Application of Hydrology to Irrigation, Drainage and Soil Conservation in Japan (Part I)

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Introduction

Application of hydrology to agriculture is found in irrigation, drainage and soil conservation.

Agriculture, which is carried on in natural environments for the most part, varies in its water use from country to country. The way how the hydrology is applied to agriculture, therefore, will differ according to the natural environments of each country.

The hydrological techniques which are in practical use in Japan will be presented briefly in this paper, with a hope that some of them may serve as useful information to other countries.

Application of hydrology to irrigation

Hydrology is applied to the estimation of effective rainfall, evapotranspiration, streamflow, and inflow into a reservoir.

1) Basic year for planning

(1) Recurrence interval of the basic year for planning

Water requirements of paddy fields in Japan are 1000–1500 mm/yr or 1000–15000 m^3/10 a/yr on the average. Of the total water requirements, 200–400 mm/yr or 200–400 m^3/10 a/yr is usually supplied from rainfall. This portion of rainfall is called effective rainfall. In a region, where streamflow, from which irrigation water is diverted, is positively correlated to rainfall, a serious drought is liable to occur in the year which has scanty rainfall. Irrigation planning is usually made against such a droughty year as occurring several times in several-ten years, so that irrigation water can meet the requirements for most years.

The average recurrence interval at which more serious drought than the planned one will occur is officially set to be ten years for major irrigation projects in Japan. Actually, the basic year for planning is determined by selecting from the past years one of such years which had scanty effective rainfall, extended dry spell, and/or great damage which would occur once in ten years on the average.

(2) Effective rainfall

Effective rainfall for paddy fields was formerly estimated to be 80% of daily rainfall between 5 and 80 mm in an irrigation period. This estimate probably includes the utilization of rainfall detained in dual-purpose canals.

The recent separation of irrigation and drainage canals reduces the utilization of the storage, so that the amount of effective rainfall seems to become a little smaller than before. Some field observations indicate that daily rainfall between 5 and 30 mm corresponds approximately to the effective rainfall, but further researches have to be made for reasonable estimation in various situations.

Effective rainfall for upland fields has to be estimated by making water budget. The upper limit of available moisture in soil corresponds to the amount of moisture held at field capacity, and the lower limit of available moisture is the amount of moisture retained at wilting point. Actually, the total readily available moisture (TRAM) should be adopted

Table 1. Evapotranspiration ratio E_T/E_P in Japan

(ϕ20 cm evaporimeter)

Surface condition	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Paddy field	0.5	0.5	0.6	0.6	0.7	1.0	1.2	1.3	1.1	0.7	0.7	0.6
Upland field	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.8	0.7	0.7	0.6

as the upper limit of available moisture.

The estimation of 10-year* effective rainfall is usually made by fitting the effective rainfall data to the normal distribution and by reading off the value corresponding to 10% of cumulative frequency. The year which had effective rainfall approximate to the 10-year value should be adopted as "a proposed basic year for planning".

(3) Successive rainless days

A drought may occur owing not only to scanty effective rainfall but also to an extended dry spell.

The statistical analysis of the number of successive rainless days is usually made by fitting the data to lognormal or extremal distribution.

The year which had the number of successive rainless days approximately corresponding to the 10-year value should be adopted as "a proposed basic year for planning".

The method of statistical analysis in this relation will be explained later.

(4) Drought damage

Drought damage data are usually collected for several-ten years. The damage may be expressed either by income deficit or by yield reduction of main crops.

The average recurrence interval assigned to a certain value may be computed using equation (1).

$$T_i=\frac{N+1}{i} \quad \cdots\cdots(1)$$

where T_i: the average recurrence interval for i-th largest damage; N: number of the damage data.

* In this context and the like, "10-year" means average recurrence interval of 10 years.

The year which had such drought damage as would occur once in ten years on the average should be adopted as "a proposed basic year for planning".

2) Evapotranspiration

Evapotranspiration occupies a large part in consumptive use of water on pady fields as well as on upland fields.

Inflow into a reservoir also is normally dependent on water losses which consist mainly of evapotranspiration from the watershed.

Thus, the estimation of evapotranspiration under various conditions is indispensable to the irrigation planning.

The methods of its estimation are classified into (1) evapotranspiration ratio, (2) water balance, and (3) heat balance.

(1) Evapotranspiration ratio

Evapotranspiration ratio is a ratio of evapotranspiration E_T to evaporation from pan evaporimeter E_P, as shown in equation (2) and Table 1.

$$f=\frac{E_T}{E_P} \quad \cdots\cdots(2)$$

E_P is usually measured with 20-cm pan evaporimeter.

The ratio, however, may change according to climate, vegetation, and cultivation.

