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SEPARATION OF RUNOFF COMPONENTS BY HYDROLOGICAL AND GEOCHEMICAL METHODS

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SYNOPSIS

Two types of separation of runoff are carried out for runoff in a small mountainous basin. One is the separation into channel precipitation and lateral inflow by the kinematic wave method. The other is the separation into current rain water and groundwater by the tracer method using $\delta^{18}O$.

The results of the analyses of $\delta^{18}O$ show that almost all of the direct runoff is originated from groundwater. The rain water component is almost equal to the channel precipitation runoff estimated by the k.w. method. Observed permeability of the soil shows that the direct runoff is possible to occur as groundwater. These facts can be the clues to understand runoff phenomena and to build a more realistic runoff model.

INTRODUCTION

In modeling of rainfall-runoff phenomena, the runoff is usually understood to consist of several components, i.e. surface runoff, subsurface runoff and groundwater runoff. This understanding is used as the basis of almost all runoff models. However, it is difficult to distinguish these three components, because the runoff discharge is observed as the summations of the outflows from numerous hillslopes and channels and the runoff occurs mainly as subsurface flow. Therefore, this separation is usually done based on the characteristics of the hydrograph, i.e. the exponential recession or the change of the gradient of hydrograph, etc.(1)

This fact means that the current method of the separation is not physical but conceptual. So the runoff separation based on the physical consideration is strongly needed both for the correct understanding of the phenomena and for the appropriate runoff modeling.

On this point of view, several types of runoff separation are discussed for the runoff from a small mountainous watershed. Firstly, the channel rainfall runoff is separated by the kinematic wave method, because this component is rather clearer than other components. Secondly, the runoff is separated by the tracer method in which $\delta^{18}O$ is used as the tracer.

EXPERIMENT BASIN

Figure 1 shows the location and the shape of Kanedaira experiment basin (Ena, Gifu Pref., Japan) in which the hydrological data have been observed since 1982.

This basin is a small mountainous watershed whose area is 0.078 Km^2. The main channel length is 500 m and average channel slope is 14 degrees. The shape of the basin is rather rectangular with uniform width except in the upper region where water courses are relatively radial. The mean slope length is about 80 m and slope angle is about 30 degrees.

The geology of this basin is Ryoke granite, and the boring data obtained at the vicinity of the basin show that the granite is deeply weathered. The surface of the hillslope is covered by Brown Forest Soil (Bb) and the total thickness of A- and B-layer is about 1m. The vegetal cover of this basin is mainly Japanese cedar and Japanese cypress, except locations of land slide in upstream area.

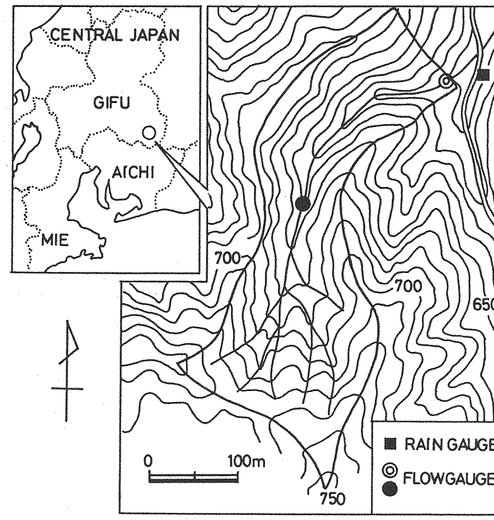

Fig.1 Experiment basin

Mean annual rainfall of this district is about 1745 mm. Runoff ratio of total runoff (from April to December) of this basin is 55 percent and runoff ratios of direct-runoff are ranging from 1.5 to 18.5 percent. Therefore this basin is very permeable and has a large amount of groundwater capacity.

Rainfall, discharges at two locations and the concentration of isotope ^{18}O are measured in this basin. The rainfall is measured by a tipping bucket rain gauge (0.5 mm per pulse) at the location marked by filled rectangle shown in Fig.1. The discharges are measured by Partial Flumes located at upstream and downstream points marked by filled circle and double circle, respectively. Samples of rainwater and outflow water are collected and concentration of ^{18}O is measured at Water Research Center, Nagoya University.

