TRAINING COURSE

ON

RESERVOIR OPERATION

(UNDER WORLD BANK AIDED HYDROLOGY PROJECT)

Module 16

Reservoir Inflow Assessment

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RESERVOIR INFLOW ASSESSEMENT

1.0 INTRODUCTION

Inflow to the reservoir is required for its capacity determination and operation. The methodology for the computation of reservoir inflow depends upon the many factors prominent among them are the temporal and spatial scales. For example, real time operation of reservoir requires the estimation of flood hydrograph in real time as inflow to the reservoir during the flood period. Ten daily, monthly, seasonal, or annual inflow values are needed to formulate the reservoir operation policies for various utilisations. A series of reservoirs existing (or proposed) on a river system requires information regarding inflow for each reservoir at different time scales.

Many factors affect the inflow depending upon the period of its determination. Some of these factors are interdependent. These factors can be classified as (i) meteorologic factors, and (ii) watershed factors. Space-time distribution of precipitation amount, intensity and duration, and space time distribution of temperature are some of the important meteorological factors. Some important watershed factors include surface vegetation, soil moisture, soil characteristics, surface topography, and drainage density. In addition to these other factors, which include pondage of artificial reservoirs, diversion of water to the neighbouring basin or within the same basin to fulfil the water demands, cultivation and change in land use practices such as afforestation, deforestation or urbanization, etc., also influence the water yield considerably.

Determination of inflow is required for solution of a number of water resources problems. Prominent among them are:

(i) Design of storage facilities;
(ii) Determination of minimum amounts of water available for agricultural, industrial or municipal use;
(iii) Estimation of future dependable water supply for power generation under varying patterns of rainfall;
(vi) Planning irrigation operation;
(v) Design of irrigation projects, etc.

There are several approaches to determine the inflow. Most of these approaches can be broadly classified in two groups:

- (a) Statistical and stochastic approaches;
- (b) Deterministic approaches, which may be further classified in two sub groups:
  - (i) Empirical approaches
  - (ii) Watershed Modelling approach

In the present lecture, methodology for the assessment of reservoir inflow has been discussed. It involves the development of the rainfall-runoff relationships based on statistical and stochastic approaches. This lecture presents the methodology, in brief, for the computation of synthetic inflows using either frequency analysis approach or time series modelling approach, in case only flow records are available. Some of the methods based on deterministic approaches are also presented. It is to be noted that the methods are greatly influenced by the selection of period for which the inflow is to be determined. Normally, larger the time period, simpler the determination. The time period of interest is generally equal to storm duration, a day, a month, a season, or a year.

2.0 VOLUMETRIC RAINFALL-RUNOFF RELATIONSHIP USING STATISTICAL AND STOCHASTIC APPROACHES

Volumetric rainfall-runoff relationships over the time periods of the day, month, season and year may be developed using the statistical and stochastic approaches. The development of daily rainfall-runoff relationships using this approach poses some difficulties. However, the problem of relating long term, say monthly, seasonal, or annual volumes of rainfall and runoff is relatively easier. Over a larger period of time, the averaging of a variety of rainfall storms tends to minimise the effect of rainfall intensity and antecedent moisture conditions on the volumetric relationship. Indeed in many cases a simple plot or linear relation may be adequate to define the relationship between annual volumes of rainfall and runoff if the water year is properly selected. In order to develop monthly, seasonal, and annual rainfall runoff relationships linear or non linear regression analysis may be carried out in different forms to relate the runoff with rainfall over the selected time periods and/or some other characteristics. Note that the records of rainfall-runoff used for developing such relationships should be homogeneous. In case some major man made changes occur in the catchment two different relationships must be accomplished:

(i) Relationship between the rainfall-runoff prior to the man made changes; and
(ii) Relationship between the rainfall-runoff after the man made changes.

In order to detect changes in hydrologic response of a watershed the hydrologists generally examine the mass curves for changes in slope. A mass curve is a plot of the accumulation over time of one variable versus the accumulation over time of a second variable. The time period usually selected for such computations is an year.

For developing the above relationships adequate record lengths are needed. In case the records are inadequate for any of the above two relationships, a single relationship may be developed relating the runoff with rainfall together with the factors representing the effects of the man made changes. Step wise regression may be performed to arrive at the suitable form of the rainfall runoff relationship.

