Application of Hydrology to Irrigation, Drainage and Soil Conservation in Japan (Part 2)*

By KINJIRO SHIBUYA

Water Management Division, National Research Institute of Agricultural Engineering

Application of hydrology to drainage

1) Design rainfall

(1) Determination of design rainfall

A drainage project must be designed not to cause any damage, more serious than allowable one, by the rainfall having the recurrence interval of 10–50 years.

An intensive short-duration rainfall having appropriate recurrence interval should be adopted as design rainfall for a small watershed with moderate slope where drainage capacity is usually based on peak discharge. A heavy rainfall having rather long duration may, however, be adopted as design rainfall for a low-lying area or a large watershed where drainage capacity is based on total discharge or runoff hydrograph. The duration of design rainfall is usually postulated as 1 day for small-size flood-control dam, 2 days for large-size flood-control dam, and 1–3 days for pumping drainage in a low-lying area.

The 20–30 years' data on rainfall having appropriate duration are analysed statistically to determine the design value with an assigned recurrence interval. Then, temporal distribution among each unit time can be determined using a matching factor together with one of the historical rains which caused serious flooding damage. The unit time is normally taken as half of the time of concentration for sloping watershed and 3–6 hrs for low-lying paddy area.

(2) Areal rainfall

If there are rainfall data available at several points within or around a watershed, they are usually averaged to areal rainfall by Thiessen method or isohyetal method.

(3) Depth-duration analysis

Any one of the well known equations, (6), (7), (8), can be used to estimate the intensity of rainfall over t for an assigned recurrence interval if adequate data are available.

$$r_t = a/(t+b) \quad \cdots\cdots (6)$$

$$r_t = a/t^n \quad \cdots\cdots (7)$$

$$r_t = a/(\sqrt{t}+b) \quad \cdots\cdots (8)$$

where r_t: rainfall intensity for the duration of t; a, b, n: const.

If data on hourly rainfall are lacking, a practical formulation would be required for obtaining rainfall intensity of arbitrary duration from daily rainfall, or, strictly speaking, from maximum 24-hr rainfall which is slightly larger than daily rainfall with small difference usually.

Since high peak discharge occurs from both large and intensive rain on a rural watershed, the average temporal distribution of the hourly intensity of such rain is important in practical use. The following equation is in use for such purpose,

$$r_t = \frac{R_{24}}{24}\left(\frac{24}{t}\right)^n \quad \cdots\cdots (9)$$

where r_t: average rainfall intensity over t hr in mm/hr; R_{24}: maximum 24-hr rainfall in mm; which is usually replaced by daily rainfall after appropriate correction; n: const. 1/3–2/3 (average: 1/2).

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(4) Probability analysis of rainfall by lognormal distribution

Since the distribution of annual maximum daily rainfall is empirically approximated by lognormal distribution, daily rainfall of arbitrary recurrence interval can be calculated using equations (11), (12), (13), (14) after the transformation to normalization by equation (10).

$$y = a \log \frac{x+b}{x_0+b} \quad or \quad \log(x+b) = \log(x_0+b) + \frac{1}{a} \cdot y \cdots\cdots(10)$$

where y: transformed variate; x: original variate; a, b: parameter; x_0: average value of original variate.

The procedure for calculation is as follows (Iwai's method)[2]:

(1) Calculation af approximate value of x_0:

$$\log x_0 = \frac{1}{n}\sum_{i=1}^{n} \log x_i \cdots\cdots(11)$$

(2) Calculation of b:

$$b = \frac{1}{m}\sum_{j=1}^{m} b_j \qquad m \doteqdot \frac{n}{10}$$

$$b_j = \frac{x_s x_t - x_0^2}{2x_0 - (x_s + x_t)} \cdots\cdots(12)$$

(3) Calculation of x_0:

$$\log(x_0 + b) = \frac{1}{n}\sum_{i=1}^{n} \log(x_i + b) \cdots(13)$$

(4) Calculation of a:

$$\frac{1}{a} = \sqrt{\frac{2}{n-1}\sum_{i=1}^{n}\left(\log \frac{x_i+b}{x_0+b}\right)^2} \cdots\cdots(14)$$

where x_s and x_t are the j-th largest and smallest value of x_i.

Calculation of the parameters in equation (10) by the above-mentioned procedure makes it possible to estimate annual maximum daily rainfall of the assigned recurrence interval which determines y value as in Table 3.