ANALYSIS

The Separation of Lateral Inflow from Hillslope based on Kinematic Wave Method

The rain water that falls on the basin comes out in various manner. One that falls on a slope infiltrates and percolates along the slope flowing out into a channel and then flows down the channel to the outlet. The other that falls on the channel and in its vicinity flows down directly to the outlet as the channel precipitation runoff. Although these different runoff components flow together,the phenomena themselves are the open channel flow which are relatively easy to analyze.

On this point of view, the total runoff is separated into the channel precipitation runoff and the lateral inflow based on the kinematic wave method. The fundamental equations of the open channel flow as the kinematic wave approximation are the continuity equation (Eq.1) and the equation of motion (Eq.2) shown below;

$$\partial A/\partial t + \partial Q/\partial x = r \cdot B + q_L \qquad (1)$$

$$A = kQ^p \qquad (2)$$

where A and Q are the cross sectional area and the discharge at the location x and time t,respectively, r is rainfall rate, B is channel width including the area which contributes to the channel precipitation runoff, and q_L is the lateral inflow rate from the hillslopes. In this analysis, the lateral inflow is assumed as uniform along the channel.

In Eq.2, k and p are constants and are estimated so that the relationship (Eq.3) between flood propagation time T_L and discharge Q mimic the observed data. Equation 3 derived from Kleitz-Seddon law and Eq.2 is shown below;

$$T_L = L \cdot k \cdot p \cdot Q^{p-1} \qquad (3)$$

Here L is length of the channel reach where T_L is observed. In Figure 2, the observed data (plots) and the estimated relationship(Eq.3) are shown. The identification of k and p by Eq.3 is rather difficult for real storm runoff, because the lag times between peaks of upper and lower hydrographs are usually affected by the lateral inflow. Therefore, the propagations of artificially produced disturbances of water surface are observed. The data obtained are plotted in Fig.2 and fitted line of Eq.3 is also drawn in the figure. The estimated values of k and p are k=1.18 ,p=0.606 in this channel reach.

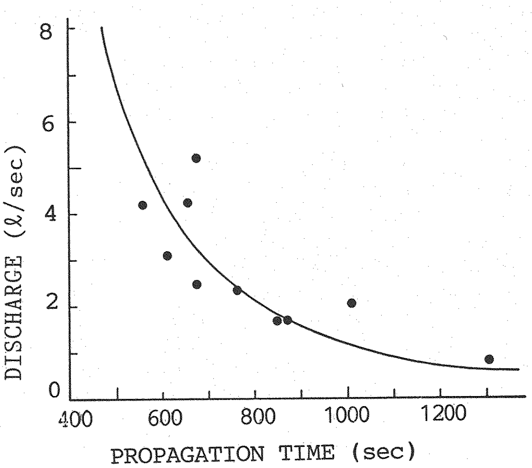

Fig.2 Q-T_L relationship

Channel width is a very important parameter to determine the amount of channel precipitation runoff. Although it varies in space and time, here it is assumed constant throughout the runoff. As the channel precipitation runoff comes out so quickly compared to the lateral inflow from a slope, the value of channel width affects rising stage of a hydrograph. Therefore, channel width B estimated by the field survey is corrected by this characteristic.

As for the boundary and initial conditions, the observed upstream discharge is used as the upper boundary condition, and the initial discharge is assumed to vary linearly along the channel.

Equations 1 and 2 are solved numerically for the channel reach between upstream and downstream points according to these initial and boundary conditions with unknown lateral inflow $q_L(t)$. Here $q_L(t)$ is estimated by trial and error method, comparing the calculated discharges with the observed ones at outlet.

