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Analytical Study on Hydrograph Separation

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Abstract

Method of hydrograph separation is discussed through runoff analysis applying the kinematic wave method. It is described that runoff components can be connected with infiltration phenomena by considering the effect of infiltration to flow process, and then the runoff analysis is carried out by using data obtained in a small mountainous basin. It is, first, shown that the runoff model predicts the relation between rainfall and runoff quite well. Consequently, it is described that the separation method used rather arbitrarily is given reasonable significance.

Introduction

In runoff analysis, it becomes a practical problem to divide the observed hydrograph into two components, direct and groundwater runoff, because they have their own characteristics. This process is known as hydrograph separation. Since there is no real basis for distinguishing between the direct flow and groundwater flow in the stream at any instant and since the definition of these two components are relativey arbitrary, the method of separation is usually equally arbitrary[1)]. And the methods of separation actually used are based on experimental studies. Therefore, several unsolved problems still remain when hydrologists study runoff analytically after dividing the hydrograph. Hydrograph separation is so important and fundamental.

The authors also have been trying to make clear the characteristics and mechanics of runoff, especially direct runoff. And they carried out hydrological observations in Kohnoura, Nagasaki Prefecture, a small mountainous basin. In the present paper, the method of hydrograph separation is discussed in connection with the mechanics of runoff which is analyzed by the kinematic wave method using the observed data in Kohnoura basin.

Method and procedure

(1) *The components of runoff and hydrograph separation*

When rain continues so long as to make the ground surface covered with a film of water, surface detention, the water travels over the surface, which is overland flow, to a stream. As infiltration continues enough to cause the detention over a rather impervious layer just under the surface layer, interflow begins in the surface layer. These two flows over the ground surface and in the surface layer which reach the stream are called surface and subsurface runoff respectively. They are the components of direct runoff. Some of the water which infiltrates downward and reaches the water table causes groundwater flow.

In a mountainous basin, usually the surface runoff is an important element of the flood peak, and the subsurface runoff is important in quantity of flood discharge. The groundwater runoff can hardly contribute to the flood, but it continues still to be discharged after direct runoff ceases, and contributes to the sustained flow of the stream during periods of dry weather. In hydrologic studies on the above, such as the relation between rainfall and runoff, direct runoff is often the object for the purpose of flood control and groundwater runoff is the one of water balance for long periods. It is, therefore, necessary to divide the observed hydrographs into two or three components on the first step.

Various kinds of separation methods have been proposed and some of them, shown in Fig. 1, are commonly used. The representative methods which are dealt with later in this paper are illustrated by line *ADB* and line *AB*. The method of separation by line *ADB* is proposed by Barnes[2]. Point *A* is the rising point of the hydrograph, and point *B* is the one of change in slope on a semilogarithmic plot. At this point the direct runoff ceases.

Line *DB* can obtained by projecting the recession of groundwater runoff after point *B* backward in time to a point, *D*, under the starting point of the falling limb. On the other hand the method by straight line *AB* divides the observed hydrograph simply into two components. And it is widely used for its simplicity. Though these two separation methods are based on the assumption of the recession characteristics of groundwater runoff or subsurface runoff, the discharge rate and the time distribution of the respective components after separation by two methods are significantly different from each other.

