RESIDENCE TIMES OF SOIL, GROUND, AND DISCHARGE WATERS IN A MOUNTAINOUS HEADWATER BASIN, CENTRAL JAPAN, TRACED BY TRITIUM

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ABSTRACT Water residence times in a mountainous headwater basin on the central of Japan were investigated using environmental tritium as a tracer. Time series of tritium concentrations were monitored for 6 years for precipitation, 4 years for streamwater, and 1 year each for soil and ground waters. Residence times estimated from a dispersive flow model of soil water and groundwater were about 4 months and 19 years, respectively. Water stored in the basin did not circulate uniformly, but streamwater was mixture of soil water having a short residence time and groundwater having a relatively long residence time. The fraction of groundwater in the streamwater mixture averaged about 30% annually as determined from a simple mixing model.

INTRODUCTION

It is important to investigate residence times of basin waters, such as soil water and groundwater, to evaluate water flow processes in a basin. Under steady state conditions, the residence time of water can be determined by a basin water balance, i.e. dividing the volume of basin water storage by the recharge/discharge fluxes. Normally, however, it is difficult to determine exact volumes of water stored in a basin. Therefore, the application of the water balance method is restricted to specific drainage basins where water storage can be determined accurately.

One excellent tool for determining the water residence time is environmental isotopes, such as deuterium ($^2$H), tritium ($^3$H) and oxygen-18 ($^{18}$O), because they are components of water molecules. In the last 20 years, environmental isotope tracer techniques have contributed remarkable new insight into the hydrologic processes in a drainage basin. Using these isotopes, storm runoff mechanisms and subsurface water dynamics have been recognized. The basic procedure for obtaining such informations is the analysis of relations between the isotopic input and output. The operational treatment of the isotopic functions is well denoted by the technique of the mean residence time calculation.

The objective of the study reported herein was to determine residence times of soil water, groundwater, and streamwater separately by evaluating the environmental tritium concentrations in each water type, and to evaluate the fraction of groundwater in the stream water.

STUDY BASIN

The study was conducted in a steep humid headwater basin on the central of Japan (35°54.9'N, 138°30.2'E). The Kawakami experimental basin (Fig. 1) has been monitored since 1985. The basin is a mountainous headwater area of 0.14 km$^2$ with elevations ranging...
from 1500 to 1680 m a.m.s.l. Mean annual precipitation is 1450 mm producing 830 mm of runoff.

The basin is underlain by Neocene volcanic rocks, called the "Meshimori-yama volcanic rocks" (Kawachi, 1977). The soils have developed to a depth of 1.6 m. The basin is densely covered with forests consisting of the Japanese larch (Larix leptolepis Gordon) and the Oak (Quercus mongolica Fisch).

**FIG. 1** Kawakami experimental basin showing water sample collecting sites, where: 1) Streamwater site (90° V-notch weir), 2) Precipitation site, 3) Soil water site, 4 & 5) Groundwater sites, and 6) Seepage water site.

**METHODS**

Samples of precipitation, soil water, groundwater, seepage water and discharge water were collected monthly for the determinations of tritium concentrations (Fig. 1). Precipitation was sampled at the basin outlet using a 210-mm diameter funnel connected to a series of 5 L bottles. Soil water was collected at the base of the slope of the north valley in the basin. Porous cups were installed to extract soil water at depths of 10, 20, 30, 50, 70, 110, 150 and 200 cm below the surface. To extract soil water at the depth, a suction of about 80 kPa was supplied using a vacuum hand pump through the collecting bottle. Groundwater was sampled directly from four piezometers distributed around the headwater of the basin. Piezometers were nested at two depths at the base of the slope and the valley bottom at 1.8 and 2.3 m, and 1.0 and 1.5 m below land surface, respectively. Seepage water was collected directly from the seepage face developed at the base of the slope of the north valley. Streamwater was collected at a gaging station consisting of the 90° V-notch weir at the basin outlet.

Tritium concentration were determined on each water in the laboratory of the Institute of Geoscience, University of Tsukuba. A 500-ml aliquot of each sample was distilled to exclude impurities of which 450-ml was enriched by an electolysis method until 15 ml of wa-
ter remained. The enriched sample was distilled again, and tritium concentrations in the final volume were measured by a Packard Liquid Scintillation Analyzer, 2000 CA/LL. The precision of the tritium concentrations ranged from 0.7 to 1.8 T.U. in the present study. The analytical method and corresponding errors for the tritium measurement system used in the study are described in detail by Shimada et al. (1992).

