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The Importance of Near Surface Riparian on Storm Runoff Generation and Stream Chemistry in Kawakami Forested Headwater Catchment

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Abstract

A distinct between the near surface component (shallow sub-surface component) and deep groundwater in the riparian zone was observed in the Kawakami headwater catchment, Nagano, Central Japan. Hydrometric and hydrochemistry data during 143.5 mm storm on August 21-22, 2001 was used to define the role of near surface riparian on storm runoff generation and stream chemistry. The near surface riparian contributed as much as 45% of the total storm runoff, the largest among the major sources of storm runoff based on the geochemical hydrograph separation predicted by end-member mixing analysis (EMMA) using Ca^{2+} and SiO_2. The relatively steady near surface lateral flow during the storm may facilitate the flushing of high concentration of solute. The chemistry of the near surface riparian appeared dominantly in the stream channel at baseflow condition, early on-set rain and post storm, which positively correlated with its contribution to storm runoff. This zone also allowed the hillslope flowpath to connect with the stream channel during peak storm, as the chemistry of the stream water has shown similar with that of the hillslope water. This suggests that not all part of the riparian zone reset the hillslope flowpath and the chemical signature.

Keywords: Near surface riparian; Storm runoff; Stream chemistry; Flushing of solute; Headwater catchment

I Introduction

In recent decade, much attention has been paid on the chemical-hydrologic interaction of the riparian zone in headwater catchments (Pionke *et al.*, 1988; Hill. 1993; Eshelman *et al.*, 1994; Cirmo and McDonnel, 1997; McGlynn *et al.*, 1999). The results have often shown that the whole riparian zone may hamper the hillslope flowpaths and chemical signature. The validity of this result rests upon the assumption that the whole riparian zone is homogene, which neglects the difference in characteristic against the flow and the solute transport. Research on the flowpath dynamic and chemistry of the riparian zone (McDonnel *et al.*, 1998; McGlynn *et al.*, 1999) suggests that the riparian plays a role in the regulation of stream water sources and the complex interaction between hillslope, riparian zone and the stream channel. Resetting the hillslope flowpaths and chemical pathways in the riparian zone has been initiated in the research done by Robson *et al.* (1992) in the Hafren

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catchment, Plynlimon, mid-Wales. Similar results were obtained by Hooper *et al.* (1998) in which hillslope solutions were chemically distinct from the riparian solutions and did not appear to make a large contribution to streamflow.

Riparian zone have been shown to be very valuable for the removal of nonpoint-source pollution from drainage water (Gilliam, 1994) and critical for elucidating controls of nitrogen transport and transformation (Cirmo and McDonnell, 1997). However, the variability within depths which may be accounted as different sources of runoff and chemistry from the riparian zone was poorly explained.

The importance of shallow subsurface storm flow has been observed and modeled for the South Fork Brokenback Run catchment in Shenandooah National Park, Virginia, USA (Scanlon *et al.*, 2000). They reported that the macroporous subsurface storm flow zone provides a hydrologic pathway for rapid runoff generation apart from underlying groundwater zone. However, lack attention has been paid on the near surface riparian zone.

The present study was focused on the near surface riparian zone with aimed to elucidate the linkage of the near surface riparian flowpath and chemical pathways determining the stream water chemistry. This study was also directed to clarify whether the riparian zone impeded the hillslope flowpath and chemical pathway.

II Study area

The Kawakami Experimental Basin (KEB), a 14 ha forested headwater catchment is located in Nagano Prefecture, central Japan (35°54.9′N, 138°30.2′E) (Fig.1). The altitude of the catchment ranges from 1500 m to 1680 m amsl with slightly steep slopes (about 20%) over the riparian zone and very steep slopes (>60%) over the hillslope area. The topography of this area is derived from mount of Meshimori (1670m) in the west and mount of Yokoo (1818m) in the northeast.

This catchment is divided into two sub-catchments comprising two valleys, which are referred to as the north and south valleys and both having the stream flow. Tsujimura (1994) describes that the stream flow of the north valley started at the altitude of about1550 m, while that of the south valley started at the altitude of about 1630 m. The area of north valley which was used for the experiment comprises an area of 5.2 ha.

This area is 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 is covered by 0.2 m to 0.3 m of peat. The surface horizons (A-horizons) of about 0.15 m in the north hillslope and about 0.35 m in the south hillslope are rich in organic matter content with large to very large hydraulic conductivity (Ks = 21.6 –93.6 cm/h). B horizon which is more clay has very low hydraulic conductivity (Ks = 0.007 - 0.9 cm/h). Tsujimura (1994) reported that infiltration rate is high in this area. The average of infiltration capacity is 260 mm/h. The soils have developed at an average depth of 1.8 m with maximum of 5 m.

The catchment is situated in the region of the humid temperate climate. The average annual air temperature is 6°C, and the monthly average of the daily minimum temperature of –5.8°C occurs in January. Mean annual precipitation is approximately 1500-1600 mm, producing 800-900 mm of runoff (Tanaka *et al.*, 1988a).

