

## **Integration of tracer techniques and hydrometric approaches in catchment hydrology: research on hydrological processes in the Kawakami experimental basin, central Japan**

**TADASHI TANAKA**

*Institute of Geoscience, University of Tsukuba, Ibaraki 305-8571, Japan*  
e-mail: tadashi@atm.geo.tsukuba.ac.jp

**MAKI TSUJIMURA**

*Department of Environmental Earth Sciences, Aichi University of Education, Aichi 448-8542, Japan*

**Abstract** The Kawakami experimental basin, located in the mountain region of central Japan, has been monitored since 1985. Complex hydrological processes occurring in the forested mountain catchment were studied using both isotope and chemical tracers and hydrometric approaches. Tritium concentration data of soil water, groundwater, and stream water provided information on residence times of each as well as the mixing ratio of stream water with soil water and groundwater. Stable isotope data, such as deuterium and oxygen-18, showed the spatial characteristics of each stream water source. Additionally, hydrometric data including tensiometric and piezometric potentials revealed the physical dynamics of subsurface water in the catchment. All these data are necessary for consideration of flow mechanisms in the catchment, especially for stormflow and water quality studies.

### **INTRODUCTION**

In recent years, catchment hydrology has progressed rapidly through application of isotope and chemical tracer techniques. These techniques have provided the opportunity to better understand the temporal and spatial hydrological processes occurring in a catchment. For example, several efforts were made to estimate the relative importance of soil water during a storm event using the natural tracer approach (e.g. Dewalle *et al.*, 1988; Mulholland, 1993; Bazemore *et al.*, 1994). However, the precise mechanism of soil water contribution to streamflow and the soil water flow paths during a storm event are still unclear (Tanaka & Ono, 1998). Chemically-based natural tracers on water and solute movement studies in the vadose zone show also strong seasonal variations of concentration in shallow soil profiles (e.g. Barnes & Allison, 1988; Maule *et al.*, 1994; Liu *et al.*, 1995). Although these seasonal variations in shallow soil profiles may have profound effects on deep soil water and groundwater, the impact of these variations on the deep soil profile is poorly understood, and few studies have evaluated the effect of water movement processes on seasonal variations of solute.

In previous studies, little attention has been paid to the integration of tracer techniques with hydrometric approaches which provide information on physical aspects of hydrological processes. To clarify the complex hydrological processes

occurring in a catchment, it is necessary to combine both techniques from the process-oriented point of view.

The objective of this study is to demonstrate the importance of integrating tracer methods and hydrometric approaches to elucidate the hydrological processes occurring in a catchment, describing the results obtained from the Kawakami experimental basin, central Japan.

## STUDY BASIN

The study was conducted in a steep mountainous headwater catchment located in central Japan. The Kawakami experimental basin, shown in Fig. 1, has been a hydrological study site since 1985. The basin area is 0.14 km<sup>2</sup> with elevations ranging from 1500 to 1680 m a.m.s.l. Mean annual precipitation is 1450 mm, producing 830 mm of annual discharge. The basin is underlain by Neocene volcanic rocks. The soils have developed to a depth of 1.6 m on average, with a maximum depth of 6 m. The basin is densely forested with Japanese larch and oak.

