Chapter IV

CHAPTER IV

WATER RESOURCES ASSESSMENT

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WATER AVAILABILITY ANALYSIS

INTRODUCTION

One of the most important aspects in planning of a water resources development project is to assess the availability of water and its time distribution. Water availability is the life line of any water resources project. The estimation of total quantity of available water and its variability on long term as well as short term basis are the major factors contributing to success of any water resources scheme. Therefore, accurate estimation of water availability is very much essential both for planning as well as operation of a water resources development scheme.

In order to ensure the success of a project, it is necessary to plan it such that desired quantity of water is available on most of the time. Of course some shortage may be permitted in order to make the project cost effective and to have optimum utilization of the scarce water resources. Necessary analyses are to be carried out for identifying the characteristics of the flows which are essentially required in decision making process. In India, the normal practice is to plan an irrigation project with 75% dependable flows. On the other hand, the hydropower and drinking water supply schemes are planned for 90% and 100% dependable flows ,respectively. The various methods for estimation of water yield, its time distribution and flow duration analysis are discussed here under.

Data Requirement for Water Availability Studies

The planning, development and operation of water resources projects is very much dependent upon the availability of requisite hydrological data of desired quantity and quality. The length of data required depends upon the type of scheme, type of development and variability of inputs. Brief guidelines regarding minimum length of data required for some of the projects are given below.

Type of Project	Minimum length of data
(a) Diversion project	10 years
(b) Within the year storage project	25 years
(c) Over the year storage project	40 years
(d) Complex System involving combination of above	Depending upon the pre-dominant element

However the above guidelines are only illustrative and not exhaustive. Many a time ,all the data are not generally available and it becomes necessary to use data of nearby site(s) also.Mutreja(1982) has summarised the data requirement for water availability studies as follows.

(a) Runoff data of the desired specific duration (daily, 10-daily, or monthly etc.) at the proposed site for atleast 40 to 50 years; or

(b) Rainfall data of specific duration for atleast 40 to 50 years for raingauge stations influencing the catchment of the proposed site as well as runoff data of specific duration at the proposed site for the last 5 to 10 years; or

(c) Rainfall data of specific duration of the catchment of the proposed site for the last 40 to 50 years and runoff data of the specific duration and concurrent rainfall data of the existing work upstream or downstream of the proposed site for the last 5 to 10 years or more; or

(d) Rainfall data of specific duration of the catchment for the last 40 to 50 years for the proposed site and runoff data and concurrent rainfall data of specific duration at existing works on a near by river for 5 to 10 years or more, provided orographic conditions of the catchment at the works are similar to that of the proposed site.

Further, the catchment characteristics are also utilised for estimating the dependable flows in case of ungauged catchments. In case the runoff data are not virgin because of construction of water resources structures upstream of the gauging site, the information about reservoir regulation such as outflows from spillway, releases for various uses etc. is required. If the runoff data series consists of the records for the period prior as well as after the construction of the structure, the runoff series is considered to be non-homogeneous. Necessary modifications have to be made to the records belonging to the period prior to the introduction of the structure. So that all available runoff records become homogeneous. Water availability studies are also carried out modifying the runoff records for virgin condition of the catchment.

PROCEDURE FOR WATER AVAILABILITY ANALYSIS

In carrying out water availability studies ,it is always desirable to use the observed runoff data.If long term (say 40 to 50 years)runoff data are not available,the runoff series can be generated by using the rainfall-runoff relationships,which may be for daily, weekly, 10-day, monthly, seasonal and/or annual period. In case rainfall data are not available,but sufficient observed runoff data are available,the same can be used for generation of long term runoff series. using a suitable stochastic model. The stochastic model usually requires atleast 10 to 15 years of daily, 10-daily or monthly record to generate the runoff within the acceptable accuracy.

In case very scanty observed or no data are available, then one has to carry out the special analysis using empirical approaches for generation of necessary data.

