Contribution of soil water and its flow path to stormflow generation in a forested headwater catchment in central Japan

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Abstract Hydrometric observations and natural tracer analysis were carried out in a small forested headwater catchment in central Japan in order to clarify the source component in stormflow generation and the actual flow path of the main component. The storm hydrograph produced by a total rainfall of 45.9 mm was separated into two and 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. Successive potential distribution maps of both soil and groundwater zones confirmed the flow path of soil water contributing to stormflow generation. The results show the important role of soil water in stormflow generation and illustrate the important place near the stream, maybe the riparian zone, for considering the mechanism of stormflow generation and the process by which the stream-water quality is formed.

INTRODUCTION

In the last decade, several efforts were made to estimate the relative importance of soil water using the natural tracer approach (e.g. DeWalle et al., 1988; Mulholland, 1993; Bazemore et al., 1994). The important role of soil water during a storm event has been stressed as a result of these studies. However, the feeding mechanism of soil water to stream channel and the soil-water flow path during a storm event have not yet been made clear and are cause for controversy.

The purposes of the present study are to estimate the source component of the stormflow generation based on two- and three-component hydrograph separation methods, and to confirm the flow path of the clarified main source component according to the continuous monitoring data of water potential in both soil and groundwater zones.

STUDY BASIN

The study was conducted in a steep humid headwater catchment in the central part of Japan (35°54.9'N, 138°30.2'E). The Kawakami experimental basin shown in Fig. 1 has been monitored since 1985. The basin area is 0.14 km² 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 covered with forest comprising Japanese larch and oak.

METHODS

In the catchment, the headwater region of the north valley was intensively instrumented as shown in Fig. 2. In this region, field data were collected from 13 to 17 September 1996. Stream discharge was monitored manually at 1-h intervals throughout the study period at a 30° V-notch weir, the location of which is shown in Fig. 2. Twenty piezometer nests were installed on the hillslopes to detect the development of a transient saturated zone in the soil mantle during the storm event. Tensiometer nests were also installed along the hillslope line a–a' represented in Fig. 2, to monitor the changes of pressure head of soil water. In total 13 tensiometers were set at different depths and sites. Thirteen ceramic cup suction lysimeters were set at five sampling sites along the hillslope line a–a'. Rainfall intensity was measured using a tipping-bucket raingauge located in an open space at the foot of hillslope.

Streamflow discharge samples were collected manually at 1-h intervals for the rising stage of the water level and at 3- to 6-h intervals for the recession period at the 30° V-notch weir. Suction lysimeter samples were retrieved manually from 3 to 6 h after suction was applied. Groundwater was sampled directly from the piezometer nests. Event water was sampled in a funnel-type rainfall collector at the cleared area at the foot of hillslope.

Stable isotopes of the water samples were measured by isotope ratio mass spectrometry (Mat 252 for D/H and Delta S for $^{18}$O/$^{16}$O analyses) at the laboratory of the Institute of Geoscience, University of Tsukuba. The total precision for D/H and $^{18}$O/$^{16}$O is ±1.0‰ and ±0.1‰, respectively.
The storm hydrograph was separated into two and three physically-based source components according to the mass balance of naturally occurring deuterium and oxygen-18.

RESULTS AND DISCUSSION

Isotopic concentrations in source components and hydrograph separation

Time variations of δD and δ18O concentrations in rain water and stream water are shown in Fig. 3 with the hydrograph of the storm. Isotopic concentrations of δD and δ18O in stream water were slightly diluted during the rising limb of the hydrograph and recovered gradually during the falling limb of the hydrograph. Pre-event baseflow appeared to be a good indicator of the pre-event groundwater, given that baseflow isotopic concentrations of -82% in δD and -11.9% in δ18O were similar to those of the averaged 12 different depths of piezometers during the study period.

The source components for the storm were isotopically distinct, as can be seen from Table 1. Two-component hydrograph separation method was used to determine the relative contributions of event and pre-event subsurface waters for the storm. The results of hydrograph separation using δ18O as a tracer indicate that the pre-event subsurface water occupies the dominant portion of stream discharge during the storm event. The relative contribution of pre-event subsurface water comprises more than 90% of the total discharge and ranges from 88% to 90% at the peak discharge. Similar results were obtained when using δD as a tracer.

