management and conservation strategies for its sustainability are somewhat lagging because of limited information regarding the dynamic behavior of nutrient transport. The conservation recommendations are mainly based on the slope and to a lesser extent surface runoff and erosion data. In addition, soil management is mainly emphasized in the tillage. In many cases, fertilizer application was based merely on the static balance of nutrient, while the dynamic behavior of

solutes due to flow of water was not considered yet. To avoid nutrient depletion, the dynamic of hydrochemical phenomenon should be considered in the design of fertilizer application. Hence, the subsurface hydrological and hydrochemical data should be created and are urgently included in the planning of sloping land conservation.

CONCLUSION

Spatial variation of water chemistry is highly influenced by the dynamic behavior of subsurface flow through the hillslope and riparian zone. Solute con-

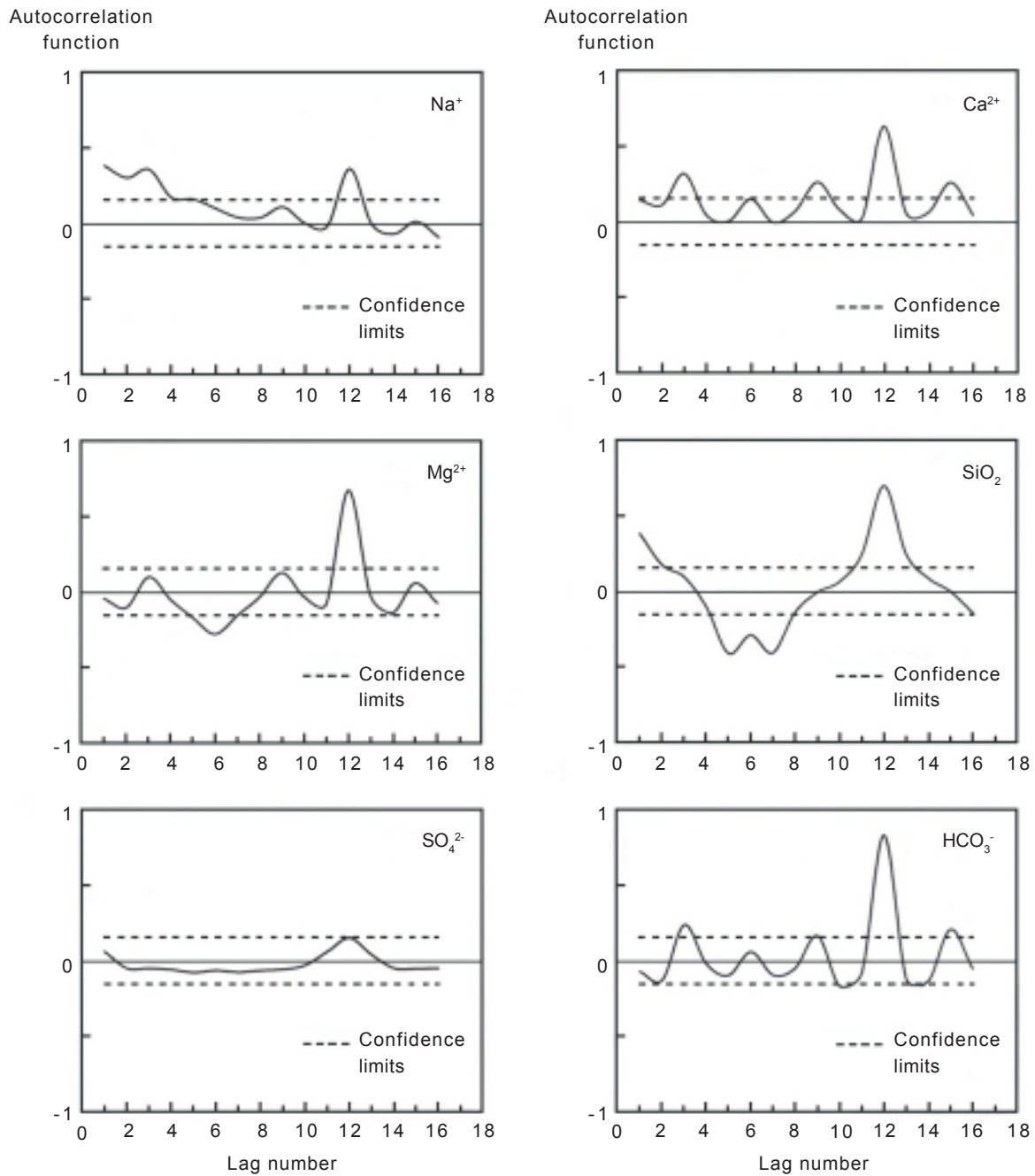


Fig. 7. Correlograms for various solutes in deep riparian groundwater, Kawakami experimental basin, Central Japan, August 2000-August 2001.

centration in the riparian (near the surface and deep groundwater) was much higher than that in the hillslope segment. A prominent downward flow in the deep riparian zone provided transport of solutes to the deeper layer, causing solute accumulation.