2.1 Daily Rainfall-Runoff Relationship

Nash and Barsi (1983) developed a model which relates daily rainfall with daily runoff. The model, originally developed for daily flow forecasting on larger catchments exhibiting seasonality, may also be applied to estimate daily flow corresponding to given daily rainfall values. In the model it was assumed that in a year in which the rainfall on each day is the exactly the seasonal mean for that day, i_d , the corresponding discharges would also agree with their seasonal means, q_d. Hence:

$$i_d \rightarrow q_d \tag{1}$$

An attractive hypothesis was made considering the departures of the rainfall and the discharge from these seasonal means linearly related in any particular year:

$$i - i_d \rightarrow q - q_d \tag{2}$$

$$\text{or } x - y \tag{3}$$

where, $x = i - i_d$

$$y = q - q_d \tag{4}$$

For testing the hypothesis of linearity in the relationship of eq. (3), the values of i_d and q_d

can be obtained by averaging the rainfall and the discharge records for each date d of over the years in the period of calibration, and smoothing by Fourier analysis. The seasonal values of i_d and q_d may be subtracted from the actual values of i and q on each day in order to obtain the departure series for x and y. Thus, the input and output series for x and y of length equal to the number of days in the calibration period are obtained.

Assuming that a general linear relationship with a memory length m exists between the x and y series, as obtained, it may be expressed as a linear multiple regression of y on the m previous x-values as independent variables.

$$y_i = h_i x_i + h_2 x_{i-1} + \dots\dots\dots + h_m x_{i-m+1} \tag{5}$$

where, h = the vector of regression coefficients which represent the discrete series of pulse response, and u_i = the disturbance term. Eq. (5) can also be expressed as:

$$y_i = \sum_{j=1}^{m} h_j x_{i-j+1} + u_i \tag{6}$$

Vector of h values, which are unknown, are estimated by method of least square after minimising the sum of error squares.

The standard errors for the estimates of h can be obtained using the following equation:

$$Se(\hat{h}) = \sqrt{V^{-1} S^2} \tag{7}$$

Vector of h values, which are unknown, are estimated by method of least square after minimising the sum of error squares.

where, $\hat{h}$ = vector of h values.
$Se(\hat{h})$ = standard error of vector, $\hat{h}$
$V = x^T x$ (8)

$$X = \begin{bmatrix} X_1 & 0 & \cdots\cdots & 0 \\ X_2 & X_1 & \cdots\cdots & 0 \\ X_3 & X_2 & \cdots\cdots & 0 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ X_m & X_{m-1} & \cdots\cdot & X_1 \\ X_n & X_{n-1} & \cdots\cdot & X_{n-m+1} \end{bmatrix} \tag{9}$$

and S is an unbiased estimate which is given by:

$$S = \sqrt{\sum_{i=1}^{n} u_i^2 / (n-m)} \qquad (10)$$

here n is the number of daily rainfall or runoff values during the calibration period.

The variance of $\hat{h}_i$ may be obtained by taking the i^{th} term of the principal diagonal of V^{-1} and multiplying by S^2. The standard error of h_i is the square root of its variance. It generally indicates the firmness in the estimation of H.

Having obtained the regression coefficients $\hat{h}$, the y values can be obtained using the following equation:

$$y_i = \sum_{j=1}^{m} h_j X_{i-j+1} \qquad (11)$$

Finally the seasonal mean q_d is added with y values to give the estimates for $\hat{q}$ values. The difference between the observed and computed q values provides a series of residual errors for the calibration period. The series of residual errors may be analysed to identify the following persistence structure:

$$e_i = b_1 e_{i-1} + b_2 e_{i-1-1} + b_3 e_{i-1-2} + \ldots\ldots\ldots b_n e_{i-1-n+1} + E_i \qquad (12)$$

where, l represent lag period to be identified from the analysis.

$b_1, b_2, \ldots, b_n$ are the regression coefficients to be obtained from least square analysis and E_i is the random component of mean zero and standard deviation 1. The estimated daily flow using eq. (11) are updated for the residual errors obtained from eq. (12).

2.2 Monthly Rainfall-Runoff Relationship For Gauged Catchments

In India more than 95% of the annual rainfall is received in monsoon season (normally from June to October). Thus, the rainfall-runoff relationships for monsoon months may be developed using linear rainfall-runoff model. However, during non-monsoon months (Nov-May) most of the runoff appears in the stream as a contribution of ground water reservoir towards stream, i.e. baseflow and contribution of the rainfall is almost negligible during this period. To the same extent few occasional thunder storms may contribute to the stream during non monsoon season. For partially fed basins melt runoff constitutes a part of the stream runoff. At the time of developing the monthly rainfall runoff relationships, it is necessary to identify the monsoon months for the study area as well as type of the basin i.e. fed or rain fed. If the basin is partially fed and partially rain fed, then monthly water equivalents are needed in addition to monthly rainfall data. The form of monthly rainfall-runoff relationships are given below for different conditions.