RESULTS AND DISCUSSION

The results of the annual basin water balance during the period from 1986 to 1991 are shown in Table 1. Based on these results, the residence time of water in the basin can be calculated by the following eqn.

$$T = \frac{H}{D}$$  (1)

where $T$ is the residence time of water (years), $H$ the mean height of basin water storage (mm) and $D$ the mean annual runoff (mm year$^{-1}$).

To calculate the residence time of the basin water based on eqn (1), steady state conditions were assumed. Also, the mean height of the basin water storage was assumed to be 720 mm, as determined from extensive field observations (Oginuma et al., 1988). The mean annual runoff was 830 mm (Table 1), and the average residence time of water in the soil mantle was estimated to be 0.87 years (about 10 months).

<table>
<thead>
<tr>
<th>Year</th>
<th>Precipitation (mm)</th>
<th>Runoff (mm)</th>
<th>Loss (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>1151</td>
<td>607</td>
<td>544</td>
</tr>
<tr>
<td>1987</td>
<td>1191</td>
<td>&gt;387</td>
<td>&lt;804</td>
</tr>
<tr>
<td>1988</td>
<td>1484</td>
<td>821</td>
<td>663</td>
</tr>
<tr>
<td>1989</td>
<td>1712</td>
<td>1058</td>
<td>654</td>
</tr>
<tr>
<td>1990</td>
<td>1358</td>
<td>&gt;503</td>
<td>&lt;855</td>
</tr>
<tr>
<td>1991</td>
<td>1837</td>
<td>&gt;954</td>
<td>&lt;883</td>
</tr>
</tbody>
</table>

Sub-surface water, generally, can be classified into two components, soil water and groundwater, and the discharge water from the basin can be considered as a mixture of these two components. Therefore, it is necessary to determine separately the residence time of these two components for obtaining average residence time of the streamwater mixture. The residence times of soil and ground waters were calculated separately by applying a dispersive flow model based on the tritium concentrations of each water type.

Time variations of tritium concentrations in precipitation, soil water, and groundwater are shown in Fig. 2. Tritium concentrations of precipitation ranged from 3.1 to 11.7 T.U. and varied seasonally with the highest concentration in spring and the lowest in fall or winter. This seasonal trend in tritium concentrations is similar to that observed at other sites in the northern hemisphere. Tritium concentrations of soil water were similar to those of precipitation and varied from 2.6 to 8.8 T.U. However, the concentrations in soil water decreased gradually with increasing depth. The concentrations in groundwater ranged from 6.4 to 11.9 T.U., which were higher than those of either the precipitation or soil water. Tri-
FIG. 2 Time variations of tritium concentrations in precipitation, soil water and groundwater in the study basin, where: 1) Precipitation, 2) Soil water (0.5-0.7 m depths), 3) Soil water (1.1-2.0 m depths), 4) Groundwater at the base of the slope (1.8 m depths), 5) Groundwater in the valley bottom (1.5 m depths), and 6) Discharge water.

Tritium concentrations of streamwater varied from 5.4 to 10.5 T.U. which were intermediate between those of soil water and groundwater.

To calculate the time series of tritium output ($C_{out}$), the input ($C_{in}$) was transformed by a convolution integral as follows:

$$C_{out}(t) = \int_0^\infty C_{in}(t-t') g(t') \, dt$$

(2)

where $C_{out}(t)$ and $C_{in}(t)$ are the output and input concentrations, respectively, $g(t)$ is the system response function, which specifies the transit time distribution of water within the system (e.g. Zuber, 1986), and $t$ is time and integration is carried out over the transit times($t'$).

To apply eqn. (2) to the present study, we assumed that water flow was at a steady state, but that dispersion occurred. Therefore, a binomial distribution function was used as the system function. Thus, the tritium time-series output was calculated as follows:

$$C_{out}(t) = \sum_{x=0}^{n} C_{in}(t-T) e^{-\lambda T} \frac{n!}{x! \{n-x\}!} \left(\frac{1}{2}\right)^x$$

(3)

where $C_{out}(t)$ and $C_{in}(t)$ are the tritium concentrations of input and output waters, respectively; $\lambda$ is the decay constant of tritium; $T$ is the residence time of water; and $n$ the dispersion factor. The tritium concentrations of Tokyo and Tsukuba's precipitation were used as the input for the period from 1953 to 1987 with a monthly time step.
The time series of tritium concentrations of the output for soil water and groundwater, as calculated from eqn (3), are shown in Fig. 3 as well as the observed data. After the parameterization of eqn (3), the residence time for the soil water that was distributed from 0.5 to 2.0 m depths below land surface was calculated to be 4 months and that for groundwater was 19 to 20 years.