The separation of runoff components based on $\delta^{18}O$

In case that each runoff component,i.e., surface runoff, subsurface runoff or groundwater runoff has significant difference in its quality characterized by its source area, it is possible to distinguish these components by using their property as the tracer. There are many kinds of tracer used for this purpose, for example, specific electric conductivity(6), radioactive isotopes (^{18}O, D)(3)(7), NO_3-N (2)(8), and inorganic ions(Fe, Ca)(4), etc. As the preferable tracer,it is required that the substance will not change its chemical characteristics during the runoff process. The tracer used in this research is a naturally existing stable isotope of oxygen ^{18}O and it satisfies this requirement. The isotope ratio $^{18}O/^{16}O$ is measured and expressed in delta unit $\delta^{18}O$ which is defined by Eq.4.(5)

$$\delta^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{SMOW} - 1\ ] \times 1000 \qquad (4)$$

where suffix SMOW denotes the Standard Mean Ocean Water. The value ($^{18}O/^{16}O$) denotes the ratio of the number of ^{18}O and ^{16}O existing in the water. The accuracy of the $\delta^{18}O$ is better than ±0.1.

To separate a runoff discharge by using a tracer, Eq.7 is usually used which is derived from the conservation equations of water and the tracer expressed by Eq.5 and Eq.6, respectively.(3)(4)

$$Q_T = Q_S + Q_G \qquad (5)$$

$$C_T \cdot Q_T = C_S \cdot Q_S + C_G \cdot Q_G \qquad (6)$$

$$Q_S = Q_T \cdot (C_T - C_G)/(C_S - C_G) \ ; \qquad Q_G = Q_T \cdot (C_T - C_S)/(C_G - C_S) \qquad (7)$$

where, Q and C denote the discharge and the concentration of the tracer,respectively. The suffices S,G and T denote the components of current rain water, groundwater originated from the previous rain water and total runoff discharge, respectively. C_S is the concentration of rain water and C_G is the concentration of groundwater which is observed before and after the storm. C_T and Q_T are corresponding observed values during the storm.

In this algorithm there are mainly two problems. The first is that C_S and C_G are assumed to be constant during the storm. In this connection, observed data show that values of C_G before and after the storm are equal in this basin, however values of C_S sometimes change during the storm. The second problem is that this method can be used only at times when C_T is observed.

To solve these problems, a new algorithm is proposed. In the new method, the delay of the tracer in the rainfall is expressed in the form of linear response model similar to the unit-graph method. Equations 8 and 9 express the components Q_S and Q_G which correspond to the tracers C_S and C_G, respectively. The conservation equations of the tracer and the water are expressed by Eqs.10 and 11,respectively.

$$Q_S(t) = \int_{-\infty}^{t} K_S(t-\tau) \cdot r(\tau) d\tau \qquad (8)$$

$$Q_G(t) = \int_{-\infty}^{t} K_G(t-\tau) \cdot r(\tau) d\tau + Q_0 \qquad (9)$$

$$Q_T(t) = \int_{-\infty}^{t} K_S(t-\tau) \cdot r(\tau) d\tau + \int_{-\infty}^{t} K_G(t-\tau) \cdot r(\tau) d\tau + Q_0 \qquad (10)$$

$$C_T(t) \cdot Q_T(t) = \int_{-\infty}^{t} K_S(t-\tau) \cdot C_S(\tau) \cdot r(\tau) d\tau + \int_{-\infty}^{t} K_G(t-\tau) \cdot C_G \cdot r(\tau) d\tau + C_G \cdot Q_0 \qquad (11)$$

where $K_S(\tau)$ and $K_G(\tau)$ are the kernel functions for the components of rain water and groundwater, respectively, and Q_0 is the constant part of the groundwater component $Q_G(t)$. In these equations, unknown variables have changed from Q_S and Q_G to $K_S(\tau)$ and $K_G(\tau)$. From Eqs.10 and 11, Eq.12 is derived by eliminating $K_G(\tau)$ and Q_0.

$$Q_T(t) \cdot (C_T(t) - C_G) = \int_{-\infty}^{t} K_S(t-\tau) \cdot (C_S(\tau) - C_G) \cdot r(\tau) d\tau \qquad (12)$$

Equation 12 is the convolution equation of unknown kernel function $K_S(\tau)$and can be solved for $K_S(\tau)$ by similar procedure of unit-graph method.