2.2.1 Monthly rainfall-runoff relationships

(a) Monsoon Months.

I. The simplest expression for runoff from a catchment, in terms of depth of water, is of the form:

$$RO_m = a\,(P_m - I_{am}) \quad (13a)$$
$$RO_m = a\,P_m - a\,I_{am}) \quad (13b)$$
$$RO_m = a\,P_m + b \quad (13c)$$

In the above equations, RO_m represent the runoff for a specific month, P_m is the rainfall for that month and I_{am} represent the initial abstraction of the specific month rainfall which does not become runoff. The coefficient a is the regression coefficient that scale the rainfall to the runoff. The coefficient b, which is also obtained from linear regression equals to $-aI_m$ knowing the values of a and b, interception loss for that specific month can be determined. The form of the relationship given by eq. (13c) is valid for small catchments wherein the contribution of the rainfall appears at the outlet of the catchment within the day.

II. The expression for runoff from large size catchment, in terms of depth of water, may be given in the following form:

$$RO_m = b_1\,(P_m - I_{am}) + b_2\,(P_{m-1} - I_{am-1}) \quad (14)$$

In eq. (14), RO_m is runoff for a specific month, P_m and P_{m-1} are precipitation in the specific month and a month prior to that month respectively, I_{am} and I_{am-1} represent the initial abstractions of the specific month rainfall and from the rainfall in the month prior to the specific month. The coefficients b_1 and b_2, of course, are the regression coefficients that scale the rainfall to the runoff. Eq. (14) may be expanded to:

$$RO_m = b_1\,P_m + b_2\,p_{m-1} - b_1\,I_{am} - b_2\,I_{am-1} \quad (15)$$

If a is substituted for the term $-(b_1\,I_{am} + b_2\,I_{am-1})$, eq (15) converts to:

$$RO_m = a + b_1\,P_m + b_2\,P_{m-1} \quad (16)$$

where $a = -(b_1\,I_{am} + b_2\,I_{am-1})$

The threshold values of I_{am} and I_{am-1} can not be determined exactly. They can only be determined if their relative values are known. For example, assuming $I_{am} = I_{am-1}$, the value of I_{am} may be estimated as:

$$\frac{a}{(b_1 + b_2)}$$

III. In addition to the above the forms of the monthly rainfall-runoff relationships, which could be tried, are given below:

$$RO_m = a + b_1\,P_m + b_2\,RO_{m-1} \quad (17)$$
$$RO_m = a\,P^b_m \quad (18)$$
$$RO_m = a\,(P_m - I_{am})^b \quad (19)$$
$$RO_m = a\,p_m^{b_1}\,RO_{m-1}^{b_2} \quad (20)$$

It is to be noted that a prior estimate for the initial abstraction, I_{am}, is necessary to develop the relationship of the form given by eq. (19) wherein only those records can be utilised that result the values of $(P_m - I_{am})$ greater than zero. Similarly, while developing the relationship of the form given by eq. (20), those records must be excluded which have P_m values equal to zero. Thus, the scope of developing the monthly rainfall-runoff relationships in the form given by eq. (19) and (20) are somewhat limited.

IV. In order to make accurate projections, it may be necessary to use a time-distributed model of the form:

$$RO_m = \bar{RO}_m + b\,(P_m - \bar{P}_m) \qquad (21)$$

In the above equation, it is necessary to estimate the value of b for each month. It requires sufficient data for calibrating the coefficient b for each time period. Here $\bar{RO}_m$ and $\bar{P}_m$ represent the monthly mean runoff and precipitation respectively for the specific month. A time distributed model in the following form can also be used for making an accurate estimation of runoff particularly for large size catchments:

$$RO_m = \bar{RO}_m + b_1\,(P_m - \bar{P}_m) + b_2\,(P_{m-1} - \bar{P}_{m-1}) \qquad (22)$$