For estimation of dependable flow using the runoff series,the runoff series is arranged in descending order. The synthetic year for a particular dependability is calculated from (N+1) years, when N is the number of years for which runoff data are available.

say,runoff data are available for N = 39 years

Hence, 75% dependable item number is $= \frac{(N+1) \times 75}{100}$

$$= \frac{(39+1) \times 75}{100}$$

$$= 30$$

Thus, the runoff corresponding to 30th observation from top in the descending annual flow series will be 75% dependable runoff in this case.In the same way 90%,100%other dependable flows may be computed.

ESTIMATION OF AVAILABLE WATER RESOURCES

The water yield is the integration of discharge for a specified duration .Many factors affect the water yield 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 fulfill 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 water yield 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.
(iv) Adjustment of long records of runoff for varying rainfall regimes for study of time trends in water yields.
(v) Planning irrigation operation
(vi) Design of irrigation projects etc.

The most appropriate and reliable approach for estimation of available water of a river is through field observation of discharges. But many a times, such observed data are not available. Further, the discharge observation is a complicated and time consuming process and therefore the observed data may not be available all the times and therefore it becomes necessary to estimate the runoff from a catchment .

There are several approaches to determine the runoff (water yield) corresponding to a given rainfall. 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 subsequent section, the methodology for the development of the rainfall-runoff relationships based on statistical and stochastic approaches is discussed. Methods based on deterministic approaches are also briefly mentioned. It is to be noted that the methods are greatly influenced by the selection of period for which the water yield is to be determined. Normally, larger the time period, simpler the determination. The time period of interest may be equal to storm duration, a day, a month or a year.

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. Generally for the purpose of project planning in India, the runoff of period less than 10-days period is not used. 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 10-daily, 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.

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.

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. base flow and contribution of the rainfall is almost negligible during this period. To some extent few occasional thunder storms may contribute to the stream during non monsoon season. For partially snow fed basins snow 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. snow fed or rain fed. If the basin is partially snow fed and partially rain fed, then monthly snow water equivalents are needed in addition to monthly rainfall data. The form of monthly rainfall - runoff relationships are given below for different conditions.

MONTHLY RAINFALL-RUNOFF RELATIONSHIPS FOR RAIN FED BASINS

(a) Monsoon Months

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

$$RO_m = a\,(P_m - I_{am}) \tag{1a}$$

$$RO_m = a\,P_m - a\,I_{am} \tag{1b}$$

$$RO_m = a\,P_m + b \tag{1c}$$

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 co-efficient a is the regression coefficient that scale the rainfall to the runoff. The co-efficient 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.(1c) 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:

$$RO_m = b_1(P_m - I_{am}) + b_2(P_{m-1} - I_{am-1}) \tag{2}$$

In eq.(2), 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 co-efficients b_1 and b_2, of course, are the regression co-efficients that scale the rainfall to the runoff. Eq.(2) may be expanded to

$$RO_m = b_1 P_m + b_2 p_{m-1} - b_1 I_{am} - b_2 I_{am-1} \tag{3}$$

If a is substituted for the term $-(b_1 I_{am} + b_2 I_{am-1})$, eq (3) converts to

$$RO_m = a + b_1 P_m + b_2 P_{m-1} \tag{4}$$

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:

$$RO_m = a + b_1 P_m + b_2 RO_{m-1} \tag{5}$$

$$RO_m = a\, P_m^{b} \tag{6}$$

$$RO_m = a\,(P_m - I_{am})^{b} \tag{7}$$

$$RO_m = a\, P_m^{b_1}\; RO_{m-1}^{b_2} \tag{8}$$

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.(7) 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.(7) and (8) are some what limited.