A natural deciduous forest of oak (*Quercus*

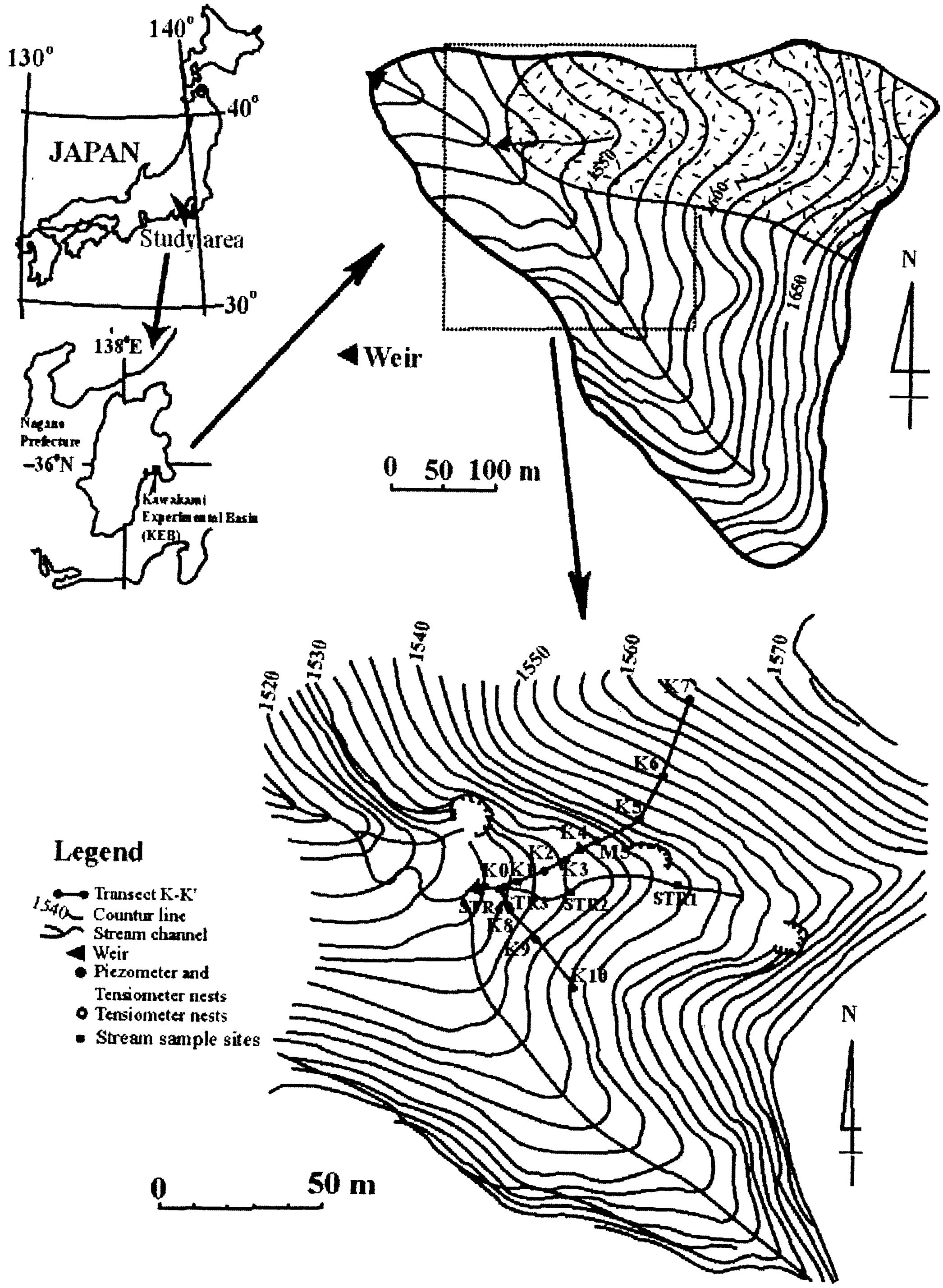

Fig. 1 Location of the study area showing the K-K'-transect

mongolica Fisch) occupies the northern part of the catchment and larch plantation (*Larix leptolepis* Gordon) covers the Southern part. The bamboo grass (*Sasa nipponica*) was very common in the surface of the hillslope side.

III Methods

(1) Experimental set up

The Kawakami catchment was instrumented for various hydrological studies since 1985. In the present study, the experimental cross section has been set up since August 2000 at the northern sub-catchment in the place where the riparian zone has prominently developed. This cross section has been instrumented with 12 nests of piezometer, tensiometer and suction samplers for intensive monitoring of groundwater and soil water flow as well as chemistry at various times and sites called K10, K9, K8, K0, K1, K2, K3, K4, M5, K5, K6, and K7 from the ridge of the southern hill slope to the ridge of the northern hillslope across the stream channel. Piezometers, tensiometers and suction sampler depths at every nest across the transect are presented in Table 1.