(2) Water balance

Evapotranspiration can be estimated by solving water-balance equation after taking field observations of each of its terms except evapotranspiration itself.

The watershed on which evapotranspiration is to be estimated must meet such conditions that it has no deep percolation, no leakage, measurable groundwater flow, and negligible

Table 2. Specific discharge of droughty flow in Japan

Region	Specific discharge in $m^3/sec/100\,km^2$	Specific discharge in mm/day
Northern coastal area of Japan	more than 2.7	more than 2.3
Central mountainous area	about 2.7	about 2.3
Coastal area on Pacific Ocean	about 1.8	about 1.6
Mountainous area of south Kyushu	more than 2.7	more than 2.3
Central area of Kyushu	1.2-1.4	1.0-1.2
Seto-inland Sea area	about 0.9	about 0.8
Shikoku Island	0.9-1.8	0.8-1.6
Southern part of Kinki district	1.0-1.8	0.9-1.6
Southern costal area on Japan Sea	about 1.8	about 1.6

change in watershed storage.

This method is suitable for the estimation of long-term areal evapotranspiration.

(3) Heat balance

Evapotranspiration can be estimated using heat balance equation, as shown below.

$$E=\frac{R-G}{L}\left(1-\frac{r}{\Delta+r}\,\frac{T_1-T_2}{T_{w1}-T_{w2}}\right) \quad \text{......(3)}$$

where E: evapotranspiration in $g/cm^2/min$; R: total net radiation flux in $cal/cm^2/min$; G: heat flux into the ground in $cal/cm^2/min$; L: latent heat of vaporization of water in cal/g; γ: psychrometric constant, Δ: slope of vapor pressure curve at the average of T_{w1} and T_{w2}; T_{w1}, T_{w2}: wet bulb temperature at the two heights; T_1, T_2: dry bulb temperature at the two heights.

This method has recently been put to practical use owing to the development of a new type of actinometer with polyethelene film cover. The polyethelene film is almost entirely transparent for both long and short wave radiation. This property makes it possible to measure total net radiation flux easily and accurately.

This method is hoped to be applied to further researches on evapotranspiration in various situations.

3) Estimation of water resources for irrigation

Water requirements of farm lands must be met by effective rainfall and irrigation water taken from reservoirs and streamflow. Hence, the estimation of those water resources in droughty years is very important in irrigation planning.

(1) Estimation of droughty discharge of streamflow

The droughty discharge, if there are adequate data available, can be estimated using lognormal or weibull distribution. If there are few data available, it has to be estimated using some hydrological techniques which will be explained later.

The droughty discharge typical of Japan is shown in Table 2.

(2) Estimation of inflow into a reservoir

The capacity of a reservoir must be determined so as to meet maximum cumulative deficit of irrigation water in the basic year for planning. If there are adequate data on inflow, the computation of reservoir capacity can be performed without difficulties, but if there are few data available, inflow must be estimated using hydrological techniques such as tank model. Moreover, if there are no data on inflow except some data on rainfall at the site in question, rainfall for longer term must first be estimated from the rainfall data at nearby sites by means of equation (4).

$$Y=\bar{Y}+\frac{S_y}{S_x}r(X-\bar{X})+u\varepsilon \quad \text{...............(4)}$$

where Y: estimate of daily rainfall for the site in question; $\bar{Y}$: mean value of y; x: daily rainfall at nearby site; $\bar{x}$: mean value of x, r: correlation coefficient between x and y; S_x: standard deviation of x; S_y: standard deviation of y; u: mean residual; ε: random number generated from $N(0, 1)$*.

4) Water balance analysis

(1) Water balance equation

Water balance equation for a delineated area and period is as follows:

$$\left.\begin{array}{l} P=E+(D_2-D_1)+(G_2-G_1)+\Delta S \\ \Delta S=\Delta H\cdot P_e+\Delta M+\Delta W_s \end{array}\right\} \quad \cdots(5)$$

where P: precipitation; E: evapotranspiration; D_1, D_2: inflow and outflow of surface water; G_1, G_2: inflow and outflow of groundwater; ΔS: change in storage; ΔH: change in groundwater level; ΔM: change in soil moisture in unsaturated zone; ΔW_s: change in storage of surface water; P_e: effective porosity of aquifer.

(2) Estimation of evapotranspiration by water balance

As mentioned in (2) of 2, evapotranspiration from a watershed can be estimated using equation (5) under the condition of $\Delta s \fallingdotseq 0$ and with observations of P, D_1, D_2, G_1, and G_2. This condition will often be met by headwater area with outcropped measuring site.