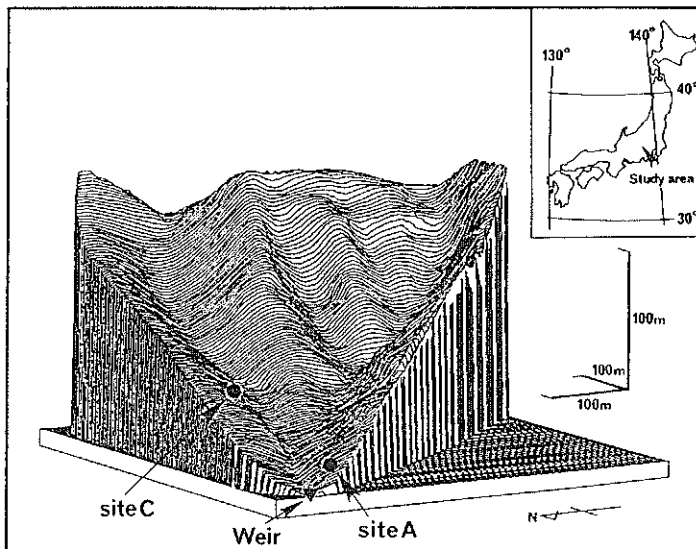


Fig. 1 Location of the study area.

## MAIN SOURCE COMPONENT OF STREAM WATER AND LINKAGE TO THE STREAM CHANNEL

In the study basin, annual stream water source components were determined based on tritium concentration data for soil water, groundwater, and stream water. Time series of tritium concentrations were monitored for 6 years for precipitation, 4 years for stream water, and 1 year each for soil water and groundwater (Matsutani *et al.*, 1993). On the basis of a dispersive flow model with a binomial distribution function,

representing the system function of the catchment, the residence times of soil water and groundwater were determined to be 4 months and 19 years, respectively. A simple mixing model was also applied to evaluate the mixing ratio of soil water and groundwater components to the stream water, assuming that stream water is a mixture of these two components. The results showed that the annual average mixing ratio of groundwater is about 33% of stream water as shown in Table 1. This means that the remaining 67% are derived from the soil water component, which has a short residence time.

**Table 1** Mixing ratio of soil water and groundwater to discharge water traced by tritium concentration with a mixing model (Matsutani *et al.*, 1993).

Date	Tritium concentration (TU):			Mixing ratio (%):	
	Discharge	Soil water	Groundwater	Soil water	Groundwater
June 1991	6.7	4.7	10.8	67	33
August 1991	6.6	5.8	9.9	80	20
October 1991	6.1	4.7	9.6	71	29
April 1992	6.1	4.7	7.5	50	50
June 1992	5.4	4.5	7.4	69	31

Flow components during a storm event in the catchment were determined by the hydrograph separation method using deuterium and oxygen-18 as tracers (Tanaka & Ono, 1998). The storm hydrograph produced by a total rainfall of 45.9 mm in September 1996 was separated into three physically-based source components. For the storm event, soil water contributed around 36% of the event discharge and nearly 52% of the peak discharge.

As mentioned above, isotope tracer studies conducted in the catchment can provide information on the source components of stream water, and stress the important role of soil water as the main component during both storm event and annual discharge. However, the mechanism explaining the rapid and large volume delivery of soil water to the stream channel is not discernible from isotope tracer studies alone.

In general, soil water cannot appear directly in the stream channel because soil water is held under negative pressure in the vadose zone. Before soil water reaches the stream channel, it is necessary to undergo the process of converting vadose water to phreatic water. To clarify this process and to confirm the flow path of soil water (vadose water) which feeds stream water, hydrometric techniques combined with the tracer method were carried out.

Tensiometer and piezometer nests were set intensively on the hillslope line close to site C shown in Fig. 1. Figure 2 shows the successive changes in potential difference between the baseflow condition and peak discharge. It can be seen from Fig. 2 that the transient saturated zone rises near the stream channel during the storm event. Rapid potential changes in both soil and groundwater zones are apparent from Fig. 2, conforming to the onset of rainfall. It is worth noting that the strong positive potential difference, represented by the black areas in Fig. 2, develops at the upper part of the transient saturated zone, and the parts of increased potential progress with time toward the stream channel. Figure 2 shows that during a storm event, the soil water draining from the hillslope does not enter deeply into the groundwater zone but flows laterally along the shallow upper parts of the transient saturated zone, and causes the strong