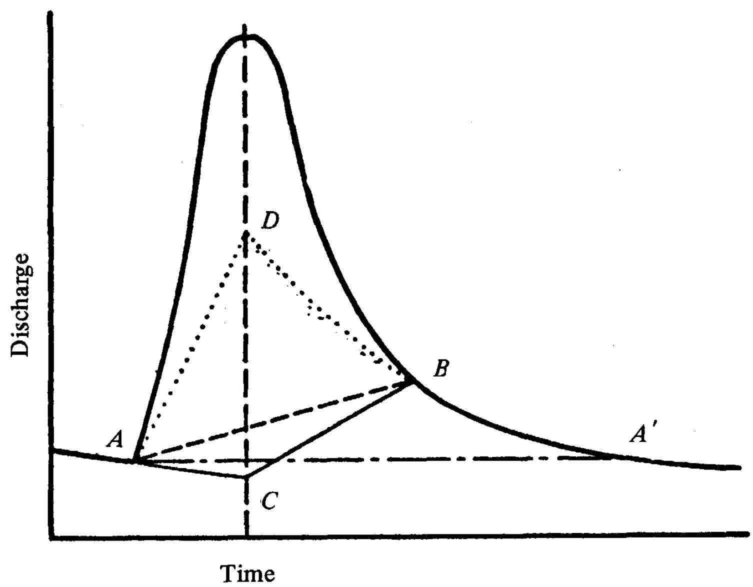


Fig. 1. Some separation procedures.

(2) *Method of runoff analysis*

In order to follow the flow process at the slope of a mountainous basin, the kinematic wave method[3),4)] is used in this paper. Applying the kinematic wave method to overland flow and interflow, and then assuming that Manning's law and Darcy's law can be used respectively for two flows, the equations of continuity and motion are

overland flow: $$\frac{h_1}{t} + \frac{q_1}{x} = r - f_1 \qquad (1)$$

$$h_1 = K_1 \cdot q_1^{-p} \qquad K_1 = (N/\sqrt{i})^p \qquad (2)$$

interflow: $$\gamma \frac{h_2}{t} + \frac{q_2}{x} = f_1 - f_2 \qquad (3)$$

$$h_2 = K_2 \cdot q_2 , \qquad K_2 = 1/(K \cdot i) \qquad (4)$$

where h_1 and h_2 are flow depth, q_1 and q_2 are the discharge rate per unit width, x is the distance measured downward from the top of basin, t is the time, f_1 and f_2 are the infiltration rate respectively into the surface layer and into the second one, i is the mean gradient of the slope, γ and K are respectively the porosity and hydraulic conductivity of the surface layer, N is equivalent roughness coefficient, and p is a parameter, *0.6*.

The kinematic equations for stream section can be written in the same way:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \qquad (5)$$

$$A = K_3 \cdot Q^P \qquad (6)$$

where A is the cross-sectional area, Q is the discharge rate, q is the distributed inflow rate, K_3 and P are coefficients determined by the slope and roughness of the stream bed and the shape of the stream cross-section. Eqs. (1) ~ (6) can be integrated by using the method of characteristic.

Though the kinematic wave method is usually applied to analyze the mechanics of runoff, actual procedures in its application are that effective rainfall and effective infiltration are respectively adopted for rainfall excess and infiltration excess as input of the relation between rainfall and runoff[5)]. Then Eqs. (1) and (2) may be written

$$\frac{\partial h_1}{\partial t} + \frac{\partial q_1}{\partial x} = r_e \qquad (7)$$

$$\gamma \frac{\partial h_2}{\partial t} + \frac{\partial q_2}{\partial x} = f_e \qquad (8)$$

where r_e is effective rainfall and f_e effective infiltration. The exchanges of effective rainfall for rainfall excess and of effective infiltration for infiltration excess are generally practiced unconsciously, mainly because they have been employed in other methods of runoff analysis up to now. But adding to the general explanation at the beginning of this section, the authors consider the flowing water over the ground surface, overland flow, as follows:

(a) The film of water that covers the surface causes the water itself to flow down the slope, but it is not effective rainfall but rainfall excess that causes the film of water:

$$\frac{dh_1}{dt} = r - f_1, \quad \text{then} \quad \frac{dx}{dt} = \frac{5}{3}u \qquad (9)$$

where u is the mean velocity.