(5) Probability analysis by extremal distribution

The extremal distribution proposed by Gumbel[3] is shown in equation (15).

$$\left.\begin{array}{l} F(x) = exp(-e^{-y}) \\ y = a(x - x_0), \quad x = x_0 + \frac{1}{a}\cdot y \end{array}\right\} \cdots\cdots(15)$$

The parameters a and x_0 are expressed as equation (16) by definition.

$$a = \frac{\sigma_y}{\sigma_x}, \quad x_0 = m_x - \frac{m_y}{a} \qquad \cdots\cdots(16)$$

where σ_x, σ_y: standard deviation of x and y; m_x, m_y: mean of x and y.

For a large sample size, m_x, m_y, σ_x, and σ_y can be reasonably replaced by sample mean, 0.5772 (Euler's constant), sample standard deviation, and 1.28255 ($=\pi/\sqrt{6}$) respectively. But for a small sample size, m_x and σ_x should be replaced by corrected values to sample size as proposed by Gumbel[3] or Kadoya[4].

The recurrence interval determines y value as in Table 4.

2) Runoff computation

(1) Outline

Rational formula is normally used to compute peak discharge. Discharge hydrographs are drawn using one of the following methods: unit hydrograph method, runoff function method, storage function method, kinematic wave method, and tank model method.

(2) Rational formula

This formulation is shown as equation (17)

$$Q = \frac{1}{3.6} r_e A \cdots\cdots(17)$$

Table 3. Probability of exceedance W(x) or recurrence interval T and y value

Recurrence interval	W(x)=1/T	y	Recurrence interval	W(x)=1/T	y
100	0.010	1.645	10	0.100	0.906
50	0.020	1.452	5	0.200	0.595
20	0.050	1.163	2	0.500	0.000

Table 4. Probability of exceedance $W(x)$ or recurrence interval T and y value

Recurrence interval	$W(x)=1/T$	y	Recurrence interval	$W(x)=1/T$	y
100	0.010	4.60015	10	0.100	2.25037
50	0.020	3.90194	5	0.200	1.49994
20	0.050	2.97020	2	0.500	0.36651

where Q: peak discharge in m^3/sec; A: catchment area in km^2; r_e: effective rainfall averaged over the time of concentration t_c of a watershed in mm/hr.

The effective rainfall r_e may be computed by either equation (18) or (19).

$$r_e = f \cdot r \quad \cdots\cdots(18)$$

$$r_e = r - f_c \quad \cdots\cdots(19)$$

where r: rainfall having the duration of t_c and an assigned recurrence interval in mm/hr; f: coefficient of runoff; f_c: minimum constant infiltration capacity averaged over a watershed.

Some typical values of coefficient of runoff are shown in Tables 5 and 6.

Table 5. Coefficient of runoff for peak discharge in Japan

Catchment conditions	Coeff. of runoff
Steep mountain	0.75~0.90
Tertiary mountain	0.70~0.80
Hilly land and forest	0.50~0.75
Flat upland field	0.45~0.60
Irrigated paddy field	0.70~0.80
A river in mountainous area	0.75~0.85
A small river in flat land	0.45~0.75
A large river more than half of whose basin consists of flat land	0.50~0.75

Time of concentration is defined as the time for rain-water to travel from the remotest point to gauging point along the water course, but there are some difficulties in determining its value in actual cases.

Time of concentration t_c is supposed to be the sum of the travel time on a slope t_s and that in a water course t_w.

Rziha's formula, equation (20), is often used to estimate t_c for relatively large watershed where t_c is supposed to approximate to t_w.

Table 6. Coefficient of runoff for peak discharge and surface conditions

Surface conditions of catchments	Coeff. of runoff
Sandy soil derived from weathered granite, deep top soil	0.1~0.2
Sandy soil derived from weathered granite, thin top soil	0.5~0.7
Volcanic ash soil	0.2~0.35
Mountainous or hilly area covered with deep top soil derived from palaeozoic or mesozoic formations	0.5~0.7
Mountainous or hilly area covered with thin top soil derived from tertiary formations	0.6~0.8
Urbanized area with adequate pavement	0.9~1.0

$$\begin{aligned} T_1 &= l/w_1 && \text{(sec)} \\ T_2 &= l/w_2 && \text{(hr)} \\ w_1 &= 20(h/\ell)^{0.6} && \text{(m/sec)} \\ w_2 &= 72(h/\ell)^{0.6} && \text{(km/hr)} \end{aligned} \quad \cdots\cdots(20)$$

where h: the fall between gauging point and uppermost point of water course in meter, ℓ: horizontal distance between gauging point and uppermost point of water course in meter, w_1: flood spreading velocity in m/sec, w_2: flood spreading velocity in km/hr.