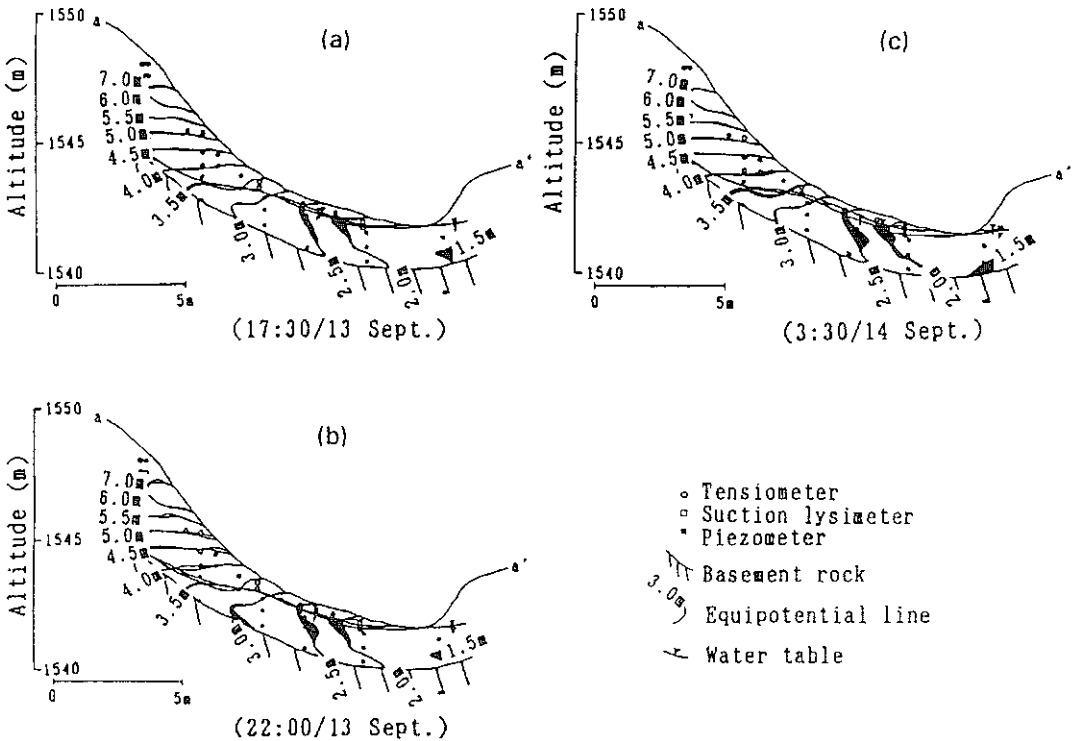


Fig. 2 Successive changes in potential difference along the hillslope during the storm event with a total rainfall of 45.9 mm in September 1996 (Tanaka & Ono, 1998).

increase in potential values in parts of the zone. Successive changes in potential distribution in the soil mantle confirm the flow path of the soil water component contributing to the stormflow. The development of a transient saturated zone at the foot of the hillslope is of importance, not only for considering the mechanism of stormflow generation but also for clarifying processes impacting on stream water quality.

### STABLE ISOTOPIC COMPOSITION PROFILE AND HOMOGENIZATION PROCESS IN VADOSE ZONE

It is well known that the isotopic composition of deuterium and oxygen-18 in precipitation widely fluctuates depending on the vapour source, its amount, and local climatic conditions. In contrast, the composition of these isotopes in groundwater and stream water in a catchment is fairly stable throughout a year. Figure 3 shows the trends in precipitation and stream water observed in the catchment. This figure indicates that the homogenization of isotopic compositions of water could operate during the water cycle in the catchment.

Figure 4 shows the variation of oxygen-18 of water profiles observed in the catchment from April to November 1991 at sites A and C shown in Fig. 1. The profiles show a relatively large seasonal variation at a depth of 70–100 cm below the surface.