(b) The infiltration can occur after rain lets up if there is water over the ground surface. So the water comes to flow down the slope reducing its flow depth:

$$\frac{dh}{dt} = h_0 - f_1 \fallingdotseq const. \tag{10}$$

where h_0 is the depth, constant, when the input stops. So when this happens,

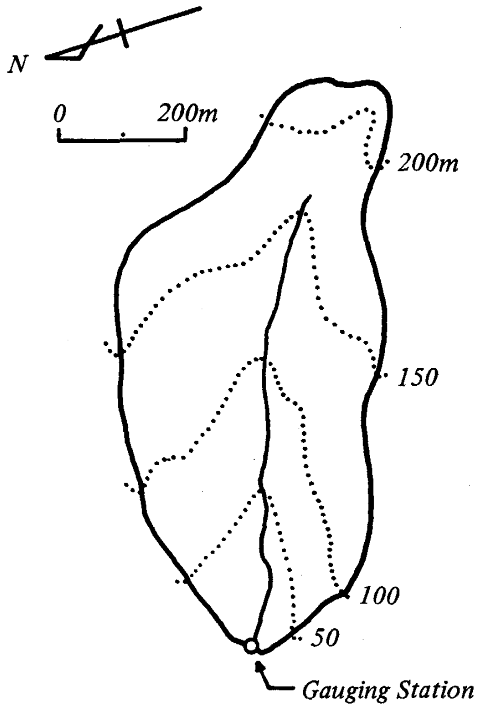
$$\int_{t_1}^{t_2} f_1 \, dt = h_0 \tag{11}$$

overland flow vanishes below the ground surface, and a characteristic curve does not reach the lower end of the slope.

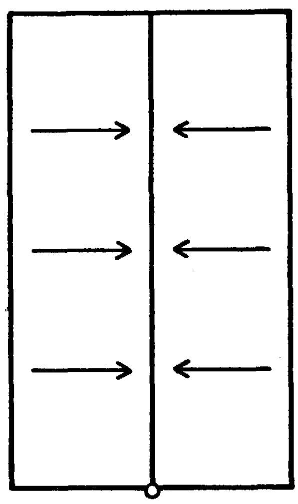
Therefore, it does not always seem to be proper to adopt effective rainfall as the input to overland flow. The above consideration can be similarly applied to interflow in the surface layer. Finally, to apply Eqs. (1) and (3) to two flows at the slope is to analyze the relation between rainfall and runoff in connection with infiltration, which can interpret the actual phenomena more clearly and seems to be able to bring new results.

Kohnoura basin

Kohnoura basin is located in the middle western part of Nishisonogi Peninsula, Nagasaki Prefecture. It was set up an experimental basin for research on the conservation of agricultural lands in 1953. And observations on rainfall, discharge and soil erosion were carried out until 1974. In the first stage after setting up, the basin was mainly used for dry fields, but most of them returned to copse in recent years because of the difficulty of their maintenance.



(A) Kohnoura basin



(B) Model basin

Fig. 2. Kohnoura basin and its model.

Kohnoura basin, shown in Fig. 2 (A), is a small and simple watershed, 27.1 ha in area. The side slope of the mountains are slightly convex and their gradient averages 46%. The elevation ranges from 12 m to 240 m. The main stream lies at the central part of the basin and its gradient averages 25%, nearly constant throughout the stream. These properties of the basin are given in Table 1. In the lower part of the basin there is a little area occupied by paddy field, dry field and orchard (mandarin orange), but the forest and the copse occupy most of the basin, about 86%. Such circumstances of land use, given in Table 2, were obtained by field survey in August, 1974[6].

Table 1. Characteristics of Kohnoura basin

Area	Elevation	Stream length	Mean width	Form factor	Mean gradient
ha 27.1	m 12 ～ 240	m 700	m 301	0.55	0.46

Table 2. Land use in Kohnoura basin (1974)

Total	Dry field	Paddy field	Orchard	Copse, wasteland	Forest	Channel, road
27.1 ha	2.0	0.4	1.5	13.9	9.0	0.3
100.0 %	7.4	1.5	5.5	51.3	33.2	1.1