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

$$RO_m = \overline{RO}_m + b\,(P_m - \bar{P}_m) \tag{9}$$

In the above equation, it is necessary to estimate the value of b for each month. It requires sufficient data for calibrating the co-efficient 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:

$$RO_m = \overline{RO}_m + b_1\,(P_m - \bar{P}_m) + b_2\,(P_{m-1} - \bar{P}_{m-1}) \tag{10}$$

(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:

$$RO_m = a + b\ RO_{m-1} \tag{11}$$

$$RO_m = \overline{RO}_m + b\ (\ RO_{m-1} - \overline{RO}_{m-1}\ ) \tag{12}$$

$$RO_m = \overline{RO}_m + b_1\ (RO_{m-1} - \overline{RO}_{m-1}\ ) + b_2\ (\ RO_{m-2} - \overline{RO}_{m-2}\ ) \tag{13}$$

$$RO_m = a + b_1\ RO_{m-1} + b_2\ RO_{m-2} \tag{14}$$

$$RO_m = a + b_1\ P_m + b_2\ RO_{m-1} \tag{15}$$

$$RO_m = a\ (RO_{m-1}\ )^b \tag{16}$$

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}:

$$RO_{NON} = K(RO_{AN}) \tag{17}$$

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:

$$RO_m = K_i\ (RO_{NON}) \tag{18}$$

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.

MONTHLY RAINFALL-RUNOFF RELATIONSHIPS FOR SNOWFED BASINS

For snow fed basins (no contribution from rainfall) monthly rainfall-runoff relationships can be developed exactly in the same forms as discussed above except that in place of rainfall, Pm, the snow water equivalents, Sm, may be used.

MONTHLY RAINFALL-RUNOFF RELATIONSHIPS FOR THE BASINS WHICH ARE PARTIALLY SNOWFED AND PARTIALLY RAINFED

Monthly rainfall-runoff relationships for the partially snow fed and partially rain fed basins can be developed considering the snow water equivalents together with the rainfall. Such types of relationships should be developed in volume terms rather than in terms of depth.

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 above. 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 samè technique can be applied for the analysis of 10-daily or weekly data as well.

VOLUMETRIC RAINFALL RUNOFF RELATIONSHIPS USING DETERMINISTIC APPROACHES.

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 simulate, for most part, the entire hydrologic cycle.

Volumetric storm Rainfall-Runoff Relationships

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). Co-axial Graphical correlation and SCS curve number methods are some of the commonly used rainfall runoff models . 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.

CO-AXIAL GRAPHICAL CORRELATION METHOD

The co-axial graphical correlation method developed by Linsley et al.(1949), 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.

SCS Curve Number Model

The Soil Conservation Service, procedure (SCS), which came into common use in the year 1954, is the product of more than 20 years of studies of rainfall-runoff relationships for small rural watershed areas. The procedure which is basically empirical was developed to provide a rational basis for estimating the effects of land treatment and land use changes upon runoff resulting from storm rainfall. Because of its simplicity, however, its use has spread through the spectrum of hydrologic applications by agriculturists, hydrologists and by soil conservation engineers.

The SCS method is the most widely used method to estimate runoff amounts from agricultural watersheds with areas unto 2500 km^2. It is also the basis of the hydrologic component of several models used for agricultural lands, for example CREAMS model, USDAHL-74 model etc. This method is widely used because i) it is a reliable procedure that has been used for many years in different parts of the world, ii) it is computationally efficient, iii) the required inputs are generally available, and iv) it relates runoff to soil type, land use and management practices.

The volume of runoff depends on both meteorologic and watershed characteristics. The precipitation volume is the single most important meteorological characteristics in estimating the runoff. The soil type, land use and the hydrologic condition of the cover are the watershed factors that will have significant effect on the volume of runoff.

ANALYSIS FOR BASINS WITH LIMITED DATA

In a number of cases, sufficiently long series are not available. As a matter in some cases no data are available at all. This can be overcome by extension of short term flow data or by establishing relationships between rainfall and runoff. In recent years, the application of systems concept of deterministic and stochastic hydrology has led to development of new approaches of synthetic generation of rainfall and runoff data. Some of the cases of dealing with problem of inadequate streamflow data are briefly discussed.