(2) Hydrometric measurements

Soil water potential and groundwater levels were recorded every two hours covering the whole process of the storm event. However, it was initiated that the groundwater recovery was slow, which inhibited the water sampling for chemical determination. Fortunately the storm occurred quite long, the recording was then extended to the period of 5 to 8 hours depending upon the amount of rainfall. Streamflow was continuously recorded at 30°V-notch gauging weir installed at upstream tributary of the northern valley of the catchment. Water level at weir is automatically recorded using data logger that was set every 10 min interval. Precipitation was measured using tipping bucket (recording) rain gauge placed at the climatological station located near the main weir.

In order to have continuous data of discharge, calibration curves was made by plotting data recorded from logger (express in volt) and the height of water level (express in cm) at the V-notch and height of water level against the discharge rate (Q).

(3) Water chemistry measurements

Groundwater, soil water, and stream water were collected at the same time with measurement of the soil water potential and groundwater levels and rain water was collected every two hours.

Groundwater samples were collected from the piezometer after groundwater level was measured, whereas soil water samples were collected from suction samplers installed at the same site with piezometer and tensiometer nests. The stream water samples were collected at upstream (STR1), middle between STR1 and STR3, the transect site (STR3), and near the sub-catchment weir (STR4). Water chemistry parameters were measured including Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Al^{3+}, Fe, SiO_2, Cl^{-} , SO_4^{2-}, NO_3^{-}, HCO_3^{-}, DOC (Dissolve Organic Carbon), DO (Dissolve Oxygen), ORP, pH, and EC at different places and time. Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Al^{3+}, Fe, SiO_2 concentrations were measured using ICP (Inductive Couple Argon Atomic Emmision Spectrophotometer), whereas Cl^{-}, SO_4^{2-}, NO_3 concentration were measured using Ion Chromatographic Analyzer (IC 7000 series II) at the Chemical Analysis Center of University of Tsukuba. Concentration of HCO_3^{-} was measured by titration with H_2SO_4. Although

Table 1 Depth of piezometers, tensiometers and suction samplers at each nest

	Depths (m)	Nests											
		K0	K1	K2	K3	K4	M5	K5	K6	K7	K8	K9	K10
Piezometers	0.5	*											
	1.0	*	*	*	*	*	*				*	*	
	1.3	*											
	1.5		*	*	*	*	*				*	*	
	1.85		*										
	2.0			*	*	*	*				*	*	
	3.0							*					
	3.85							*					
Tensiometers	0.2		*	*	*	*							
	0.3												*
	0.4		*	*	*	*							
	0.5						*	*	*	*	*	*	
	0.6												*
	1.0						*	*	*	*	*	*	
	1.5						*	*	*	*	*	*	
	2.0							*	*			*	
	3.0								*				
Suction samplers	0.3		*	*	*	*					*	*	*
	0.4							*	*	*			
	0.5		*	*	*	*	*						
	0.6										*	*	*
	1.0							*	*	*	*	*	
	1.1						*						
	1.5						*	*	*	*			
	2.0							*	*				
	3.0								*				
	4.0								*				

various chemical parameters were measured, not all of them are discussed but some, which have prominently changed during the hydrological process, are used.

(4) Hydrograph separation

Geochemical hydrograph separation was used to separate storm runoff into its process related components using the observed data of the August 21-22, 2001 storm during the typhoon no. 11. End-member mixing analysis (EMMA) using Ca^{2+} and SiO_2 was performed according to the procedure introduced by Hooper *et al.* (1990) to calculate the proportion of stream water from three principle source components of storm runoff. Both were chosen because there were differences between the end members and both often appeared in the stream. This approach was used with regard on the fact that all selected solutes assumed to be mix conservatively before reaching the stream channel under the condition of Kawakami catchment. In addition, the stream water chemistry is derived from the chemistry of each component with regard on the principle that water can pick up a chemical signature from each source area.

The first step of this analysis is the screening of data by plotting bevariate solute vs solute (mixing diagrams). This mixing diagram was made by generating solute vs solute plots of stream water for all combinations of the above parameters. Potential end-members were selected and plotted on the same graph. Mean and standard deviation of data for each end-member were calculated and then plotted on the same graph of solute vs solute of stream water.

It was observed in this catchment that the near surface riparian chemistry often appeared in the stream channel. The high solute concentration was observed in the deep riparian groundwater. The hillslope soil water was chosen because it was appeared dominantly in the stream during high-flow. It has also been clearly observed that near surface riparian (about 60 cm depth) water chemistry differed with that of the deep riparian groundwater. This variation leads to choose the near surface riparian water as the third component of potential end-member.