Table 3. Physical properties of the soil

Layer	Thickness of layer	Particle density	Dry density	Porosity	Hydraulic conductivity	Soil texture
	m	g/cm^3	g/cm^3	%	cm/sec	
Surface	15 ～ 20	2.54	0.64 ～ 0.95	62.7 ～ 75.6	$1.1 \sim 5.4 \times 10^{-2}$	SL
Second	——	2.70	1.53 ～ 1.60	40.8 ～ 43.4	$1.2 \sim 8.7 \times 10^{-4}$	LiS

Rainfall and discharge were observed at the lowest point of the stream, shown in Fig. 1, with gauges and a weir. The weir was repaired to improve the accuracy and range of measurement in 1971. The data used in this paper are data that had been recorded for four years since then. The field survey for interflow analysis was done in August, 1976[7]. The physical properties of the soil, given in Table 3, were grasped by experiments upon twenty-four 100 ml soil samples. By these results of the survey and the experiments, it was comfirmed that there is the surface layer in which water flows, interflow, and then judged that in this basin, subsurface runoff has most important characteristics in quantity and quality among the three components.

In case of an analysis by using the kinematic wave method, it is necessary to regard a basin as a model which, in general, consists of some sets of two identical rectangular planes[8]. Each set of two planes shows a *V*-shaped valley which is equall to the length of the stream, L. So the downstrean length of each half of the unit basin is equall to $A/2L$, where A is the area of the unit basin. In Kohnoura basin, the line stream flows in the middle of the basin with nearly constant gradient. Therefore, it seems to be appropriate to take the basin itself as the unit which is formed by two identical rectangular planes as shown in Fig. 1 (B). Parameters, coefficients and other values for the calculation are given in Table 4.

Table 4. Properties of the slope and the stream

Slope			Stream				
Basin area	Length (B)	Mean gradient	Length (L)	Mean gradient	Roughness coeffic.	K	P
ha	m		m		sec·cm$^{-1/3}$		
27.1	193	0.46	700	0.25	0.05	0.339	0.69

K, P : Parameters in Eq. (6)

Results and discussion

(1) *Overland flow and surface runoff*

First of all, the hydrograph which the subsurface runoff did not affect so much was analyzed in order to make clear the flow process on the slope in connection with the infiltration phenomena. This runoff datum was obtained under the condition of 38 mm rainfall for two hours on October 15th, 1972. It has been pointed out that subsurface runoff usually arises in most mountainous basins, because there is a humus and porous layer just under the ground surface where water can flow, and has an important effect on total runoff[9). And though so as in Kohnoura basin, the observed hydrograph is one of the few instances which do not seem to include the subsurface runoff component, judging from the shape of the hydrograph, especially from the recession characteristics.

Eqs. (1) and (2) are used to calculate the process of overland flow and Eqs. (5) and (6) are for the stream flow. Figs. 3 and 4 show the results of the analysis. The distribution of the infiltration rate shown with a broken line at the upper part in Fig. 3 (A) is determined by the conditions that the input of the difference between the infiltration rate and the rainfall intensity and the negative input of infiltration itself after rain, can give the optimum hydrograph compared to the observed one. The hydrograph shown with a solid line in Fig. 4 is the surface runoff component excluding groundwater runoff. The groundwater component is divided here by the method of line *AB* in Fig. 1. This separation method is to be discussed later on. Fig. 4 illustrates that the runoff model applied in the present paper predicts the time distribution of overland flow and infiltration quite well. The analysis by using effective rainfall as the input, Eqs. (7) and (8), could not follow such an abruptly varied distribution as the hydrograph in Fig. 3 (A).