(3) Estimation of groundwater flow

In equation (5), for a period with $\Delta s \fallingdotseq 0$, field observation of D_1, D_2 and P together with estimation of E may reveal groundwater flow G_2-G_1. G_2-G_1, if positive, means the recharge of groundwater from surface water in the area.

(4) Some results of water balance analysis in Japan

(i) In paddy field areas on low-lying alluvial plains, G_2-G_1 is small owing to small hydraulic gradient of groundwater, and the value of D_1-D_2 in equation (5) approximates to E regardless the size of the area.

ii) In paddy field areas, where almost all water percolated into ground flows out of the area as groundwater flow, the value of D_1-D_2 in equation (5) approximates to average water requirements of paddy fields over the area, but the larger the area, the nearer to E it becomes.

(iii) In alluvial or delluvial fans where G_2-G_1 is commonly negative, i.e., the seeping-out of groundwater takes place, D_1-D_2 is smaller than E.

(5) Estimation of return flow

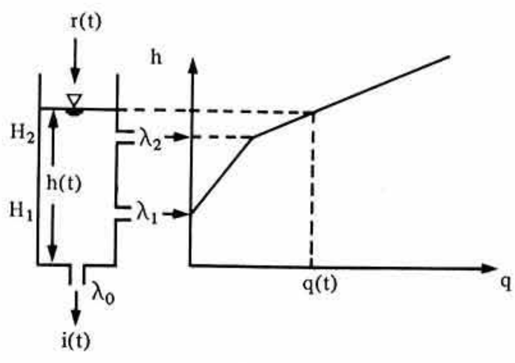
Outflow of surface water D_2 may be supposed to be return flow, if inflow of surface water D_1 is at reasonable rate. But the return flow on which downstream paddy fields can rely has to be a steady flow after such a long dry spell as anticipated in planning. A careful study must be made of steadiness of return flow using water balance equation.

(6) Change in storage

Manipulation of storage of surface water is an important part of water management for paddy fields. This must, however, be done taking into account the influence upon surface flow, groundwater flow, and storage in soil and groundwater.

5) Serial storage model or tank model

This model which was proposed by M. Sugawara is frequently used today for water resources engineering.



$q(t) = q_1(t)+q_2(t)$	$h(t)$:	Storage (mm)
$q_1(t)=(h(t)-H_1)\cdot\lambda_1$	λ_0:	Coeff. of seepage hole
$q_2(t)=(h(t)-H_2)\cdot\lambda_2$	λ_1, λ_2:	Coef. of discharge hole
$i(t) = h(t)\cdot\lambda_0$	$r(t)$:	Input (mm)
	$i(t)$:	Output seepage (mm)
$r(t)-q(t)-i(t)=\frac{dh}{dt}$	$q(t)$:	Output discharge (mm)

Fig. 1. Operation of the tank model

The operation rules of this model can be seen in Fig. 1.

The working procedure for calculation using

* Normal distribution with mean=0, and variance =1.

this model will be explained briefly as follows.

(1) Zoning of watershed

Since a long-term rainfall may increase according to the altitude, the zoning of a watershed should be carried out into 4 zones or so, according to difference in altitude within the watershed. Then the correction factors for each zone should be assumed using relevant data.

(2) For seasonally-snow-packed area, snowmelt calculation should follow.

(3) The next step is the estimation of areal evapotranspiration, which may be made using reduction factor of 0.5-0.8 together with evaporations from ϕ-20-cm pan evaporimeter. On rainy days, evapotranspiration may be assumed to be half of the value on rainless days.

(4) Initial storage for each tank should be assumed at one day before the starting day of calculation.

(5) Coefficients of discharge and seepage holes and their height should be assumed.

(6) The coefficients and the height of the holes should be adjusted repeatedly so that the difference between observed and calculated values may become reasonably small using trial-and-error method. Recently some effort is being made of automatic fitting of parameters by electronic computer.

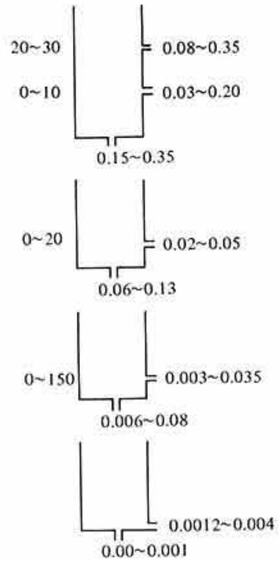


Fig. 2. Average values of parameters of tank models for major rivers in Japan (T. Kinosita)

Average values of the coefficients and the height of discharge holes are shown in Fig. 2.

This model, after parameter-fitting using rainfall-runoff data for three years or so, can be best used for the estimation of the runoff for many years using rainfall data only.