For a relatively small watershed, travel time on a slope t_s should be added to the value which is calculated from Rziha's formula. The estimation of t_s can be made using either assumed traveling velocity of 10–30 cm/sec or kinematic wave theory explained later.

An example of the time of concentration is shown in Fig. 3.

The time of concentration calculated from Kirpich's formula is drawn between the lines

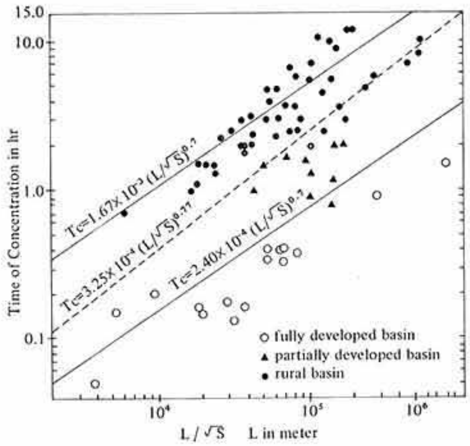

Fig. 3. Tc vs. $L/\sqrt{S}$ (F. Yoshino, partially modified)

of rural and urban watersheds.

A unique formula proposed by M. Kadoya is shown in equation (21)

$$t_c = CA^{0.22}\, r_e^{-0.35} \cdots\cdots\cdots\cdots\cdots\cdots (21)$$

where t_c: time of concentration in minute; A: watershed area in km^2; r_e: intensity of effective rainfall averaged over t_c; $r_e = f\cdot r$, where f is coefficient of runoff and r is the intensity of rainfall averaged over t_c; C: const. corresponding to land use of watershed, that is, C=290 for forest and upland field, C=200 for pasture, C=60–90 for urbanized area.

(3) Unit hydrograph method

This well known method, proposed by L. K. Sherman in 1932, is one of the most popular methods for the analysis of rainfall-runoff relations. It is based on the two assumptions that rainfall-runoff process should be linear and time-invariant. Although rainfall-runoff process may be essentially nonlinear, local linear approximation may be reasonable for many practical purposes.

A mathematical expression of this method is shown in equation (22).

$$Q(t) = \int_0^t h(\tau) r(t-\tau)\, d\tau \cdots\cdots\cdots\cdots\cdots (22)$$

where $h(\tau)$: unit hydrograph; $r(t\text{-}\tau)$: effective rainfall; $Q(t)$: runoff.

The discrete equation corresponding to the above equation is as follows.

$$Q_k = \sum_{i=1}^{\ell} U_i\, r_{k-i+1} \cdots\cdots\cdots\cdots\cdots\cdots (23)$$

where U_i: unit hydrograph or distribution factors; r_{k-i+1} effective rainfall; ℓ: the number of distribution factors corresponding to the base length of a unit hydrograph; Q_k: runoff. Cares must be taken in using unit hydrograph for computing design flood as follows:

(a) If a unit hydrograph is computed from a short-duration rainfall, uniform areal distribution of the rain should be confirmed.

(b) Since a unit hydrograph is likely to change according to the magnitude of flood, a set of unit hydrographs may well be prepared in practice according either to the intensity of rainfall for sloping watersheds or to the cumulative amount of rainfall for low-lying basins.

(c) Unit time for computation may be chosen as about half of lag time of peak discharge. The lag time is 1–4 hrs for mountainous watersheds and 4–6 hrs for low-lying basins in Japan.