After $K_S(\tau)$ is obtained, $Q_G(t)$ is calculated from Eq.10, and $K_G(\tau)$ and Q_0 can be obtained by the same way as $K_S(\tau)$. Here it should be noted that the kernel functions $K_S(\tau)$ and $K_G(\tau)$ are not the unit-graphs themselves because they do not satisfy the conditions:

$$\int_0^{\infty} K_S(\tau) d\tau = A_B \ ; \qquad \int_0^{\infty} K_G(\tau) d\tau = A_B \qquad (13)$$

where A_B is the area of a basin. In this sense, the forms of Eqs.8 and 9 are not the physically based expressions. The physical meaning of the runoff process should be discussed based on the results of the separation.

The separation of the channel precipitation runoff by the tracer

The methods explained above are anyway the ones to analyze the phenomena as lumped system. In order to understand the phenomena, it is more helpful to analyze them as the distributed system ,in other word, as the flow process.

On this point of view, the following expressions (Eqs. 14 and 15) of the flow process of the water and the tracer are introduced.

$$Q_T(t)= \int_0^{Lc} \left[r(t-\tau_c(x))\cdot B + 2\cdot\int_0^{Ls} f(s)\cdot r(t-\tau_c(x)-\tau_s(s))ds + q_G(t-\tau_c(x))\right]dx \tag{14}$$

$$Q_T(t)\cdot C_T(t) = \int_0^{Lc}\left[r(t-\tau_c(x))\cdot C_S(t-\tau_c(x))\ B + 2\cdot\int_0^{Ls} f(s)\cdot r(t-\tau_c(x)-\tau_s(s))\cdot C_S(t-\tau_c(x)-\tau_s(s))ds + q_G(t-\tau_c(x))\cdot C_G\right]dx \tag{15}$$

where Lc and Ls are channel length and slope length, respectively. $\tau_c(x)$ denotes the lag time from a location x in the channel to the down stream end, and $\tau_s(s)$ denotes the lag time from a location s on the slope to the nearest channel. f(s) is the runoff ratio of the rainfall at the location s on the slope. The term $r(t-r_c(x))\cdot B$ in Eq.14 corresponds to the channel precipitation, and the second term under intergral denotes the lateral inflow of current rain water. The term $q_G(t- \tau_c(x))$ is the lateral inflow of previous rain water. By eliminating the term q_G from Eqs.14 and 15, the Eq.16 similar to Eq.12 is obtained.

$$B\ R(t)+2\ \cdot\int_0^{Ls}f(s)\cdot R(t-\tau_s(s))ds = Q_T(t)\cdot(C_T(t)-C_G) \tag{16}$$

$$R(t)= \int_0^{Lc}[C_S(t-\tau_c(x))-C_G]\cdot r(t-\tau_c(x))dx \tag{17}$$

If it is assumed that the velocity of channel flow is constant during the storm, the lag time $\tau_c(x)$ is expressed by Eq.18.

$$\tau_c(x)= \int_0^{Lc}(1/v(x))dx = (k/p)\cdot(\overline{Q}_T/Lc)^{p-1}\cdot(Lc^p-x^p) \tag{18}$$

In the derivation of Eq.18 the velocity v(x) is evaluated by Eq(2) and relationship $Q = A\cdot v$ based on the assumption :

$$Q(x)=\overline{Q}_T\cdot(x/Lc) \tag{19}$$

where $\overline{Q}_T$ is the average downstream discharge.

RESULTS OF THE ANALYSIS AND DISCUSSIONS

The data analyzed here are concerning to the runoff caused by the storm occurred on September 17 and 18, 1986. This case is a relatively small runoff with total rainfall of 34 mm. During these days there occurred three groups of rain events with different values of $\delta^{18}O$. Figure 3 shows the observed hydrograph Q_T(solid line), hyetograph r(t) and values of $\delta^{18}O$ sampled from the total runoff C_T(filled circle) and rainfall C_S (blank circle with straight line). Here C_G is equal to C_T at the low flow before and long after the storm.