(b) Non-monsoon months

During non-monsoon months the contribution of runoff resulting from the precipitation may not be that predominant. Therefore most of the relationships may be developed involving the runoff of the previous months. However, some relationships could be tried retaining the precipitation term in the equation and testing its significance in statistical sense before arriving at the definite conclusions about the form of the relationships for non-monsoon months. The possible forms of relationships which could be tried are:

$$RO_m = a + b\,RO_{m-1} \qquad (23)$$

$$RO_m = \bar{RO}_m + b\,(RO_{m-1} - \bar{RO}_{m-1}) \qquad (24)$$

$$RO_m = \bar{RO}_m + b_1\,(RO_{m-1} - \bar{RO}_{m-1}) + b_2\,(RO_{m-2} - \bar{RO}_{m-2}) \qquad (25)$$

$$RO_m = a + b_1\,RO_{m-1} + b_2\,RO_{m-2} \qquad (26)$$

$$RO_m = a + b_1\,P_m + b_2\,RO_{m-1} \qquad (27)$$

$$RO_m = a\,(RO_{m-1})^b \qquad (28)$$

The relationships for non-monsoon months can also be developed based on non-monsoon flows and annual flows, computed using available data of monthly flows. Non-monsoon flows (RO_{NON}) is usually taken as total of runoff values for seven non-monsoon months within a year. Total runoff for twelve months of a year represents annual flow (RO_{AN}). Two relationships may be obtained in the following steps:

(i) Develop the following relationship between RO_{NON} and RO_{AN}:

$$RO_{NON} = K\,(RO_{AN}) \qquad (29)$$

The value of constants K may be obtained as a ratio of average non-monsoon flow to average annual flow for a site.

(ii) Distribute non-monsoon flows, RO_{NON}, in each of seven months using the following form of relationships:

$$RO_m = K_i (RO_{NON}) \tag{30}$$

The value of K_i for each of seven months may be evaluated as a ratio of average monthly flow for the concerned month to average non-monsoon flow for particular site.

2.3 Monthly rainfall runoff relationships for ungauged catchments

The runoff records are not available for an ungauged catchment. For such catchments it is not possible to develop the monthly rainfall-runoff relationships using the methodology discussed in section 2.2. It involves the regionalization of the regression coefficients estimated for different gauged catchments of a hydro-meteorologically homogeneous region. intercept component of the regression equation may be related with the physiographic characteristics of the catchments. However, the regional values of the slope components may be determined taking their median values from different gauged catchments. The step by step procedures to develop the regional monthly rainfall-runoff relationships are explained taking the following form of relationship:

$$RO_m = \bar{RO}_m + b(P_m - \bar{P}_m) \tag{31}$$

Step (i) : Identify the hydrometeorologically homogeneous region wherein the ungauged catchment is located.

Step (ii): Analyse the monthly rainfall-runoff records of all the gauged catchments in the region and develop monthly rainfall-runoff relationships for them in the form given by eq. (31) for different months.

Step (iii): For a specific month relate the intercept term with the physiographic characteristics of the catchments such as area, length, and drainage density, etc.

Step (iv): For the same month, find out the median value of b from its estimates obtained for different gauged catchments or take the value of b for a catchment having almost similar hydrologic characteristics as that of the ungauged catchments.

Step (v): Repeat step (iii) and (iv) for different months in order to derive the regional monthly rainfall runoff relationships for each month.

Step (vi): For an ungauged catchment, estimate RO_m using the relationship developed at step (iii) for the specific month.

Step (vii): Derive the monthly rainfall-runoff relationship in the form of eq. (31) for the ungauged catchment putting the value of $\bar{RO}_m$ obtained from step (vi) and median value of b obtained from step (iv) for the specific month.

Step (viii): Repeat step (vi) and (vii) for different months.

2.4 Seasonal Rainfall Runoff Relationships

A water year consists of twelve months starting from Ist June of the current calendar year up to 31st May of the next calendar year. The sum of the runoff for five months i.e. June, July, August, September and October represent monsoon runoff (RO_{MON}). Total runoff value for seven non-monsoon months, i.e. November, December, January, February, March, April and May is considered to be non-monsoon runoff (RO_{NON}), as discussed earlier. Thus the sum of monsoon as well as non-monsoon runoff represents the annual runoff (RO_{AN}) which can also be computed as the total runoff of twelve months in a water year. Different form of relationships may be developed for monsoon and non-monsoon runoff.

(a) Monsoon season rainfall-runoff relationship

The following form of the rainfall runoff relationships may be considered for monsoon season:

$$RO_{MON} = a + b\, P_{MON} \quad (32)$$

$$RO_{MON} = a\, .\, RO^{b}{}_{AN} \quad (33)$$

$$RO_{MON} = a\, (RO_{AN})^{b} \quad (34)$$

$$RO_{MON} = a\, P_{AN} \quad (35)$$

$$RO_{MON} = a\, RO_{AN} + b \quad (36)$$

$$RO_{MON} = a\, P_{AN} + b \quad (37)$$

$$RO_{MON} = a\, (P_{AN} - P_{o})^{b} \quad (38)$$

Here, P_{MON} = Rainfall for monsoon season,
P_{AN} = Annual rainfall, and
P_{o} = Threshold value of the rainfall, below which no runoff occurs. It is considered to be lost as initial loss without contributing the runoff.