(d) Effective rainfall can be computed using either cumulative-rainfall-vs.-cumulative-losses relation or infiltration capacity as in equation (24) and (25).

$$\left.\begin{aligned}
&R_L = aR^n,\ R_e = R - R_L,\ R_L \leqq R_{Lu}\\
&R = \sum_{i=1}^{n} r_i,\ R_L = \sum_{i=1}^{n} r_{Li},\ R_e = \sum_{i=1}^{n} r_{ei}\\
&r_{Lk} = a\left(\sum_{i=1}^{k} r_i\right)^n - \sum_{i-1}^{k-1} r_{Li},\ r_{ek} = r_k - r_{Lk},\\
&\text{if } r_k \leqq r_{Lk}, \text{ then } r_{ek} = 0
\end{aligned}\right\} \cdots (24)$$

where R_{Lu}: upper limit of losses; r_{Li}: losses in the i-th time interval

$$\left.\begin{aligned}
&f(t) = f_c + (f_0 - f_c)e^{-kt}\\
&f_i = \int_{(i-1)\Delta t}^{i\Delta t} f(t)\, dt\\
&r_{ei} = r_i - f_i, \text{ if } r_i \leqq f_i, \text{ then } r_{ei} = 0
\end{aligned}\right\} \cdots\cdots\cdots (25)$$

where $f(t)$: infiltration rate at t; f_c: minimum constant infiltration rate; f_0: initial infiltration rate; Δt: time increment; f_i: infiltration in the i-th time interval.

(4) Runoff function method

This method uses a mathematical function, equation (26), as a substitution for unit hydrograph.

$$U(t)=\frac{1}{K\Gamma(n)}(t/k)^{n-1}e^{-t/k} \quad \cdots\cdots(26)$$

where $U(t)$: instantaneous unit hydrograph; n, k: const.; Γ: gamma function; e: the base of natural logarithm.

(5) Storage function method

This method can be outlined as the routing of rain water through nonlinear reservoir with a proper time lag taken into account. It is based on the following equation.

$$S_l=KQ_l^p$$
$$I-Q_l=\frac{dS_l}{dt} \quad \cdots\cdots(27)$$

where S_l: apparent storage in watershed in m^3, Q_l: discharge in m^3/sec with a proper time lag T_l, $Q_l(t)=Q(t+T_l)$; I: inflow in m^3/s into the watershed K, P: const. Inflow I can be computed using equation (28).

$$I=\frac{1}{3.6}\sum_j r_j f_j A_j \quad \cdots\cdots(28)$$

where A_j: area in km^2 of j-th block in a watershed; r_j: average rainfall in mm/hr on j-th block; f_j: coefficient of runoff for j-th block.

This method is based on the assumption that apparent storage in a watershed S_l can be a single-valued function of lagged discharge Q_l if proper time lag is taken into account. The lag time T_l must, accordingly, be chosen to meet the above-mentioned condition by trial-and-error method.

Actual procedures are as follows.

(a) If the time t_1' and t_2' are chosen on both side of peak discharge of a hydrograph so that the discharges at t_1' and t_2' may be equal to each other and if T_l is assumed properly, then coefficient of runoff f can be computed using equation (29) together with $t_1=t_1'-T_l$ and $t_2=t_2'-T_l$.

$$f=\int_{t_1'}^{t_2'}Qdt \Big/ \int_{t_1}^{t_2}\frac{rA}{3.6}dt \quad \cdots\cdots(29)$$

(b) Apparent storage in watershed can be estimated using equation (30) with $t=t'-T_l$.

$$S_l(t')=\int_0^{t}\frac{frA}{3.6}dt-\int_0^{t'}Qdt \quad \cdots\cdots(30)$$

(c) S_l-vs.-Q_l relation should be drawn on a graph so as to reduce it to a single-valued functional relation with proper time lag chosen.

(d) If f, T_l, K, and P are assumed, flood discharge can be computed either numerically or graphically using equation (27) together with a given rainfall. Some difficulties are pointed out about this formulation as follows.

(a) The determination of lag time is not easy in some actual cases.

(b) Although the lag time is fixed to a value specific to watershed characteristics in this formulation, it should be essentially variable according to the magnitude of flood.

(6) Kinematic wave method

In this method, a watershed is divided into several blocks and is assumed to be an assembly of several rectangular slopes and adjoining channels, and the movement of the direct runoff therefrom is assumed to take place in accordance with equation (31) and (32) presented in m-sec units.

(1) Basic equation for the flow over a slope

$$h=kq^p$$
$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=\alpha r_e \quad \cdots\cdots(31)$$

where h: water depth; q: discharge per unit width; x: distance along the slope; t: time; r_e: effective rainfall in mm/hr; and

$$\alpha=\frac{1}{3.6}\times 10^{-6};\ k,\ p\text{: const.}$$

(2) Basic equation for the flow in a channel

$$A=KQ^P$$
$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \quad \cdots\cdots(32)$$

where A: cross-sectional area of the flowing water in a channel; Q: discharge; q: lateral inflow per unit length of the channel; K, p: const.