The separation by the kinematic wave method

Through the numerical analysis based on the kinematic wave method the channel width B and the lateral inflow $q_L(t)$ to the channel are estimated. The estimated value of B is 1.0 m. This value is reasonable referring to the field survey. According to this value, the ratio of channel precipitation runoff compared to the direct runoff is about 20 percent, where direct runoff is considered as the part of the discharge which exceeds the initial discharge.

The estimated total lateral inflow to this channel reach is shown in Fig.4. The result shows that the lateral inflow is similar to the upstream and downstream hydrographs, and consists of the base flow and the direct runoff of the traditional meaning.

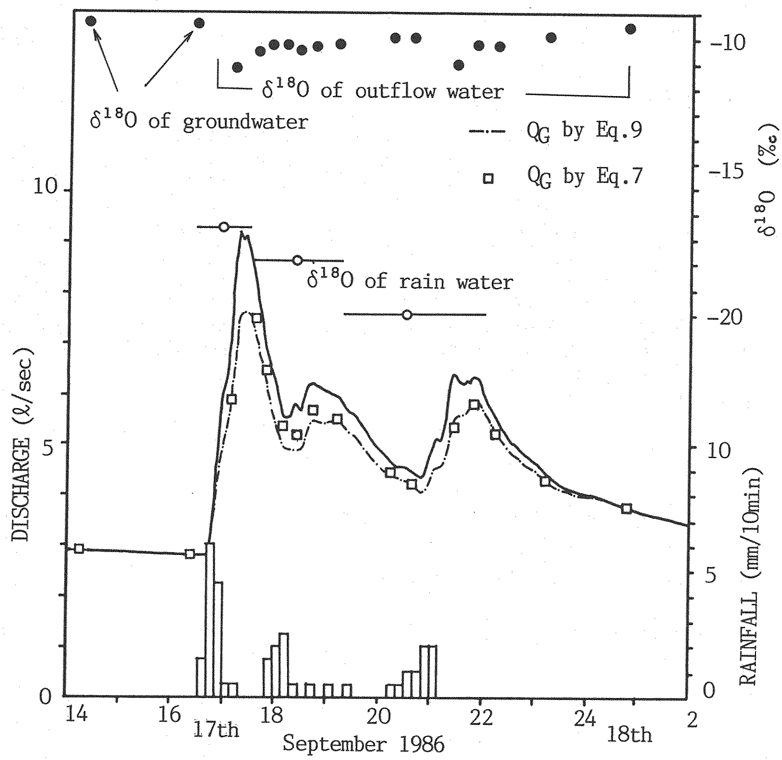

Fig.3 Hydrological and geochemical data

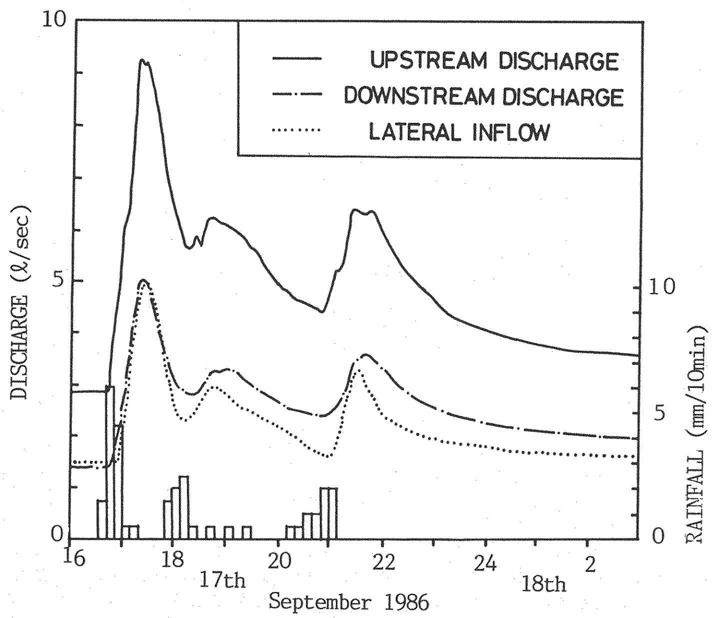

Fig.4 The separation of lateral inflow by the kinematic wave method

The separation by $\delta^{18}O$

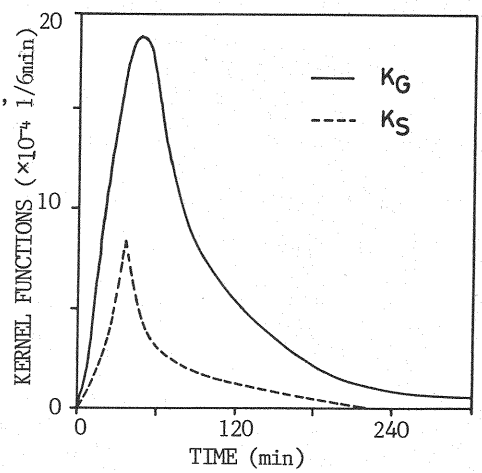

Fig.5 Kernel functions of rain water and groundwater

Based on Eqs.8 to 12, the total runoff discharge can be separated into two components, i.e., the one with $\delta^{18}O$ of current rain water and the other with $\delta^{18}O$ of groundwater. The data used in the procedure are $Q_T(t)$, $C_T(t)$, C_S and C_G shown in Fig.3.

Figure 5 shows the kernel functions $K_S(\tau)$ and $K_G(\tau)$ obtained by solving Eq.12 and Eq.9 respectively. The groundwater components calculated by two equations, i.e., Eq.7 and Eq.9 are plotted in Fig.3. These two plots approximately coincide with each other and this result shows the applicability of the proposed method.

