Rainfall-Runoff Relationship in Small Slope Drainage Area in Japan

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Aim of investigation

More than 60 % in area of this country is slope land of over 15 degrees in gradient. The slope farmland of over 5 degrees in gradient covers 1,220,000 ha in total, and the steeper one of 15 degrees or more 500,000 ha. And it is said that fertility is decreasing in the slope farmland covering at least 100,000 ha owing to soil erosion. Therefore, soil conservation, which aims mainly at preservation of soil erosion, is an important problem in considering a plan for the management of slope farmland.

The work of soil conservation in Japan came into operation for the first time in Hiroshima Prefecture in 1950. And its promotion was provided in the law of special soil and steep slope land in 1952. The main problem of this work is construction of a network of watercourses to drain away water from the area before its force increases. For the design of this construction data on rainfall-runoff relationship are necessary.

However, there were only a small number of research data on this problem and practically no available ones on the runoff in the small slope drainage areas owing to the fact that the paddy field had been the main constituent and upland farm secondary in Japanese agriculture.

The data only available at that time were those of the Ministry of Construction, electric power companies and their parties on large drainage areas, or of forestry authorities on forest lands. And necessary use of those data for the estimation of runoff often led to the construction of water-courses with too small area of vertical section to meet a large quantity of runoff, or with too large section area. The construction was liable to result in fruitless investment.

The Agricultural Land Bureau of the Ministry of Agriculture and Forestry, therefore, established 7 runoff experiment stations (each has an area of several tens of hectares) in representative soil erosion regions in Japan in 1953 and the proper prefectures were entrusted with the observation. Since then the observation has been continued for about fifteen years up to this day. Such a lasting observation is invaluable, being unparalleled on matters related to farmland.

The following is mainly the results obtained in these stations with the effects of short term experiments and observations carried out in various places.:

Rainfall-runoff relationship

1) Total rainfall and total runoff

The total runoff described here is the runoff due to rainfall less the ground water flow after the end of interflow. The interflow is the quantity of water which exudes from the soil layer after penetration into it and a short time's flow through it. It is a component of direct runoff together with surface flow. There is also ground water flow during the period of direct flow. So, strictly speaking, the total ground water flow during the period of runoff must be taken into consideration. It, however, is not necessary to separate the ground water flow, as its quantity is inconsiderable in small slope drainage areas.

The total runoff increases in quantity, when both surface flow and interflow are large, or either of them is extremely large, in quantity. In many cases the runoff is medium or little, when interflow dominates the runoff. When the runoff which is the total of those flows in each rainfall is plotted against each drainage area, plotted points are scattered rather widely. This scattering, however, is natural since there are differences in the characteristics of watershed at the time of rainfall and in the characteristics of rainfall. And to put those points on a curve, they must be classified into groups by the equality in such influential factors, as soil moisture, condition of soil surface and time distribution of rainfall intensity. When the upper limit of the scattered points in every drainage area is connected successively, a curve is obtained which shows the runoff due to a comparatively heavy rainfall in the moist drainage area easy to cause runoff. The curve is represented by the following formula:

$$Q=C \cdot R^{a}$$

where α is a constant determined by the characteristics of watershed and R is the total rainfall (mm).

When they were shown by numerical values, the runoff coefficients in case of a rainfall of 100-120 mm after the initial loss were as fllows:

- Grassland and farmland on a slope of volcano ···10-15%
- Farmland and residential land of shirasu (pumice, rich volcanic ashes) upland ···20-25%
- Farmland on a hill ·······················30-35%
- Mostly forested mountain area·········50-55%
- Bench terrace on a steep slope ······65-70%

2) Initial loss, initial flow and water deficit.

The initial loss means the total rainfall from the beginning of rainfall to the abrupt rise of hydrograph. During this period it is expected that the rainfall is intercepted by the vegetation and only balances up the water deficit of soil without causing any runoff. It, however, is usual that the hydrograph goes up slowly even in the period of initial loss, because the rain water comes down on the fixed water ways (including water-courses) and flows out. The water deficit is a loss of the normal retention of water in the soil by evaporation. And when it rains, the rain water balances the loss. The flow at the beginning of rainfall is called initial flow. This shows the condition of moisture in the dnainage area.

When there is correlation between the initial flow or water deficit and the initial loss, it is expected that the initial loss can be estimated before the end of the period of initial loss, and the direct runoff can be predicted. There, however, is no correlation between the initial flow and the water deficit, and also between the initial loss and the water deficit. There is some degree of correlation between the initial loss and the initial flow.

3) Arrival time of peak discharge.

As the arrival time is a compound of various characteristics of the drainage area, it is an important index together with the recession constant mentioned below.

The formula of Rziha has been used hitherto to calculate the arrival time. The arrival time calculated from this formula, however, represents the time for the arrival of water from the furthermost place in the drainage area to the water-measuring station in the optimum condition. Among the many influential factors on the arrival time, as stream length, difference in height between the furthermost place and the station, hydraulic radius and roughness, only the first two are taken into consideration in this calculation. In many cases, however, it takes a considerably long time for the arrival from a nearer place being influenced by hill side slope, hillside length, condition of water way, soil and vegetation, etc. And actual arrival time of peak discharge is later than the estimated time. The results in every experiment station show that the actual time is usually 40-60 minutes behind the estimation in case the latter is less than 10 minutes.