The contribution of each end-member to the storm runoff generation that is predicted by EMMA was, then, calculated based on the mass balance method for water and the total solute using the formula which is similarly used by Hinton *et al.* (1994) as follow:

$$Q_{NSR} = Q_T \frac{[(c_T - c_{DRG})(C_{HS} - C_{DRG}) - (C_{DRG} - C_T)(c_{DRG} - c_{HS})]}{[(c_{NSR} - c_{DRG})(C_{HS} - C_{DRG}) - (C_{DRG} - C_{NSR})(c_{DRG} - c_{HS})]} \tag{1}$$

$$Q_{DRG} = Q_T \frac{[(c_T - c_{NSR})(C_{HS} - C_{NSR}) - (C_{NSR} - C_T)(c_{NSR} - c_{HS})]}{[(c_{DRG} - c_{NSR})(C_{HS} - C_{NSR}) - (C_{NSR} - C_{DRG})(c_{NSR} - c_{HS})]} \tag{2}$$

Then, Q_{HS} was calculated optionally as follow:

$$Q_{HS} = Q_T \frac{[(c_T - c_{DRG})(C_{NSR} - C_{DRG}) - (C_{DRG} - C_T)(c_{DRG} - c_{NSR})]}{[(c_{HS} - c_{DRG})(C_{NSR} - C_{DRG}) - (C_{DRG} - C_{HS})(c_{DRG} - c_{NSR})]} \tag{3}$$

$$Q_{HS} = Q_T \frac{[(c_T - c_{NSR})(C_{DRG} - C_{NSR}) - (C_{NSR} - C_T)(c_{NSR} - c_{DRG})]}{[(c_{HS} - c_{NSR})(C_{DRG} - C_{NSR}) - (C_{NSR} - C_{HS})(c_{NSR} - c_{DRG})]} \tag{4}$$

Where Q is the water flow (discharge); c is concentration of Ca^{2+} and C is concentration of SiO_2; and NSR, DRG, HS, and T refer respectively to the inflows of near surface riparian, deep riparian groundwater and hillslope soil water and the combined total outflow. Similar with that done by Mulholland (1993), these equations were solved for every time at which there was stream water chemistry data over the entire storm hydrograph.

IV Results and discussion

(1) Sources of runoff

Geochemical hydrograph separation for the 143.5 mm storm showed that the near surface riparian, hillslope soil water and deep riparian groundwater were the major sources of storm runoff comprising 45%, 35% and 20% of the total runoff respectively (Fig.2). As depicted in Fig. 3, the near surface riparian dominated baseflow (87%), early on-set rain (58%), storm end (66%) and post storm (76%). This source area contributed less between the period of the peak and the end of storm, where the hillslope soil water was dominance. The deep riparian groundwater, which composed the major part of the saturated zone, has never dominated storm runoff although its contribution increased during the peak (41%) and when the storm ended (32%).

This finding differed with that found by Tanaka *et al.* (1988b) in the Hachioji basin near Tokyo, Japan, McGlynn *et al.* (1999) in the Sleepers Rivers Research Watershed, north-east Vermont, USA, where the groundwater was the most dominant contributor to runoff generation. From their research in Conventwald basin, Germany, Hangen *et al.* (2001) reported that stormflow supposedly is generated by rapidly responding groundwater, which is augmented by runoff from

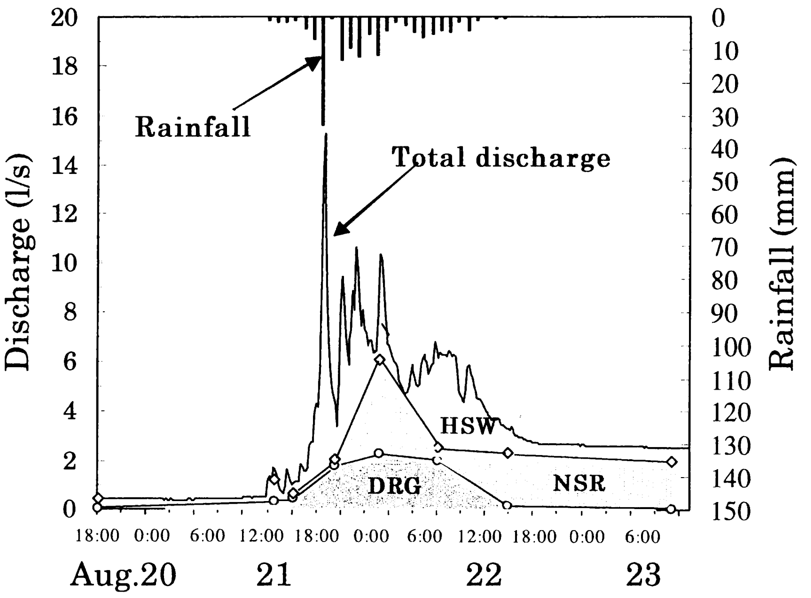

Fig. 2 Hydrograph separation for August 21-22, 2001 storm. DRG: deep riparian groundwater, HSW: hillslope soil water, and NSR: near surface riparian