Fig. 3 (B), kinematic wave diagram, shows the situation of overland flow. The characteristics curve through the origin, $x = 0$ and $t = 1$ in this case, does not reach $x = 193$, the end of the slope, but intersects $x = 150$ when inflow ceases. This is caused by the negative input of infiltration, which reduces the depth of flowing water and makes it nil finally at $x = 150$, which can be explained by Eqs. (10) and (11). The above fact indicates that in this event of rainfall and runoff, overland flow at the upper part of the slope, from $x = 43$ to $x = 0$, does not reach the stream as shown with the broken line, the upper boundary of overland flow. Incidentally the solid line illustrates the upper

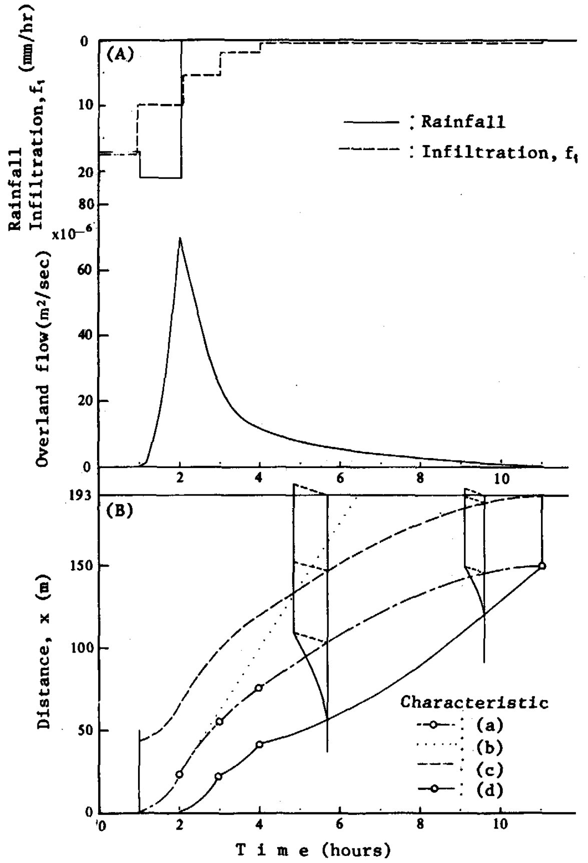


Fig. 3. Analysis of overland flow process. (A) Distribution of overland flow at x = 193, inflow. (B) Kinematic wave diagram; (a) limiting characterictic, (b) dx/dt = const., (c) upper boundary of overland flow and (d) upper boundary of infiltration.

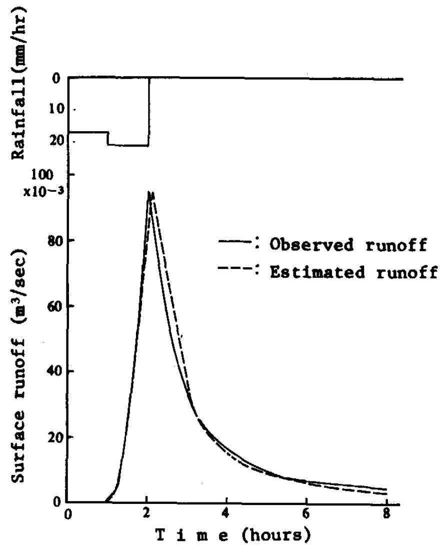


Fig. 4. Prediction of surface runoff hydrograph for rainfall event of October 15, 1972.

boundary of infiltration. So, in the domain between the broken and solid lines overland flow can come out no longer as surface runoff. The schematic graphs on the longitudinal axes illustrate the distributions of overland flow along the slope at optional time. The upper boundary of infiltration has another important significance in that it restrictes spatially the input to interflow in the surface layer when the subsurface runoff analysis is carried out.

On the other hand, the dotted straight line of *dx/dt= const.* which does not include the infiltration effect after rain reaches the stream with the maximum gradient. This gradient is given when the input of effective rainfall stops and overland flow rate comes to the peak. And during the period the dotted line is running to *x = 193* the inflow rate, as is generally known[10], keeps itself at the peak discharge rate, which does not seem to produce a well predicted hydrograph compared to the observed one.