![Diagram showing model outputs and observed data for tritium concentrations over time.]

**FIG. 3 Comparisons of model outputs calculated from eqn (3) where: 1) Soil water (0.5-0.7 m depths), 2) Soil water (1.1-2.0 m depths), 3) Groundwater at the base of the slope (1.8 m depths), and 4) Groundwater at valley bottom (1.5 m depths).**

For the soil mantle, the residence time was estimated by the water balance method to be about 10 months. Although the tritium results suggest a somewhat shorter residence time, the results of the two methods agreed quite well. Stewart and McDonnell (1991) have reported that residence times of soil water in the M8 basin on the South Island of New Zealand ranged from 13 to 63 days as determined from deuterium concentrations in soil water. The residence time of soil water in the Kawakami experimental basin was longer than for the M8 basin of Stewart and McDonnell.

As mentioned previously, tritium concentrations of streamwater fell between those of soil water and groundwater (Fig. 2). If we assume that streamwater was a mixture of these two components, a simple mixing model can be applied to calculate the contribution of each component to the streamwater as follows:
\[ C_d = (1 - x) C_s + x C_g \]  
\[ x = \frac{(C_d - C_s)}{(C_g - C_s)} \]

where \( C \) is the tritium concentration and \( x \) the fraction of groundwater in the mixture. Subscripts, \( s \), \( g \), and \( d \) denote soil water, groundwater, and streamwater, respectively. Eqn (4) is the difference equation for an exponential distribution.

**TABLE 2 Mixing ratios of soil and ground waters using the mixing model.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Tritium concentration(T.U.)</th>
<th>Mixing ratio(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Discharge</td>
<td>Soil water</td>
</tr>
<tr>
<td>June 1991</td>
<td>6.7</td>
<td>4.7</td>
</tr>
<tr>
<td>August 1991</td>
<td>6.6</td>
<td>5.8</td>
</tr>
<tr>
<td>October 1991</td>
<td>6.1</td>
<td>4.7</td>
</tr>
<tr>
<td>April 1992</td>
<td>6.1</td>
<td>4.7</td>
</tr>
<tr>
<td>June 1992</td>
<td>5.4</td>
<td>4.5</td>
</tr>
</tbody>
</table>

The tritium concentrations of the two components and streamwater, and the fraction of components derived from eqn (5) are listed in Table 2 for 5 sampling periods. The contribution of groundwater in the mixture varied from 20 to 50% depending on climatic conditions for each period, and averaged about 33% of streamwater. Consequently, the remaining 67% of the streamwater was derived from soil water which had a short residence time in the basin.

Mean residence times of the streamwater (mixture) for each period were calculated as follows:

\[ t' = \frac{1}{ln(1-x)}; \text{ in years} \]

A mean residence time of 2.5 years was obtained for the streamwater. Sanjo (1987) determined mean residence times of discharge water at base flow conditions for 40 small headwater basins distributed around the Kanto district, Japan, by the tritium tracer method. On average, the residence times for these basins was 5 year, which was similar to that computed for the streamwater in the study herein.

**CONCLUDING REMARKS**

The results of the study demonstrated that tritium concentrations of basin waters, such as precipitation, soil water, groundwater, and streamwater, were distinctively different. The residence times of soil water and groundwater based on the dispersive flow model were estimated to be 4 months and 19 years, respectively. Therefore, waters stored in the basin did not circulate uniformly. However, streamwater was a mixture of soil water, which had a
short residence time, and groundwater, which had a relatively long residence time. The apparent residence time of this mixture was computed to be about 2.5 years. According to a mixing model, the contribution of groundwater in streamwater was about 30% annually.

The mixing process or the flow mechanism of a large fraction of the soil water contributing to streamflow is not still obvious. The subject of this point is an important problem to be solved in a future study.

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REFERENCES