(b) Non-monsoon season rainfall-runoff relationship

For non-monsoon season, the following form of the relationships may be considered.

$$RO_{NON} = a.\, RO_{AN} \quad (39)$$

$$RO_{NON} = a.\, RO_{MON} \quad (40)$$

$$RO_{NON} = a(RO_{MON})^{b} \quad (41)$$

$$RO_{NON} = a(RO_{AN})^{b} \quad (42)$$

$$RO_{NON} = a(P_{AN})^{b} \quad (43)$$

$$RO_{NON} = a(P_{AN}) \quad (44)$$

$$RO_{NON} = a\, P_{MON} \quad (45)$$

$$RO_{NON} = a.P_{MON} + b.P_{NON}. \quad (46)$$

$$RO_{NON} = a.(P_{MON})^{b} \quad (47)$$

$$RO_{NON} = a.P_{MON} + b \quad (48)$$

$$RO_{NON} = a.(P_{MON} - P_{O})^{b} \quad (49)$$

$$RO_{NON} = a.P_{MON} + b \quad (50)$$

$$RO_{NON} = a.(P_{MON} - P_{o})^{b} \quad (51)$$

$$RO_{NON} = A.\, P_{MON} + B.\, P_{NON} .+ C \quad (52)$$

Here, P_{MON} represents the rainfall during non-monsoon period.

2.5 Annual Rainfall-Runoff Relationships For The Gauged Catchments

For annual (water year) rainfall-runoff relationship the following types of equations may be tried:

$$RO_{NON} = a\ P_{AN} \tag{53}$$

$$RO_{NON} = a\ P_{AN} + b \tag{54}$$

$$RO_{NON} = a\ P_{AN}^{b} \tag{55}$$

$$RO_{AN} = .a\ .(P_{AN}-P_o)^b \tag{56}$$

2.6 Seasonal and annual rainfall-runoff relationships for ungauged catchments

Seasonal and annual rainfall-runoff relationships for ungauged catchments can be developed by regionalizing the regression coefficients, involved in their respective relationships using the methodology discussed in section 2.3.

3.0 FREQUENCY ANALYSIS APPROACH

As discussed above, the regression approach may be used to develop rainfall-runoff relationships on different time scales. In case the rainfall data is not available and only runoff records are available such relationships cannot be developed. In such a situation either frequency analysis approach or time series modelling approach may be used depending upon the nature of the flow series. If the available flow series is random and independent, then some popular theoretical frequency distributions such as log normal, extreme value type I distribution, Pearson type 3 distribution and log Pearson type 3 distribution, etc. may be fitted to the available flow series and best fit distribution is chosen based on some goodness of fit criteria. Alternatively, power transformation technique may be used to normalise the available flow series. The synthetic sequence of inflow series may be generated using the form of the chosen distribution wherein the probability values are considered as the generated pseudo numbers between 0 and 1 using the computer.

4.0 TIME SERIES MODELLING APPROACH

This approach is utilised when the available time series of flow exhibits dependence. The time series models such as auto regressive (AR), moving average (MA), ARMA, ARIMa, etc. may be applied to the historical time series of flows. The synthetic sequences of the flows are generated using those time series models. The best fit model is the one which preserves the statistical properties of the generated flow sequences close to those of the historical flow sequences. The selected time series model is used to generate the synthetic sequence of inflow to the reservoir.

5.0 VOLUMETRIC RAINFALL RUNOFF RELATIONSHIPS USING DETERMINISTIC APPROACHES

As mentioned earlier part of this lecture, the deterministic approaches can be grouped in two classes: (i) Empirical approaches, and (ii) Continuous time simulation approaches i.e. watershed modelling approaches employing the water balance equation. The latter approaches simulates, for most part, the entire hydrologic cycle. These are discussed in other lectures on hydrological modelling. Here some of the empirical deterministic approaches that are greatly influenced by the selection of period for which the water yield is to be determined are discussed

5.1 Volumetric storm rainfall-runoff relationship

Several models have been developed to estimate direct runoff amounts from storm rainfall (Hamon, 1963, Singh and Dickinson, 1975a, 1975b, Kohler and Richards, 1963, Kohler, 1963a, 1963b, SCS, 1964, 1973, Williams and Laseur, 1976, Hewlett, et.al.1977a, 1977b, Linsley et al, 1975). Here only two methods i.e. co-axial Graphical correlation and SCS curve number model have been described for illustrating the storm rainfall runoff relationship. These models consider the important factors affecting storm rainfall-runoff relationship such: (i) the amount of rainfall; (ii) the duration of rainfall; (iii) a parameter in dictating antecedent soil moisture conditions; and (iv) watershed storage.