The situation that overland flow does not always come out from the whole basin because of the infiltration effect, is found under the conditions of such rainfall as shower which is shown in Fig. 3 and as ordinary quantity below about 50 mm, judging from the results of analysis for each rainfall and runoff relation. With more or less than about 50 mm, the runoff characteristics vary, especially in direct runoff percentage and recession coefficient of surface runoff. Equivalent roughness coefficient may also change. And above all, it seems to be necessary to reconsider the conception of effective rainfall, because the field of runoff itself varies, which needs further investigation.

(2) *Runoff process and hydrograph separation*

The input in subsurface runoff analysis is the difference between the infiltration rate to the surface soil layer f_1, and that to the second layer, f_2. And still infiltation f_2 is effective as the negative input after the infiltration f_1 ceases, as represented in Eq. (3). In the prediction of interflow distribution, the values in Table 3 are used, and the bed gradient of the surface layer is assumed to be equal to the one of the ground surface, 0.46 on the average. For surface runoff analysis the same procedure as described before is employed.

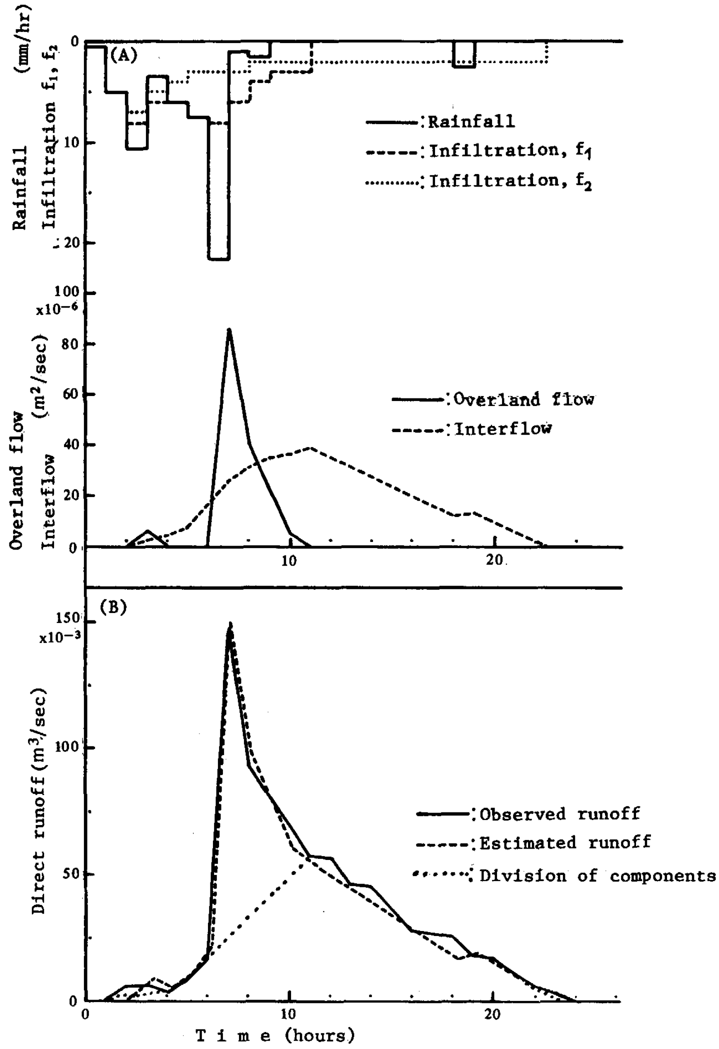
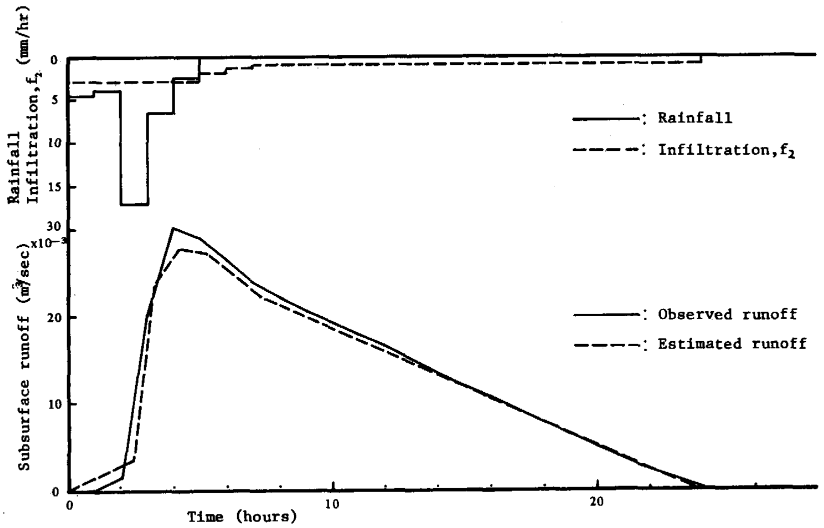
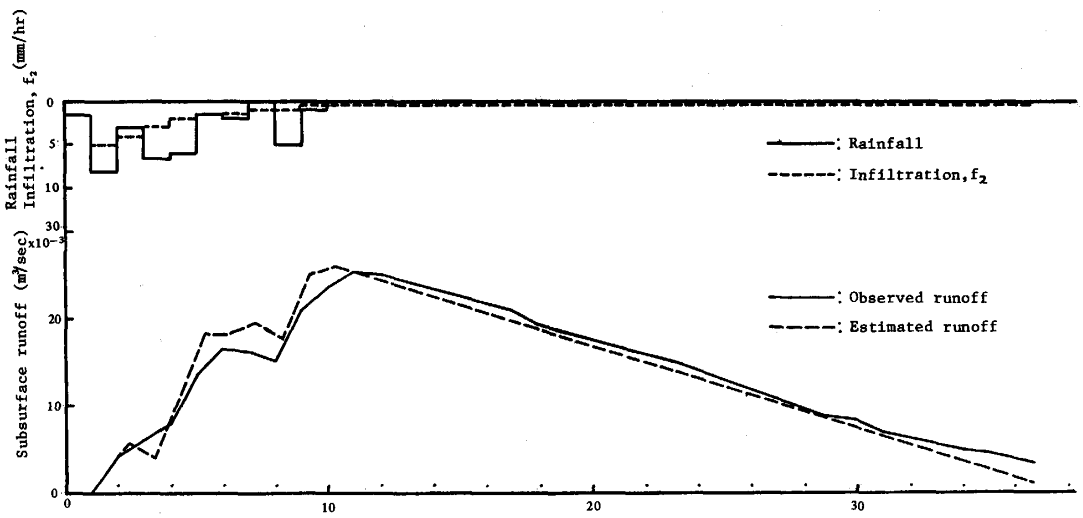