Based on these results, the following can be pointed out. In Fig.3, it is shown that the component $Q_G(t)$ covers not only the base flow but also the direct runoff. The current rain water component $Q_S(t)$ covers a small percentage of the total runoff and appears only in the period of storm. These facts are also supported by Fig.5, that is, the kernel function $K_G(\tau)$ is remarkably large compared to $K_S(\tau)$. In addition, the shapes of these two kernels are similar to each other and have unexpectedly small time difference between both peaks. The ratio of the current rain water component Qs compared to the direct runoff is 16% which is almost equal to the percentage of channel precipitation runoff stated in the previous section.

These facts imply that the main part of the direct runoff is supplied by the groundwater, i.e., the water originated from a previous rainfall. This result is contradictory to the usual concept used in the runoff models that the current rain water itself flows out at each storm event. For example, unit-graph method requires the condition that the area of the kernel function is unity. Therefore, it is important to investigate how the rain water pushes the groundwater to the channel.

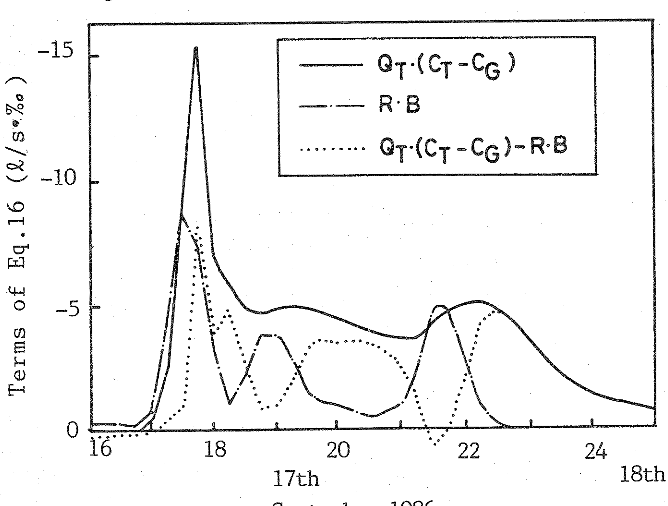

Fig.6 Terms of Equation 16

The characteristics of the channel precipitation runoff

Based on Eq.16, the channel precipitation runoff component can be discussed more precisely. Figure 6 shows each term of Eq.16, where R(t) is calculated by Eq.17 with the characteristics of channel flow expressed by Eq.18.