5.1.1 Coaxial graphical correlation

The coaxial graphical correlation method was developed by Linsley et al. (1949) and is discussed in Kohler and Linsley (1951) and Linsley et al. (1975). This method represents perhaps the earliest satisfactory attempt to estimate storm runoff from a given volume of rainfall.

(a) Selection of Variables

A large number of factors, some of them being interactive, affect the storm runoff. A detailed catalog of these factors is given by Chow (1964). In their analysis Linsley et al. (1949) selected the following independent variables: (1) antecedent precipitation index API; (2) Season or week of the year; (3) storm duration; and (4) storm rainfall. They replaced the dependent variable, storm runoff, by basin recharge, defined as the difference between rainfall and runoff. The reason for selecting these variables are discussed by Kohler and Linsley (1951). Nash (1966) has discussed the motivation underlying this selection.

The variables to be selected for graphical correlations may change from one watershed to another. This is shown by Witherspoon (1961), where he selected storm runoff as the dependent variable and antecedent precipitation index, cover condition, duration of the effective rainfall, and the amount of the effective rainfall as independent variables.

(b) Definition of Variables

The API is a measure of soil-moisture deficiency existing prior to the occurrence of a storm. By assuming a logarithmic recession of antecedent moisture. API can be defined during period of no precipitation as:

$$I_{at} = I_{ao}\ k^{t} \tag{57}$$

where, I_{at} is the API at time t, I is the initial API, and k is a constant. t is usually in days. If I t equals unity:

$$I_{at} = kI_{ao} \tag{58}$$

Thus, the API for any day is equal to that of the a previous day multiplied by k. If it rains on a given day, then the amount of rain must be added to the API of that day. The value of k usually depends upon basin physiography..

API can be computed either from average daily rainfall values over the watershed or from daily rainfall recorded at various stations, which are then averaged. The usual practice to compute API is either to start computations at the end of a dry spell with an assumed flow value thereof or to start computations 2 or 3 week in advance of the first storm with an assumed value equal to the normal 10 day precipitation for the season.

The effective rainfall is the rainfall volume per unit area that generates runoff. The rainfall volume is determined from only those rainfall intensities that are in excess of a specified value, say 1.5 cm/h depending upon the infiltration characteristics, interception, and detention storage. The duration of this effective rainfall is the effective storm duration.

The cover conditions can be defined variously. Their specification by the Soil conservation Service (1975) is one example. Witherspoon (1961) classified these conditions as poor, intermediate, and good. If we follow his classification, then the cover conditions are defined as follows. Poor cover condition is when the surface is not covered by vegetation or vegetative residues. This is a common condition in agricultural watersheds prior to planting or subsequent to harvesting. Intermediate cover condition is when the surface is partially protected by vegetation. This occurs after planting but before the crop reaches its height. Good cover condition is when the surface is fully covered by vegetation, such as a good grass cover or a crop fully grown.

(c) Derivation of Graphical Correlation

The graphical correlation consists of four graphs, designated as A,B,C and D, as shown in Fig.1. The construction of these graphs may involve the following steps.

1. Construct graph A which is a three-variable relation. Plot storm runoff versus API, labelling the points with cover condition and fitting a smooth family of curves representing the various cover conditions.

2. Construct graph B, which plots computed versus observed runoff such that computed runoff is on the vertical scale matching exactly the vertical scale of graph A. Label the points with the effective rainfall duration. The computed runoff is obtained from graph A by entering API and cover condition. A smooth family of curves is then drawn, which incorporate the effect of the effective rainfall duration on storm runoff. Graphs A and B, when combined, represent a graphical relation for estimation of storm runoff from API, cover condition, and effective rainfall duration.

3. Construct graph C by plotting computed versus observed storm runoff, such that computed runoff is on the horizontal scale matching exactly the horizontal scale of graph B. Label the points with the effective rainfall amount. The computed runoff is obtained from graphs A and B in a manner similar to that of step (2) Fit a smooth family of curves, which incorporate the effect of effective rainfall on storm runoff. Graphs A, B and C represent the first approximation of the coaxial graphical correlation.

4. Construct graph D by plotting computed versus observed storm runoff. Computed storm runoff is obtained from graphs A,B and C. This graph is an indication of the overall correlation.