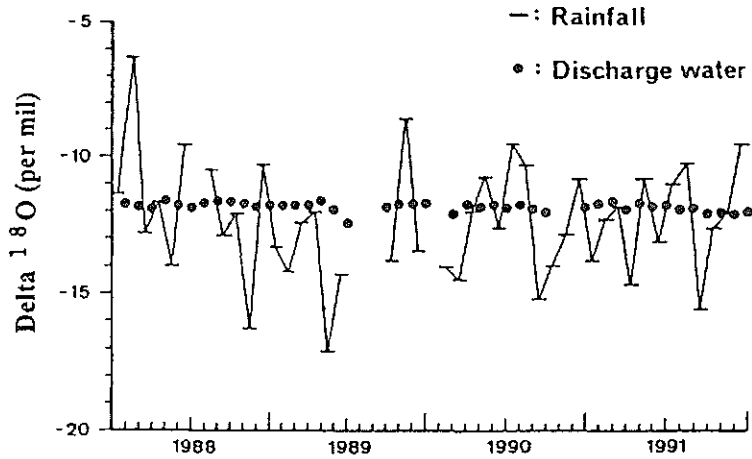


Fig. 3 Monthly variation of oxygen-18 in precipitation and discharge water (Tsujiura *et al.*, 1993).

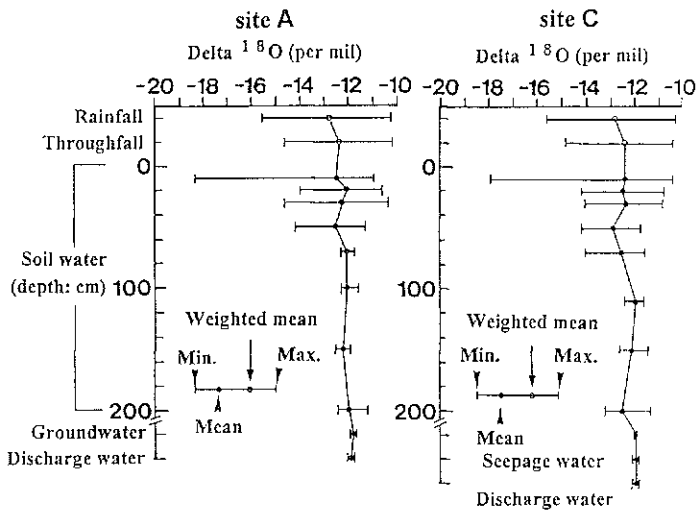


Fig. 4 Variation range profiles of oxygen-18 of waters at sites A and C observed from April to November 1991 (Tsujiura, 1994).

On the other hand,  $\delta^{18}\text{O}$  profiles of deep soil water show little change for all seasonal profiles, and tend to converge the value of groundwater or discharge water showing a constant value throughout the year. This indicates that the homogenization process for the stable isotopic composition in precipitation might occur within the shallow soil depth in the catchment. It seems that the dynamic soil water behaviour that occurred in the shallow soil profiles may have a profound effect on this process.

Figure 5 shows isopleths of potential distribution of soil water expressed by the hydraulic head at sites A and C during late summer in 1991. In this figure, positions of the divergent zero flux plane (DZFP) and convergent zero flux plane (CZFP) are also indicated. During the rainless period, DZFP is formed at the evaporation front in the vadose zone. The direction of soil water movement above DZFP is upward as it is