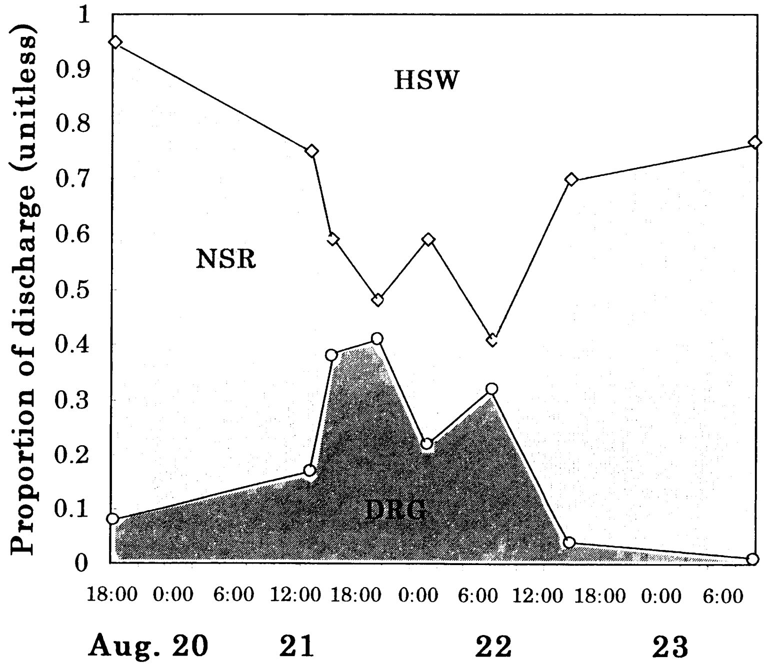

Fig. 3 Comparison of the relative importance of each runoff component during the period of August 21-22, 2001 storm. DRG: deep riparian groundwater, HSW: hillslope soil water, and NSR: near surface riparian. BF: baseflow, 2ST: 2 hrs after storm start, 1.5PS: 1.5 hrs after peak storm, SE: storm end, PoS: post storm

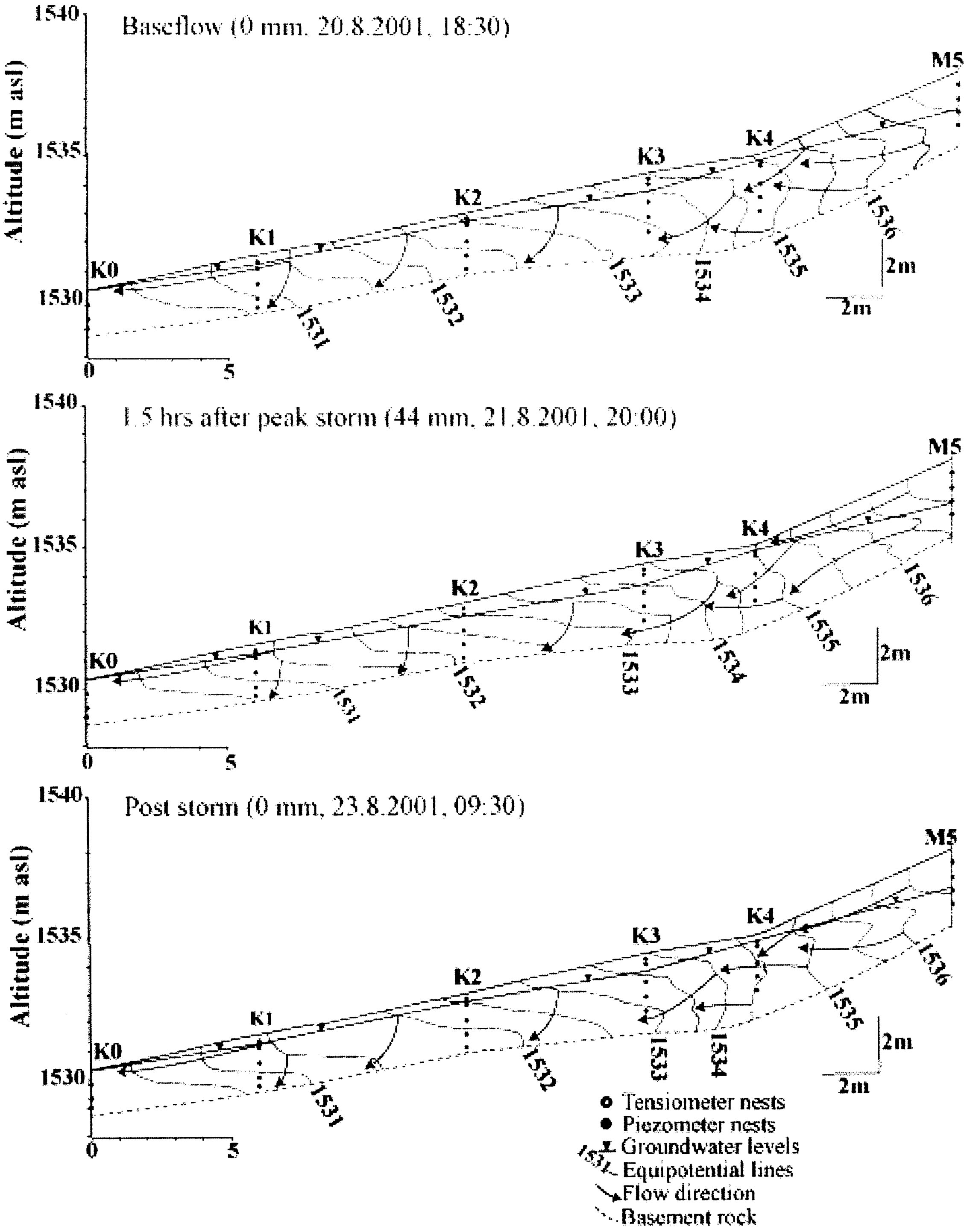

Fig. 4 Spatial and temporal variations of the riparian flowpaths

saturated areas. In Matsuzawa catchment, Shiga, Japan, Katsuyama *et al.* (2001) identified that the groundwater in the transient saturated zone (which may similar with the near surface riparian water in the present study), contributed much to the stream flow only when the groundwater level rose and the saturated zone spread.