5. Check the accuracy of the first approximation. First graph A can be checked with the assumption that other graphs are correct. The vertical coordinate of an adjusted point and graph A can be obtained by first entering into graph C and then B the observed runoff, effective rainfall amount, and duration. The abscissa for the adjusted point corresponds to the observed API. Therefore, the cover-condition curves must be revised first to the adjusted point so that the relation yields a computed value equal to the observed value.

Likewise, graphs B and C can be checked for the second approximation. Subsequent approximations are made in a like manner. In each case the points are plotted by entering the graph sequence from both ends with observed values to determine the adjusted coordinates.

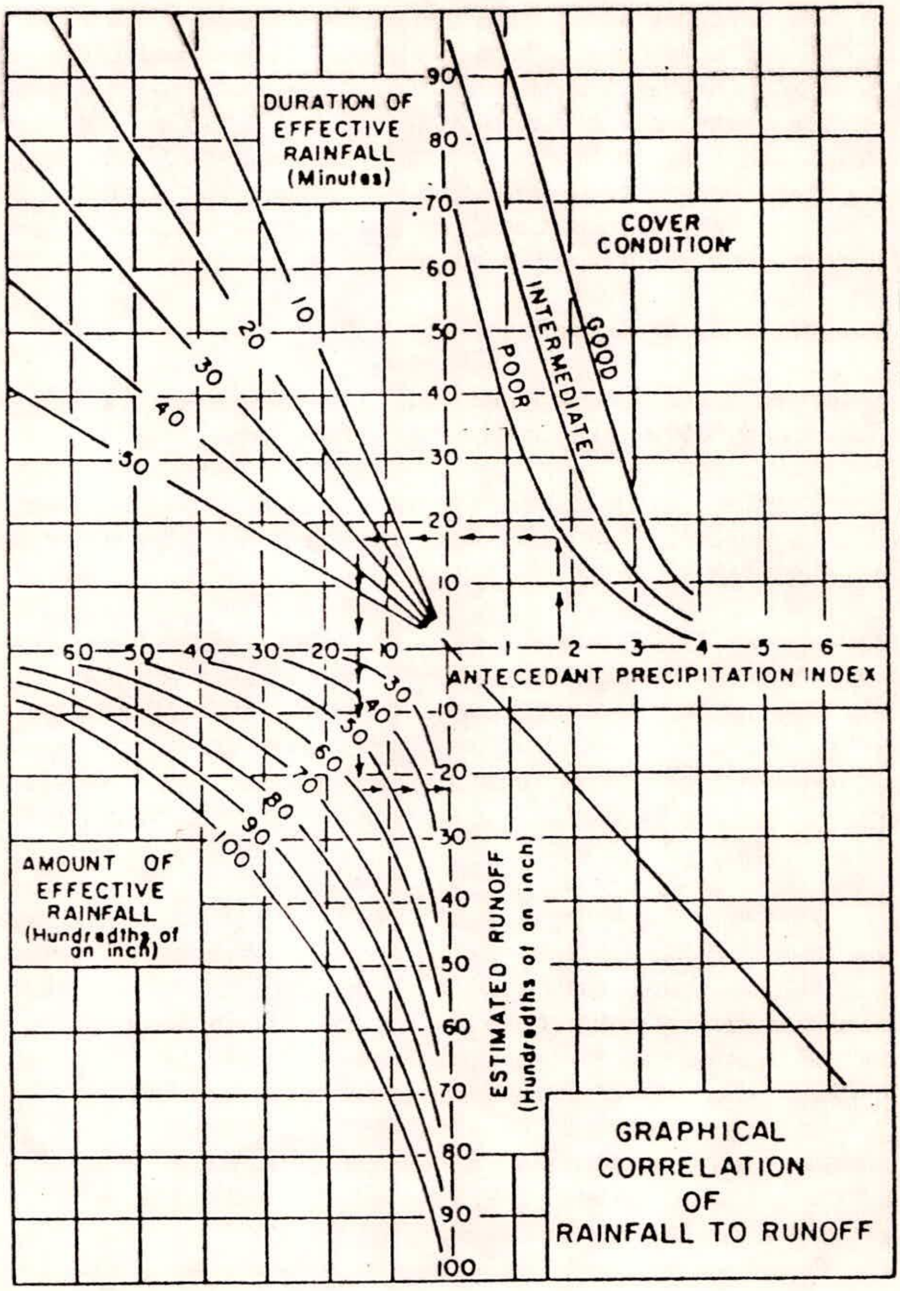

Fig. 1 Co-axial Graphical Method.