Fig. 5. Analyses of overland flow and interflow process.
(A) Distributions of inflow and infiltration.
(B) Prediction of direct runoff hydrograph for rainfall event of June 29, 1973, and hydrograph separation.

The results are shown in Fig. 5. The broken curve in Fig. 5 (B) is the predicted hydrograph obtained through the calculation for the overland flow and interflow distribution in Fig. 5 (A). It is in reasonable agreement with the observed hydrograph. We carry out further investigation with the runoff model verified being reasonable. The distribution of rainfall intensity, r, and infiltration rates, f_1 and f_2, shown in Fig. 5 (A) are divided into three portions by themselves which are the input to overland flow and interflow, and the infiltration f_2 itself, having the negative effect on interflow. The distribution of lateral overland flow indicates its peak at $t = 7$, when the input of rainfall excess stops, and reduces the rate by infiltration loss. It becomes, finally, nil at $t = 11$ when the input to interflow stops and the interflow distribution indicates the peak.



(A) March 9, 1974.



(B) September 13, 1973.

Fig. 6. Prediction of subsurface runoff hydrograph for rainfall event of (A) March 9, 1974 and (B) September 13, 1973.

Figs. 6 (A) and (B) show the calculated subsurface runoff hydrographs compared to the observed data which does not include surface runoff. And the distribution of the infiltration f_1 is not shown, for it exceeds the distribution of the rainfall intensity. Then rainfall itself becomes the source of input to interflow, having the same role as the infiltration f_1. And the input is the difference between the rainfall intensity and infiltration f_2. In this case also the infiltration after rain effects the recession characteristics of subsurface runoff. It has been often reported and, in fact, often occurs that surface runoff does not take place under the rainfall conditions of low intensity or a little in quantity in the mountainous basin, for the infiltration rate is more than the rainfall intensity. In addition to the above reason the following may be considered through the present runoff model; there are some situations that overland flow cannot come out to the stream as surface runoff by the negative effect of infiltration even in the case of causing the surface detention by rainfall excess. The maximum infiltration rate is influenced mainly by the conditions of soil moisture, so it is generally difficult to evaluate the critical rainfall intensity to cause surface runoff. In Kohnoura basin the following values are rough criteria; over 15 ~ 20 mm/hr in the peak intensity for duration of one hour and over 35 ~ 40 mm in the total quantity.

In Figs. 6 (A) and (B), the predicted hydrographs which represent the observed ones quite well indicate the peak just after stopping the input. Comparing these predicted hydrographs to that of subsurface runoff in Fig. 5, even in the case that the source of input to interflow are respectively the infiltration f_1 and rainfall, the following rule is introduced; the distribution of subsurface runoff indicates the peak when the input stops. Overland flow, of course, ceases when the input to interflow stops. It is too difficult to evaluate quantitatively the input and output relation, especially the relation of time of their peaks, as all of the factors in the conditions of rainfall and runoff are involved in these problems. It seems, however, to be capable to apply that rule to the rainfall and runoff relation in ordinary mountainous basins except those that are too small in area or those involving urbanized area in a fairly high ratio. The above results make us consider the hydrograph separation as follows.

At first, the point of change in slope on the semilogarithmic plot when surface runoff ceases, indicates the peak of the subsurface runoff distribution. In this sense, Barnes method tends to estimate the peak greater and earlier. Secondly, there remain two problems, one is that it is generally difficult to select the point of change in slope on the semilogarithmic plot, for the point is on the gradual changing curve. The recession limb of the hydrograph is not directly effected by rainfall, so some studies are carried out to make clear the relation between the the basin characteristics and runoff characteristics[11),12)]. But unsettled factors still remain, which need further investigation. Another problem is how to connect the point of change in slope with the starting point of the rising limb. Predicting through the present runoff model, the rising limb of the subsurface runoff hydrograph shows the following curve according to the conditions of the input; concave curve under increasing distribution, convex under decreasing and straight increasing line under constant. In general, it shows a slightly S-shaped curve reflecting the ordinary pattern of the convex input distribution as illustrated in Fig. 5 and 6. So it seems to be able to approximate the rising limb of the subsurface runoff hydrograph with the straight line which connects the point of change in slope with the rising point, illustrated by line AB in Fig. 1 and by a dotted line in Fig. 5 (B). The separation method of line AB is so simple that it is used frequently but rather arbitrarily, being only based on the experiments. In such circumstances, the above analytically considered result may make this separation method reasonable. This method can be, of course, applied to the separation of direct and groundwater runoff components from the total hydrograph, judging from the stage that the same type of continuity and motion equations as to subsurface runoff can follow the process of groundwater runoff. If the problem of the process and mechanics of the infiltration which connects interflow and groundwater with overland flow can be tackled, the whole runoff phenomena will be more clear.

Conclusion

From the results of analyses by using the runoff model connected with the infiltration effect, it is made clear that a time distribution of runoff component indicates the peak when the input stops in the relation between rainfall and runoff. Consequently, it can be safely concluded that it is reasonable to approximate the rising limb of a runoff component with the straight line which connects a point of change in slope on the semilogarithmic plot with a rising point as a hydrograph separation method.

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