(2) Variability of the riparian flowpaths

The spatial and temporal variations of water potential and flow line in the riparian zone are depicted in Fig. 4. Three distinct flowpaths were spatially identified during August 21-22, 2001 storm in the riparian zone including (a) lateral flow at the near surface riparian, (b) downward flow in the deep riparian groundwater and (c) variable flowpaths in the border between the riparian and the hillslope zones. During all consecutive period of storm, the flows in the near surface riparian remain laterally in the direction of the stream channel. Unlike the near surface riparian flowpaths, the deep riparian groundwater flowpath and the flowpath of the border changed arbitrary. The flow above the soil-bedrock interface developed laterally in the deep riparian groundwater zone as the storm was developed. However, this lateral flow did not give a quick response to the stream since it was reset by the downward flow, which was more dominance in this zone. These flow patterns were a bit difference with that found by Pionke *et al.* (1988). They found that the groundwater flow direction changed prominently in the shallow depth resulting in a development of the seep zone, but did not so in the deep groundwater when the storm developed. In addition, the lateral flow above the soil-bedrock interface was not observed. In the present study the direction of the near surface riparian flow did not change considerably.

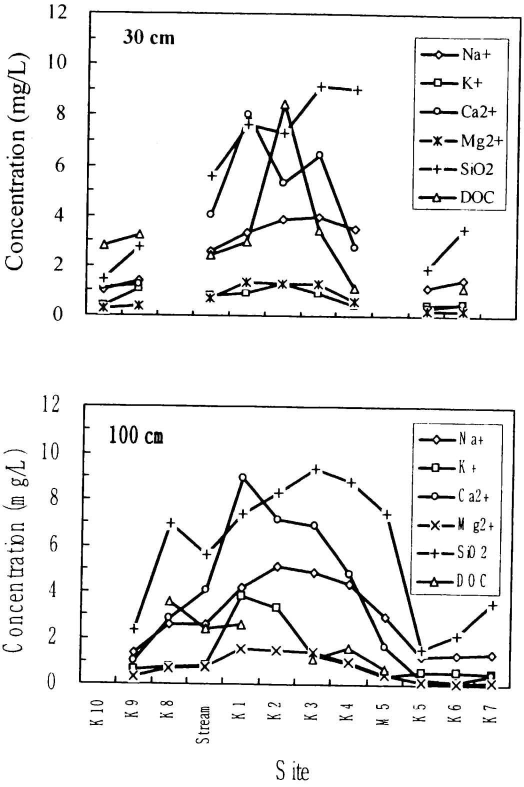

Fig. 5 Spatial variation of water chemistry across different end-member during August 21-22, 2001 storm

The upward gradient was developed at the border during the on set rain providing an increase in groundwater level in this zone. The flowpaths varied in this zone, which was due to the interaction between the hillslope and the riparian flow process. The flows were predominantly upward. This finding is similar with that found by McGlynn *et al.* (1999). They recognized a variable gradient existed at the break in slope, which suggested that the flow was variable in this zone. The influence of downslope flux of water from the hillslope on the sustained high water table has been documented.

The spatial variability in flow pattern has given various responses to the runoff generation process. The steady lateral flow of the near surface riparian may account for this zone to quickly response to the stream flow as the hydrograph separation data has shown that this zone was the most dominant contributor. The dominance downward flow in the deep riparian groundwater through out the period of storm could perform a delay response to the stream flow generation.

(3) Subsurface hydrochemical response to flow process

A significant distinct between the riparian and the hillslope chemistry is illustrated in Fig. 5. In general, solutes concentration in the riparian was much higher than those in the hilslope soil water. Ca^{2+}, SiO_2, SO_4^{2-} and DOC were identified to be the major solute component in the catchment. Ca^{2+} and SiO_2 concentrations have a similar trend either in the near surface riparian or in the deep riparian groundwater although the magnitude was difference. Those concentrations increased away from the stream and decreased in the border between the riparian and the hillslope. However, SO_4^{2-} concentration in the near surface riparian (0.3 m depth) was lower, whereas that in the deep riparian groundwater (1 m depth) was high, which has a similar trend with that of Ca^{2+} and SiO_2 concentrations. In addition, DOC concentration has an opposite trend with SO_4^{2-} concentration.

The change in those dominant solutes concentration was clearly controlled by the flow pattern. In the near surface riparian, where the lateral flow was relatively steady and sustained in the direction of the stream, could facilitate the flushing high concentration of solutes. This clearly occurred for SO_4^{2-} and DOC concentration. Account for the origin of SO_4^{2-}, which much probably from the dominant organic matter in the near surface riparian, its production should be high. The lower concentration of SO_4^{2-} in the near surface riparian attributed to the flushing.