In this case, channel width B is assumed to be 0.4 m instead of 1.0 m which is used in the kinematic wave method. Nevertheless, values of R•B using B=1.0m exceeds those of $Q_T \cdot (C_T - C_G)$ at its three peaks. The second term of Eq.15 (the rain water came from the slope; dotted line) shows almost the same pattern as R•B term, but has the delay of thirty minutes to one hour. From these two results it may be inferred that the delayed component consists of the rain water falling in the vicinity of the channel and once infiltrated into soil and/or the rain water falling on the slope and coming out through the pipes (root channels).

The possibility of lateral inflow as the groundwater

In the previous section it has been made clear that the direct runoff is mainly supplied by the groundwater. In this section it is investigated whether the groundwater can yield such amount of direct runoff. Table 1 shows the components of runoff,i.e. the rain water as the channel precipitation runoff, groundwater as the direct runoff and groundwater as the base flow. Values in first line represent the volume of each component from 9:00 AM of 17 September to 6:00 AM of 18 September. The sum of 2nd and 3rd terms (= 298 m^3) is the total lateral inflow occurring from groundwater. From this value the zone of the saturated soil which yields the runoff is calculated as about 1.5 m^2 per unit length of channel, assuming the effective porosity as 0.4. This value of the saturated area is feasible as the source of the discharge.

The other two lines in Table 1 show the discharges about the peak of the hydrograph. The second line is the peak discharge of downstream end, and the 3rd line shows the velocity of two components calculated by assuming the depth of saturated groundwater as 2 m. This velocity of the ground water of about 10^{-5} m/sec is in the same order of the permeability of saturated soil in the slope of this basin.

Table 1 The volume and the flux of runoff components

Channel precipitation runoff	Direct runoff as Groundwater	Base flow as Groundwater	Total	Unit
13	70	228	311	m^3
1.5	4.5	3.0	9.0	$10^{-3} m^3/sec$
-	1.15	0.70	-	$10^{-5} m/sec$

CONCLUSION

In this research, the runoff components are discussed by the separation based on the kinematic wave method and the tracer method. The results obtained in this research are summarized as follows;

(1) The new method is proposed to separate the runoff into two components ,i.e., the current rain water component and the groundwater component, by using the tracer $\delta^{18}O$. This method can deal with the change of the tracer in rain water during the storm and can separate the runoff continuously even if the observation of the tracer is discrete. The applicability of this method is also shown.

(2) More than eighty percent of the direct runoff occurs as the outflow of groundwater in this basin. This is contradictory to the traditional concept of runoff model.

(3) There are two components which have $\delta^{18}O$ of current rain water. One is the channel precipitation runoff and the other is the component which once infiltrates and/or comes out through the pipe system.

(4) The feasibility of the occurrence of the direct runoff from the groundwater is proved.

The research has been done in a very small watershed (0.078 Km^2) of deeply weathered granite, whose runoff ratio is very small. Even so, the results of this research contain a clue to understand runoff phenomena.

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APPENDIX - NOTATION

The following symbols are used in this paper:

A	= cross sectional area of channel;
A_B	= area of basin;
B	= width of channel
C_S, C_G, C_T	= $\delta^{18}O$ of rain water, groundwater and outflow water, respectively;
$f(s)$	= runoff ratio of the rainfall at the location s on the slope;
k, p	= constants in Eq.2;
K_S, K_G, Q_O	= kernel functions of rain water and groundwater components and constant term of groundwater component, respectively;
Lc, Ls	= channel length and slope length, respectively;
q_G	= rain water component of lateral inflow into channel;
q_L	= lateral inflow
Q	= discharge of channel;
Q_S, Q_G, Q_T	= outflow discharge of rain water component, groundwater component and total discharge, respectively;
$\overline{Q}_T$	= average downstream discharge;
r	= rainfall rate;
s, x	= location on the slope and location in the channel,respectively;
t	= time;
T_L	= flood propagation time between upstream and downstream flow gauge;
v	= velocity of channel flow;
τ_c, τ_s	= lag time in the channel and lag time on the slope,respectively.