The shorter the duration time is, the larger the maximum rainfall per hour. Accordingly, the calculated rainfall is larger than the actual one in case the value obtained by Rziha's formula is used as it is. When it rains heavily for a short time, even if a part of the rain water soon arrives, the greater part of it is reserved on the surface of the soil as water film and water way retention. Thus the runoff is regulated. Therefore, the runoff coefficient must be made smaller to meet the larger difference between the rainfall intensity at present and the precedent one in case short time rainfall intensity is the object of consideration.

4) Peak runoff coefficient.

When peak rainfall per hour is plotted against peak discharge, and the upper limit of the points is connected successively, a curve is obtained. It represents the peak runoff in the drainage area which is sufficiently moist and the minimum in the resistance to runoff. The values were :

well-covered slope of volcano ············0. 15
upland field of volcanic ashes (Shirasu)
(a little flat) ································0. 20
well-covered bench terrace and farmland
area on a gentle slope of hill ·········0. 30
farmland area at the foot of volcano
and farmland area on a diluvial plateau
(water ways are well developed in
both) ···0. 35
bench terrace area on a steep slope······0. 50

The runoff coefficient included in the formula of the rational method for calculation of flood discharge is not the total coeffcient, but the peak runoff coefficient. This value is fairly smaller than that hitherto used. A larger value may be used in future. But it is not conceivable that the value will be increased sharply. Such values as 0.7-0.8 have been adopted for the runoff coefficient of paddy fields confusing with the total runoff coefficient. The unit hydrograph of paddy field alone is below 10 % in the peak value, even if the total runoff coefficient is taken as 100%. This is due to the long base length. And the peak runoff synthesized from these factors is also small as shown by actual measurement in the paddy field area, being 0.30 or so in the maximum ratio to a corresponding rainfall. Therefore, it is wrong to take a larger peak runoff coefficient for the paddy field included in a slope drainage area than for the slope. It must be below the mean value taking the storage effect into consideration.

5) Recession constant

Among the various indexes which represent the characteristics of the drainage areas, the most important one is the recession constant. All the characteristics, as the lay of the land, condition of the soil surface, and hardiness of the surface and lower layers against runoff, are more or less concentrated on this value.

There are three kinds of recession constants which belong to the surface flow, interflow, and ground water flow, respectively. The recession constant of ground water flow is not so important in a small drainage area as in a larger area where it comes into question concerning water utilization.

The recession constant of surface flow is influenced by the lay of the land, cover, surface percolation, rainfall and season, etc. And it is more difficult to obtain this coefficient than the other two, becauce the work must be done soon after the end of the rainfall. This value was 0.15-0.22 or so.

The recession coefficient of interflow is mainly influenced by the underground conditions, as the lay of the land, surface and subsurface percolation, and thickness and water retention of surface layer. It is easier to obtain this constant than that of surface flow. The value is 0.04-0.1. Both the constants are the value of c in the formula $Q=Q_0e^{-ct}$, where Q_0 and Q are the surface flow or interflow at t=0, t=t.

Plan of the work in future

The abovementioned is an outline of the results obtained by the observations of runoff in the small slope drainage areas.

The object of the investigation of rainfall-runoff relationship is to obtain the time distribution of flow at a water-measuring station by the calculation based on the rainfall (total rainfall and area and time distribution) in the proper drainage area. In this sense, it is insufficient to marshal only every result of investigations, and synthesis from them is necessary. We, however, have no universal method for this calculation because the physical conditions of drainage areas are not constant, and the characteristics of rainfall change every time. There are several methods in use, as the empirical formula which is applicable only to a specific river or drainage area, the rational method which does not take storage into cosideration, but only the concentration time (this method is full of mistakes as described in paragraph 4), and the unit hydorograph method which makes unit hydrographs by free use of observation data, and puts them to use for synthesis. Every method has many weak points.

As to the aim of popularization and generalization of the results in future, it is desirable to take up as many influential factors relating to the rainfall-runoff relationship as possible, and to obtain a formula simplifying the complicated relation among them. It is needless to say that the correction and improvement of the abovementioned methods are also necessary to approach the true form of the phenomenon.

The old empirical formula is not universal, because its essential point is the characteristics of watershed, and the characteristics of rainfall are treated rather lightly in it. Such a thought is also found in the coaxial method (a method to obtain the runoff on the graph giving influential factors). In this method, however, it becomes acceleratingly difficult to make the graph, when the factors increase in number. So the right course of the work is to obtain a formula–it is not always a single one–simplifying the complicated relation between the factors.

The values obtained by observations for a short term are not sufficient for the time series as in the hydrologic phenomena. It is necessary to continue the observations as long as possible in future. And the arrangement for this work has been completed.