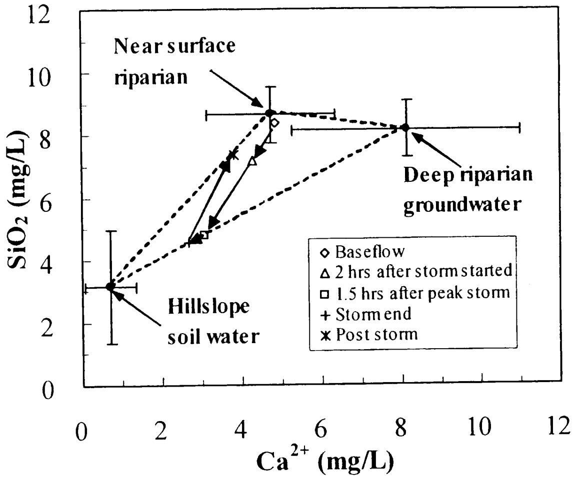

Fig. 6 Mixing diagram showing end-members contributing to the storm runoff and the change of stream chemistry during August 21-22, 2001 storm

Due to the relatively steady downward flow in the deep riparian groundwater zone, most of the solute was concentrated in this zone. The stream chemistry response to the deep riparian groundwater flowpath was very low suggesting that it was a little transport of solute to the stream.

(4) The role of near surface riparian in controlling stream chemistry

The present study proved that the near surface riparian was differed from the deep riparian groundwater and contributed significantly on the storm runoff generation. This finding was in accordance with that mentioned by Scanlon *et al.* (2001), that the use of a shallow subsurface component in catchment hydro- chemical models assumes that this reservoir is distinct from the groundwater zone and is a significant contributor to stream discharge.

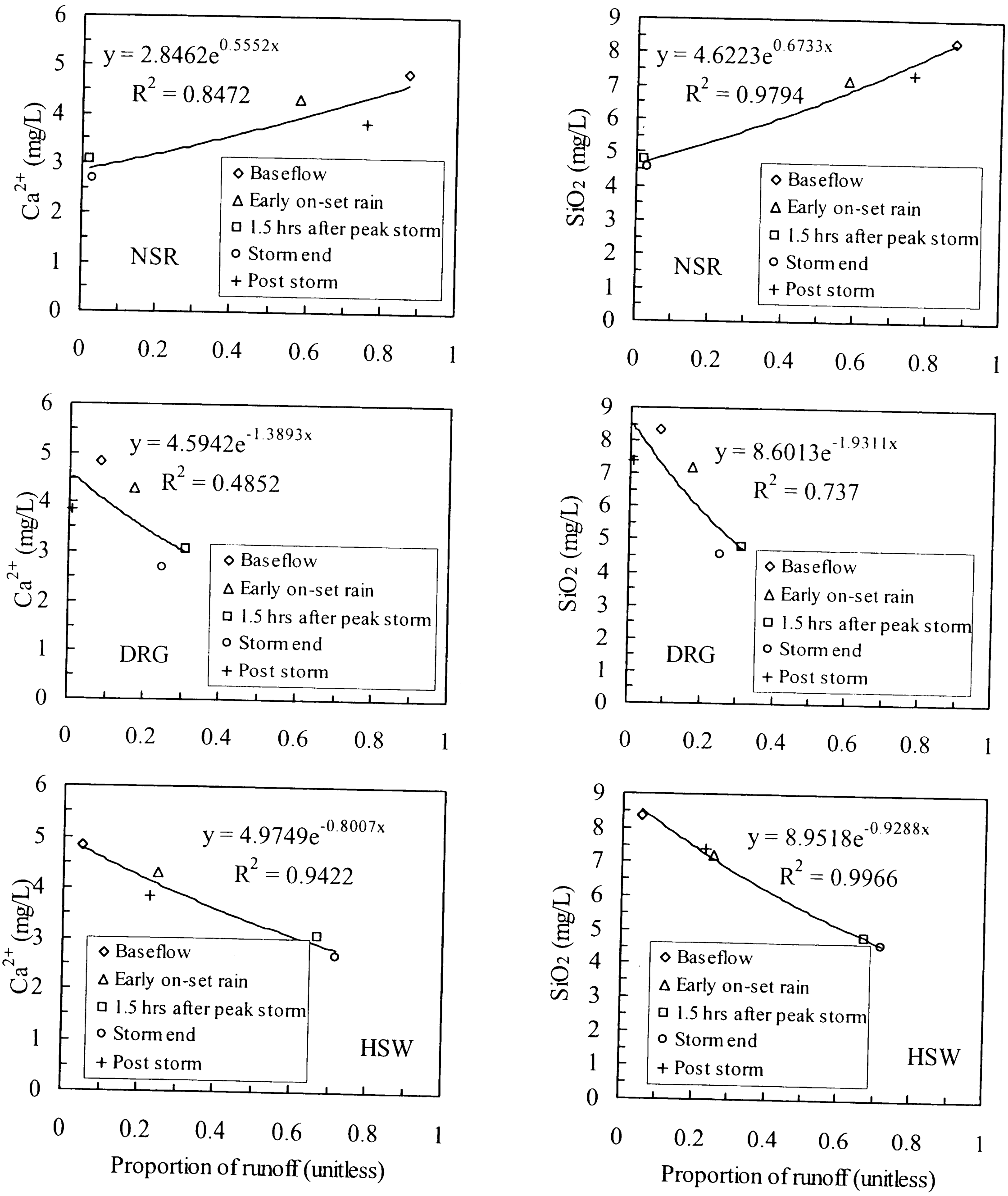

Fig. 7 Relationship between the relative contribution of the end-member to runoff generation and the change in stream chemistry during storm event on August 21-22, 2001. NSR : near surface riparian; DRG : deep riparian groundwater; HSW : hillslope soil water