(d) Further comments on co-axial graphical correlation

The coaxial method is flexible and predicts storm runoff satisfactorily. Because the variables selected for estimation of runoff are considerably interactive, it is very difficult to develop a regression equation. This problem is circumvented by coaxial correlation.

On the other hand, the coaxial method has certain deficiencies. The method involves successive approximation and it is, therefore, time-consuming. The selection of variables and their plotting in a preferable sequence requires considerable judgement. Only a limited number of variables can be used to keep the method a practically attractive tool. Rainfall intensity has usually been omitted in the analysis. Since rainfall depth and duration are considered, average rainfall intensity becomes an integral part of the coaxial method. This however, does not account for the effect of space-time variations in rainfall intensity on runoff.

5.2 Monthly Volumetric Rainfall-Runoff Relationship

Based on water balance some realistic models are developed. Some of the simple models are:

(i) Water balance Model (Van Der Beken and Byloos, 1977)
(ii) Haan Model (Haan, 1972), and
(iii) TVA Model (Snyder, 1963) etc.

5.3 Yearly Volumetric Rainfall-Runoff Models

The difference between annual rainfall and runoff from a watershed comprises principally evapotranspiration (E) seepage (R) and the change in ground water storage, ΔS:

$$P_{AN} = RO_{AN} + E + R_S + \Delta S \tag{59}$$

The term ΔS in eq. (59) can be negative or positive. If the watershed is watertight and ΔS is negligible, then eq. (59) reduces to:

$$RO_{AN} = P_{AN} - E \tag{60}$$

The simplest linear models for annual volume take form:

$$RO_{AN} = a\, P_{AN} - b \tag{61}$$

Equating eq. (60) and (61) one will get:

$$E = b + P_{AN}\,(1-a) \tag{62}$$

It is thus seen from eq. (61) and (62) that the inflow and evaporation increase linearly with precipitation. This assumption is reasonable in temperature and sub-humid regions where precipitation is moderate and well distributed temporally. On comparing eq. (61) with eq. (59), it is clear that the key to determination of annual inflow is the accurate determination of annual evapotranspiration. Ayers (1962) suggested that the annual evaporation is approximately half the annual precipitation for the relationship expressed by eq. (61). On the other hand, eq. (62) gives a linear relationship between them. Several other types of evapotranspiration-precipitation relationships have been proposed (Pike, 1964; Solomon, 1967; Majtenyi, 1972). Once an accurate estimation for evaporation is made, the hydrologic water balance equation is used for estimating the inflow.

5.4 Watershed Modelling Approach

There are two group of models available, viz. (i) Event based model, and (ii) Continuous model. Event based models are developed to simulate the flood events (flows at shorter time interval, say one hour). These models are normally based on linear system theory. The parameters of these models are estimated from the historical rainfall-runoff records available for the severe flood events. Such models generally provide the estimates for instantaneous unit hydrograph. Principle of linearity is applied to estimate the flood hydrograph. Nash model and Clark model are some of the examples of such type of models which belong to the group of event based models.

The continuous models are developed to simulate the continuous time series of flow available at specific time interval, say daily, monthly, etc. In these models different components of hydrologic cycle are conceptualised in the form of mathematical equations. These components are then integrated together representing their interaction to arrive at the continuous model structure. The continuous models may be classed as: (i) lumped conceptual models, and (ii) physically based distributed models. For computation of reservoir inflow, lumped conceptual models such as Tank Model, HBV Model, and SSAAR Model, etc. are widely used. However, the scope of application of physically based distributed models like SHE Model is limited for this purpose as it requires an extensive data base which is normally not available under the Indian scenario.

6.0 REMARKS

In this lecture two approaches, viz. (i) Statistical and stochastic, and (ii) deterministic have been discussed for the estimation of inflows. Different forms of the relationships have been presented for monthly, seasonal, and annual rainfall-runoff under the first approach. Daily rainfall-runoff relationship has also been presented utilizing the concepts involved in the first approach. The suitable relationships can also be developed for other periods such as weekly, ten daily etc. not discussed in the lecture after trying the various form of the relationships using the first approach. In case only flow data is available frequency analysis approach or time series modelling approach may be used. The methods for volumetric rainfall runoff relationships under second approach have been dealt only in brief. For computing the storm runoff volume, co-axial graphical method which involves the trail and error procedure for drawing the co-axial diagram, may be utilised. This method provides an approximation in the estimation of storm runoff volume. Watershed modelling approach is becoming much popular now-a-days. This approach provides a rational methodology for the computation of the inflows.

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