(a) Correlation with the flow of nearby long term base station

A correlation is established by a graphical plotting of the contemporaneous discharges of the flows at the short term and long term stations. The useful practice is to correlate monthly mean discharges, although flood peaks, daily mean flows or annual mean flows could also be used. For removing skewness inherent in river discharge data, the correlations are made in terms of logarithms of the discharges. For each station, the monthly means of the logarithms of the flows during each month are computed and then the monthly deviations for each month are computed from their respective means. The corresponding monthly deviations for two stations are plotted on the graph and a straight line is fitted, 3which is used for data extension. This method is known as W.B. Langbaein's log-deviation method.

(b) Correlation with precipitation records in the drainage basin

As precipitation records are often longer than streamflow records, they provide a basis for extension of streamflow records. In this method, mean precipitation over a catchment is computed for each time interval (say month). The runoff for a given period of time, such as a month is considered as a function of the concurrent and preceding precipitation.

(c) Using Deterministic Hydrologic Models

Long term streamflow data may be obtained using deterministic hydrologic models. In case of cathcment models, the formulation of model is based on processes of the real naturals catchment.

(d) Synthetic generation

When the observed record is too meagre to be considered as a representative smaple, the statistical parameters derived from it can be used to develop a stochastic model that will generate hydrologic record for as long a period of time as desired. As the statistical parameters of the population of the generated data are the same as those estimated from the historical data, so the new information is limited by errors of measurement and sampling that are inherent in the observed record. As far as quality of information is concerned, the new data are no better then the data from which the new data were generated. The major advantage of sequential generation is to create synthetic records longer than the historical records. This can produce desired number of combinations of hydrologic sequences for use in hydrologic analysis. In design of a system of water resources projects, the generated information helps to overcome the paucity of possible patterns of extreme cases by providing a large number of new data sets that could be obtained from the given hydrologic record. This provides flexibility and the possibility of examining the broad spectrum or extent to which a specific design may be overloaded or underloaded by different sets of statistically compatible generated sequences of hydrologic events, leading to a fairly well balanced designs.

FLOW DURATION CURVES

It is a popular method of studying the streamflow variability . A flow-duration curve of a stream is a plot of discharge against the per cent of time the flow was equaled or exceeded. This curve is also known as discharge-frequency curve.For drawing flow duration curve

The streamflow data is arranged in the descending order of discharges, using class intervals. The data used can be daily, weekly, ten daily or monthly values. If N number of data points are used in this listing, the plotting position of any discharge (or class value) Q is

$$P = m/(N+1) * 100\% \qquad (19)$$

where m is the order number of the discharge (or class value), P is percentage probability of the flow magnitude being equaled or exceeded. The plot of the discharge Q against P is the flow duration curve as shown in Fig.1.Arithmetic scale paper, or

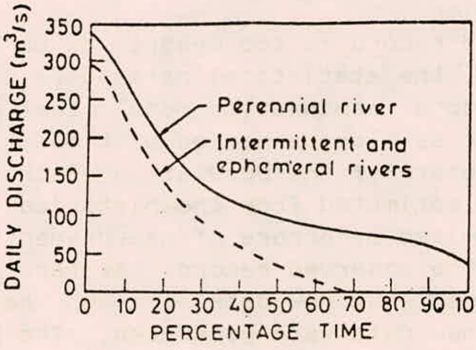

Fig. 1 A typical flow duration curve

semi-log or log-log paper is used depending upon the range of data and use of the plot. The flow duration curve represents the cumulative frequency distribution and can be considered to represent the streamflow variation of an average year. The ordinate Q_P at any percentage probability P represents the flow magnitude in an average year that can be expected to be equalled or exceeded P per cent of time and is termed as P % dependable flow. In a perennial river Q_{100} = 100% dependable flow is a finite value. On the other hand in an intermittent or ephemeral river the streamflow is zero for a finite part of an year and as such Q_{100} is equal to zero.

Some important characteristics of a flow duration curve are :

1. The slope of a flow duration curve depends upon the interval of data selected. For example a daily streamflow data gives a steeper curve than a curve based on monthly data for the same stream. This is due to the smoothening of small peaks in monthly data.
2. The presence of a reservoir stream considerably modifies the virgin-flow duration curve depending on the nature of flow regulation. Fig. 2 shows the typical reservoir regulation effect.