Although the importance of storm flow zone on storm runoff generation has been documented (Scanlon *et al.*, 2000), the behavior of stream chemistry under the influence of this zone was poorly understood. Quantifying the role of the near surface riparian has not been done in the previous study since many studies concentrated in the riparian zone as a whole system.

It is proved in the present study that by geochemical hydrograph separation predicted by EMMA model showed that the riparian was not only a simple part of the cacthment but two importance parts of sources of runoff and chemistry were well characterized. Although some evidences included (a) the largest contribution of the near surface riparian to total storm runoff generation and (b) the relatively steady lateral flow near the stream might prove the fact that the stream chemistry appeared to be similar with that of the near surface riparian.

To define dynamic contribution of the near surface riparian to stream chemistry during the storm period, proportional contribution of this zone to storm runoff generation then plotted against the dynamic of stream chemistry. During large storm of August 21-22, 2001, stream chemistry was similar with that of the near surface riparian at baseflow condition, early on-set rain (2 hrs after storm started) and during post storm (Fig. 6). A positive correlation between its contribution to runoff and that to the change of stream chemistry suggests that intensively flushing of high concentration of solutes occurred in the near surface riparian. This was in contrast with those found in the deep riparian groundwater as well as in the hillslope, where the correlations were negative (Fig. 7).

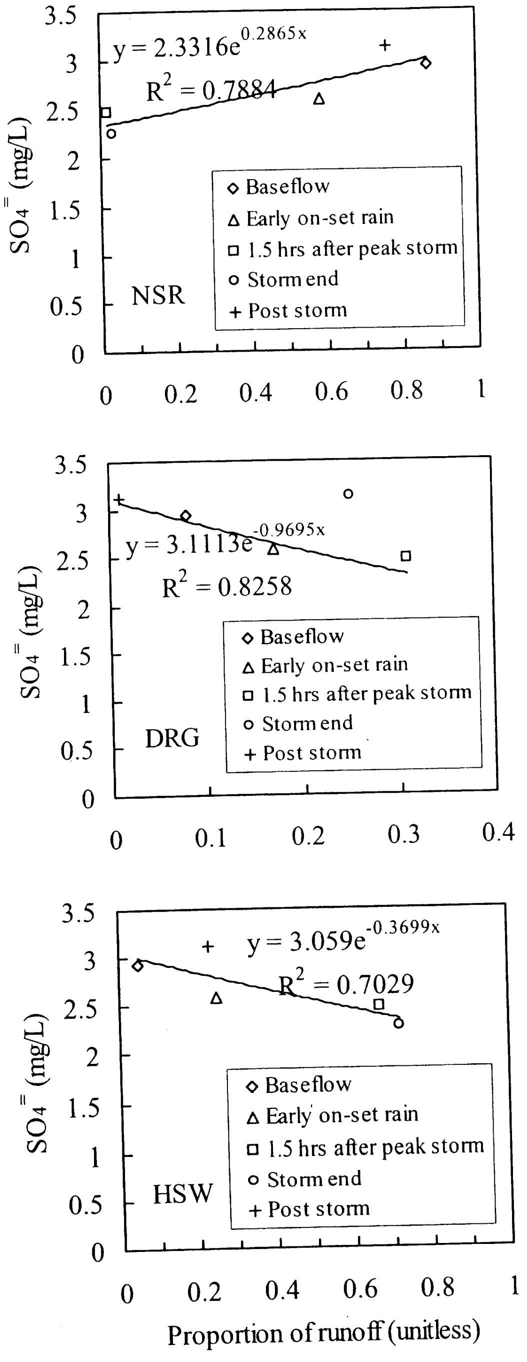

Fig. 7 (Continued)

V Conclusions

The significance of the near surface riparian on storm runoff generation and stream chemistry was clearly defined by the following evidences: (a) Based on the geochemical hydrograph separation, contribution of the near surface riparian was the largest (45% of the total of runoff) among the major sources of storm runoff, (b) the relatively steady lateral flow in the near stream channel that facilitated a quick response of water and solute transport to the stream channel, and (c) the near surface riparian chemistry appeared frequently in the stream channel during baseflow condition, early on-set rain and post storm. This zone also allowed the hillslope flowpath to connect with the stream channel during peak storm, as the chemistry of the stream water has shown similar with that of the hillslope water. This suggests that not all part of the riparian zone reset the hillslope flowpath as initiated in the previous study (for example, Robson *et al.*, 1992).

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