As the characteristics of solutes were different from one another and the subsurface flow varied with time, the temporal variation of solutes was influenced by the different random process, trend process, periodic process, and their combination. In the deep riparian

groundwater, Ca^{2+} , Mg^{2+} , SO_4^{2-} and HCO_3^- series were determined by a random process, Na^+ series by a random process superimposed by a trend process, and SiO_2 by random and periodic processes. Near the riparian surface, SO_4^{2-} concentration was influenced by random and periodic processes, whereas other solutes mainly by a random process. In the hillslope soil water, there was no trend process observed in the Na^+ concentration series, except for Ca^{2+} and Mg^{2+} which underwent a trend process. The magnitude and

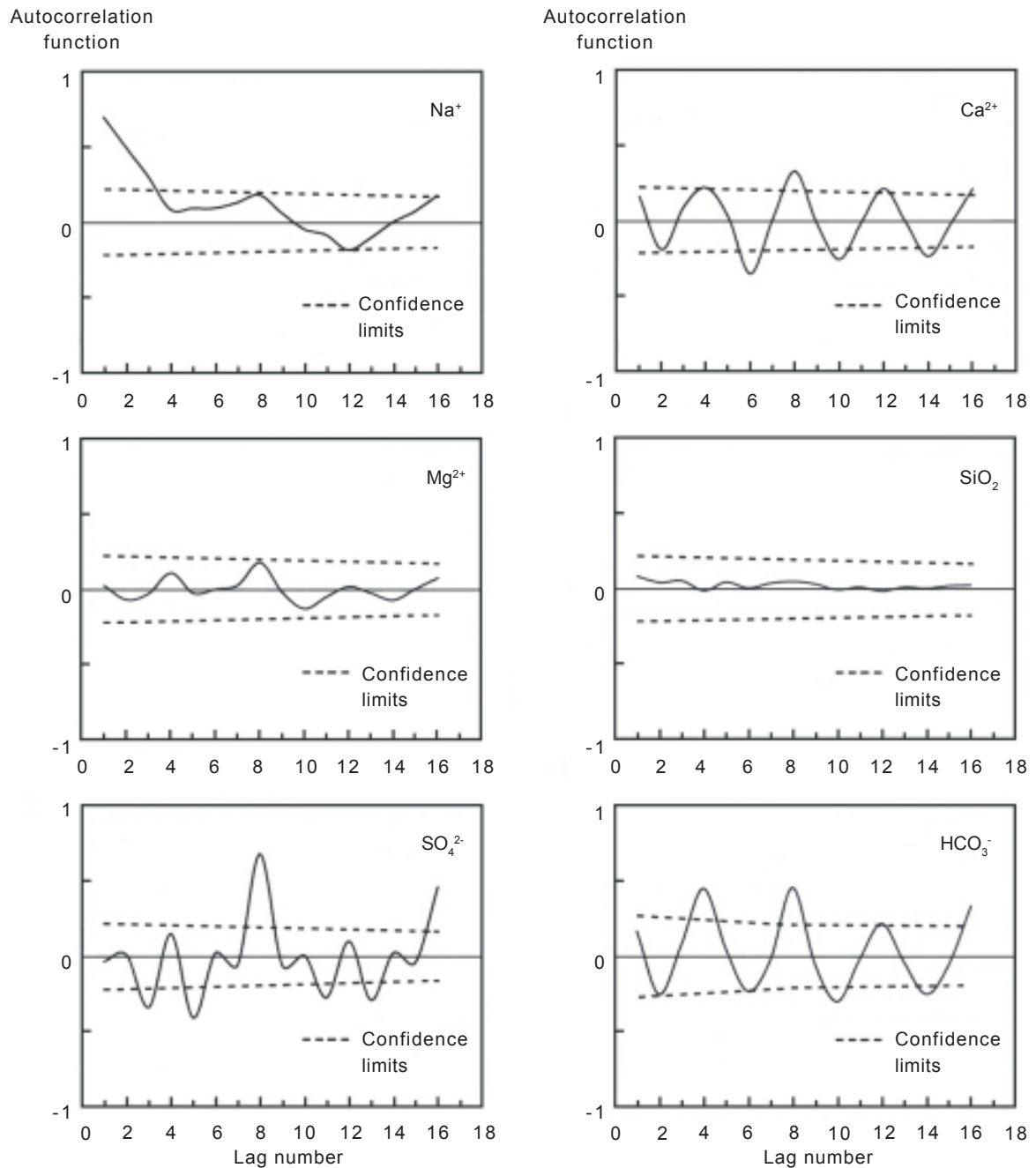


Fig. 8. Correlograms for various solutes near the riparian surface, Kawakami experimental basin, Central Japan, August 2000-August 2001.

direction of subsurface flow across hillslope and riparian zone created transport and deposition processes by which the solute concentration changed spatially and temporally.