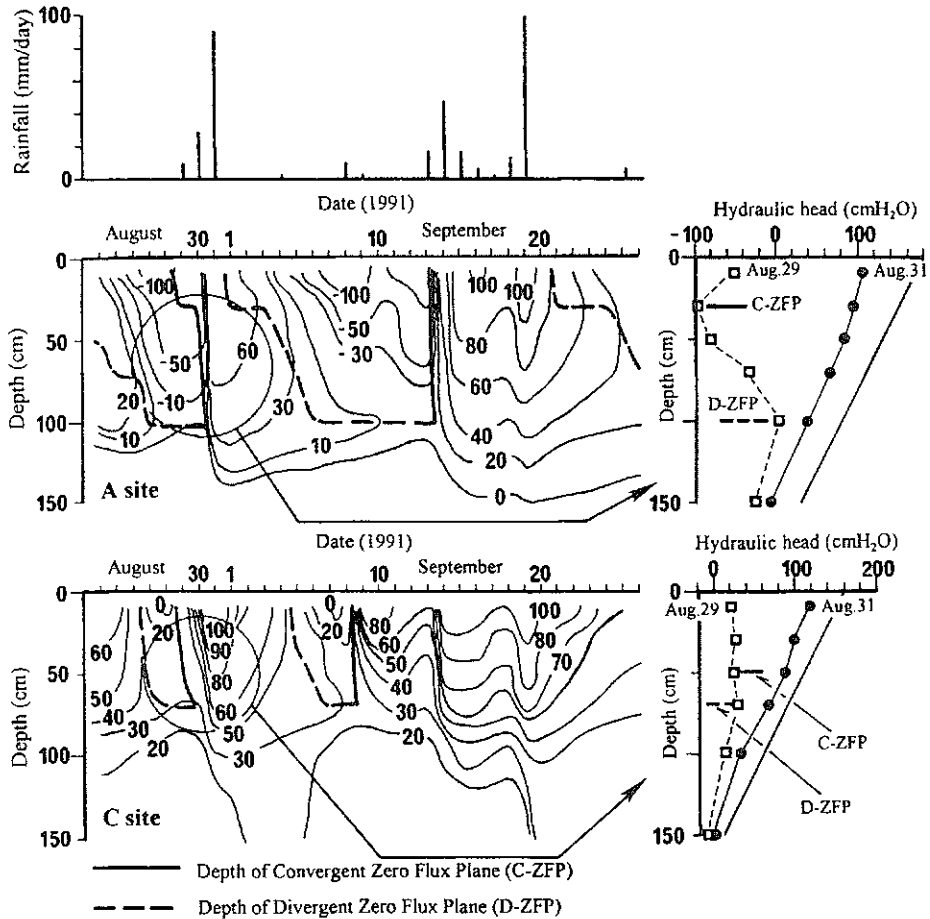


Fig. 5 Isoleths of potential distribution of soil water and positions of DZFP and CZFP at sites A and C in late summer 1991 (Tsujimura & Tanaka, 1998).

affected by the evaporation process, and therefore the isotopic composition of pre-event soil water may be enriched. On the other hand, with the onset of rainfall, CZFP appears at the soil surface and this plane moves downward with the wetting front which has the isotopic composition of the new rainwater.

As can be seen from Fig. 5, both planes appear cyclically between rainfall events. The maximum depth for developing DZFP is approximately 70–100 cm below the surface in the catchment (Tsujimura & Tanaka, 1998). This depth coincides well with the isotopic profiles which show large variation in the range of compositions represented in Fig. 4. Figure 5 shows that the top metre of the vadose zone is a dynamic zone; the direction of soil water and the corresponding water transport phase change cyclically between rainfall events. The isotopic profiles clearly demonstrate this behaviour. Similar phenomena were reported by Liu *et al.* (1995) in the desert area where the seasonal cyclic process is dominant.

The cyclic movement of soil water corresponding to the formation of DZFP and CZFP, which appear in the top dynamic vadose zone between rainfall events, can homogenize stable isotopic compositions of soil water before it is displaced to depth.

## CONCLUDING REMARKS

Integration of tracer techniques and hydrometric approaches adapted in the catchment made it possible to clarify important hydrological processes such as flow path of soil water during a storm event, the role of the formation of divergent and convergent zero flux planes in the homogenization processes of the stable isotopic composition of waters, and the importance of the near-stream riparian zone for water flow and streamwater quality.

The optimization of the combination of both techniques will be attained when applying both techniques simultaneously, and if we can interpret both types of data from the process-oriented point of view, we can clarify the black-box nature of hydrological processes occurring in a catchment.

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