In the present study, pre-event subsurface water was further separated into physically-defined source components, soil water and groundwater, by the three-
component hydrograph separation method. The results of three-component hydrograph separation are shown in Fig. 4. The results of the study indicate that the soil water component contributes nearly 52% at the peak of discharge and 36% of total volume during the analytical period represented in Fig. 4. On the other hand, the groundwater flow component contributes 38% at the peak of discharge and 51% during the same period as mentioned above. The results of three-component hydrograph separation suggest a rather important contribution of soil water in the storm event, especially at peak discharge.

**Hydrological response in soil mantle and flow path of soil water during the storm event**

Although several mechanisms have been proposed to explain a rapid response of pre-event subsurface water during a storm event, the feeding mechanism of soil water to the stream channel and the flow path of soil water during a storm event have not yet
been made clear.

Figure 5 shows potential distribution and the flow line of subsurface water before the onset of rainfall (baseflow condition) along the hillslope line of a–a′, as indicated in Fig. 2. It can be seen that at baseflow, the flow direction of soil water is nearly vertical in the direction of the water table and stream water is sustained by the upward flow of groundwater. After the onset of rainfall, subsurface water increases its potential value dynamically as shown in Fig. 6, where successive changes in potential distribution along the same lines as in Fig. 5 are represented. During the
rising of the hydrograph limb shown in Fig. 6(b), transient saturated zone rises near the stream channel and the soil water flow direction changes noticeably from vertical to horizontal toward the stream. Furthermore, it is worth noting that the draining soil water from the hillslope does not enter deeply into the groundwater zone but flows laterally along the shallow upper parts of the transient saturated zone. These flows may be caused by the strong increase in potential values in the transient saturated zone.

Figure 7 shows successive changes in potential difference between the baseflow condition shown in Fig. 5 and the corresponding time of Figs 6(a)–(c). Rapid potential changes in both soil and groundwater zones are obvious from Figs 6 and 7 conforming to the onset of rainfall, especially in the transient saturated zone. It also can be seen that the parts of increased potential in the transient saturated zone represented by the black areas in Fig. 7 progress with time toward the stream channel.

The standard deviation in isotopic concentrations of soil water collected at each depth in the transient saturated zone during and after the storm is rather small as summarized in Table 2, and the spatial and temporal variabilities of soil water are relatively stable throughout the storm event. This means that although displaced soil water enters once into the transient saturated zone before reaching the stream channel, good mixing of soil water with groundwater does not occur. As suggested by McDonnell et al. (1991), this may indicate that the subsurface reservoir is poorly mixed using the time scale of hours to days.
Table 2: Spatial and temporal variabilities of $\delta D$ and $\delta^{18}O$ in soil water collected in each depth in transient saturated zone during and after the storm.

<table>
<thead>
<tr>
<th>Sampling period</th>
<th>Depth below surface</th>
<th>$\delta D$ (%o) mean ± SD ($n$)</th>
<th>$\delta^{18}O$ (%o) mean ± SD ($n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13–15 September</td>
<td>20–50 cm</td>
<td>$-80.8 \pm 1.99$ (40)</td>
<td>$-11.84 \pm 0.18$ (42)</td>
</tr>
</tbody>
</table>

CONCLUDING REMARKS

The study shows the relative importance of the role of soil water in stormflow generation, and illustrates the dynamic behaviour of subsurface water conditions on the hillslope during the storm event. Successive changes in potential distribution in the soil mantle confirm the flow path of the soil water component contributing to the stormflow. Occurrence of this flow path during the storm event depends on the development of a transient saturated zone at the foot of the hillslope. In this context, the place near a stream channel, maybe the riparian zone, is of importance, not only for considering the mechanism of stormflow generation but also for clarifying processes impacting stream-water quality.

A mechanism explaining the rapid delivery of soil water to the stream channel during a storm event is not discernible from hydrograph separation analysis alone. Continuous monitoring of soil water potential conditions is of great importance for illustrating the black box of hillslope flow processes.
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REFERENCES