Information on the dynamic behavior of hydrological and hydrochemical processes in the catchment areas may be valuable for a better planning of agricultural management in the sloping land. Since soil fertility is mainly determined by the behavior of nutrients, the

soil fertility status of the catchment may also be very dynamic and may affect agricultural production status.

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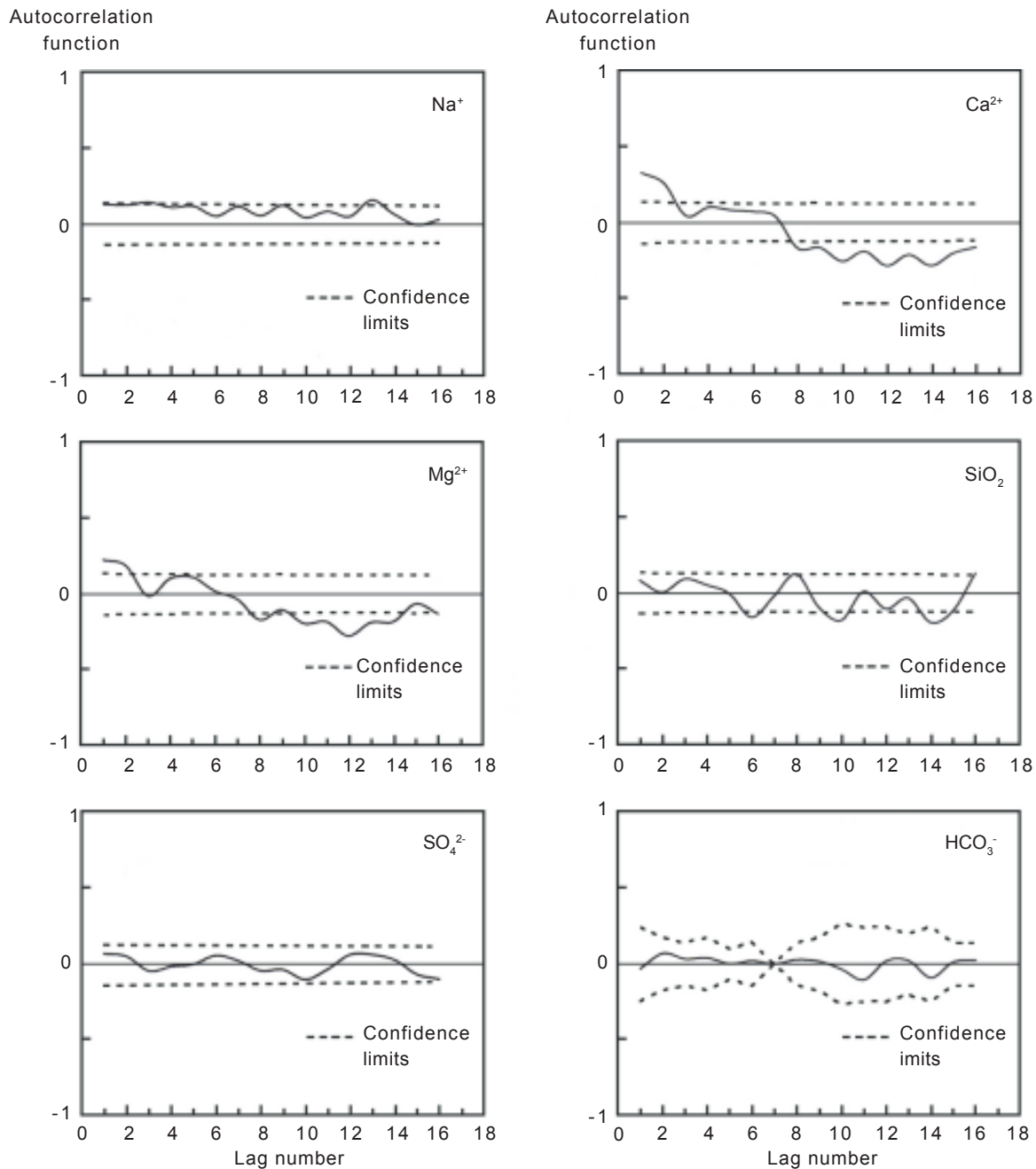


Fig. 9. Correlograms for various solutes in hillslope soil water, Kawakami experimental basin, Central Japan, August 2000-August 2001.

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