The working formulae for calculation are shown as follows.

(1) $(r_e)_{i-1\sim i} \neq 0 \quad q_i^p = \frac{(r_e)_{i-1\sim i} \cdot \Delta t_{i-1\sim i}}{k} + q_{i-1}^p$

$$\Delta x_{i-1\sim i} = \frac{q_i - q_{i-1}}{(\alpha r_e)_{i-1\sim i}} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (33)$$

(2) $(r_e)_{i-1\sim i} = 0 \quad q_i = q_{i-1}$

$$\Delta x_{i-1\sim i} = \frac{q_i^{1-p}}{pk} \Delta t_{i-1\sim i} \quad \cdots\cdots\cdots\cdots\cdots\cdots (34)$$

(3) The q at t, which is obtained with $\Sigma \Delta x = \ell$, where ℓ is the slope length, is the runoff q at the time t on the downstream side of the slope.

(4) Q and q are to be substituted for q and αr_e respectively, when using equation (33) for channel flow.

The applicability of this method to sloping urban areas in Japan proved to be excellent, but its applicability to low-lying paddy fields seems not so good as to urban areas.

When Manning's formula is adopted in the equation of motion, p and k in equation (31) take the values of 0.6 and $\left(\frac{N}{\sqrt{\sin\theta}}\right)^{0.6}$, respectively, where θ is the angle of a slope and N is equivalent roughness of the slope. Equivalent roughness is analogous to Manning's roughness for a channel but the model-building of a watershed makes its physical meaning a little vague.

A proposal for the value of N was made by M. Kadoya et al. as shown in Table 7.

Table 7. Equivalent roughness (N) for various watershed conditions (M. Kadoya et al.)

Watershed conditions	Equivalent roughness N ($m^{-1/3}$. sec)
Forest	0.6~2.0
Pasture, golf links, and upland field	0.3~0.5
Urbanized area with adequate pavement	0.01~0.04
Paddy field	2~3

(7) Serial storage model or tank model

When applied to flood flow analysis or synthesis, this model should be used with relatively short unit time.

An example of this model is shown in Fig. 4.

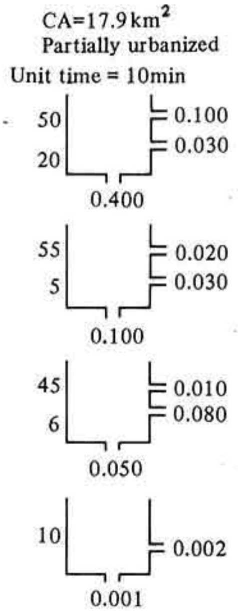

Fig. 4. Tank model for flood discharge (T. Kinosita)

Application of hydrology to soil conservation

1) Outline

Soil conservation project should be planned to meet such conditions as follows.

(1) Individual works should be designed after a close deliberation of erosive factors and a pertinent consideration of regional characteristics of erosion.

(2) A comprehensive plan should be worked out on drainage canal network and cropping system in order to maintain a high productivity of farm land.

(3) The plan should serve to improve farm management and land-use, and is conformed to a regional development plan in its purpose and dimension.

(4) A drainage canal on sloping land should have capacity enough for peak discharge from design rainfall. Furthermore, any serious damage must not be caused even by a heavier than the design rainfall.

(5) The recurrence interval of design peak discharge is normally 10 years for main and greater lateral drainage canals and 5 years for lateral drainage canals.

2) Runoff computation

Design peak discharge is normally computed using the Rational formula as explained in (2) Rational formula in page 89.

Care should be taken of the reduction of time of concentration by installation of lateral drainage canals and also by rectification of main drainage canals.

The reduction of time of concentration for a slope may be estimated using equation (35).

$$tc'/tc=\left[\left(\frac{B'}{\sqrt{s'}}\right)\Big/\left(\frac{B}{\sqrt{s}}\right)\right]^{0.6} \quad\cdots\cdots\cdots\cdots(35)$$

where tc, tc': time of concentration for a slope before and after the installation of a lateral canal; B, B': length of the slope before and after the installation; s, s': gradient of the slope before and after the installation.

References

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