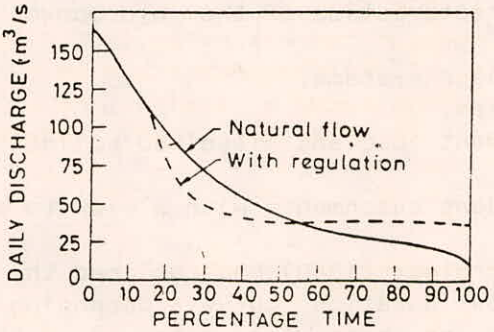

Fig. 2 Reservoir regulation effect on flow duration curve

3. The virgin-flow duration curve when plotted on a log probability paper plots as a straight line at least over the central region. From this property various coefficients expressing the variability of the flow in a stream can be developed for the description and comparison of different streams.
4. The chronological sequence of occurrence of the flow is marked in the flow-duration curve. A discharge of say 1000 cumecs in a stream will have the same percentage P whether it occurred in January or June. This aspect, a serious handicap, must be kept in mind while interpreting a flow-duration curve.

5. The flow-duration curve plotted on a log-log paper is useful in comparing the flow characteristics of different streams. A steep slope of the curve indicates a stream with a highly variable discharge. On the other hand, a flat slope indicates a slow response of the catchment to the rainfall and also indicates small variability. At the lower end of the curve, a flat portion indicates considerable base flow. A flat curve on the upper portion is typical of river basins having large flood plains and also of rivers having large snowfall during a wet season.

Use of Flow Duration Curves

As mentioned above, according to the current practice, the irrigation projects are planned using 75% dependable flow. Hydropower and drinking water projects are planned with 90% and 100% dependable flows respectively. The 90% value is also used as a measure of ground water contribution to stream flow. This same value can also be used as a measure of run-of-the-river hydropower potential. Other important uses of flow duration curves are :

1. In evaluating various dependable flows in the planning or water resources engineering projects,
2. In evaluating the characteristics of the hydropower potential of a river,
3. In the design of drainage systems,
4. In flood-control studies,
5. In computing the sediment load and dissolved solids load of a stream, and
6. In comparing the adjacent catchments with a view to extend the streamflow data.

The Institute of Hydrology (1980) has outlined the procedure for estimating the flow duration curve depending on the availability of data at or near the site of interest. The guidelines suggested for a given length of record are described below.

More than ten years of records - this length of records need no adjustment or standardization as this period of data will probably provide a sufficiently accurate flow duration curve.

Two to ten years of records - for this length of records, divide the daily flow data by the average flow over the period of record before analysis. This overcomes to a great extent the departures due to wet or dry years. The conversion to the long term flow duration curve is made using an estimate of long term average flow.

Less than two years - this length of record may be treated as short records and some indirect approaches are used for flow duration curve computations. These approaches are based on the use of catchment characteristics.

Flow duration Curve for Gauged Catchments

PLOTTING FLOW DURATION CURVES FROM DAILY FLOW DATA

The flow duration curves from daily flow data may be plotted using the following steps :

i. Choose a constant width class intervals (ci)such that about 25 to 30 classes are formed,
ii. Assign each day's discharge to its appropriate class interval,
iii.Count the total number of days in each c i,
iv. Cumulate the number of days - each c i and get the number of days the lower limit of each c. i. to get the number of days above the lower limit. of each c.i.
v. Compute probabilities of exceedence dividing the quantities obtained from step (iv)by total number of days in the record (for example 365 if one year record is considered for the construction of flow duration curve),
vi. Multiply the probabilities of exceedance obtained from step (vii) by 100 to get percentage exceedance,
viii) Plot the probabilities of exceedance in percentage against the corresponding lower bound of class interval on linear graph paper. Sometimes the flow duration curve better approximates to a straight line if log normal probability paper is used in place of linear graph paper.

FLOW DURATION CURVES FOR DIFFERENT DURATIONS

Flow duration curves for other durations (for example 10 days flows) can be prepared as follows :

i. Derive a hydrograph whose values are not simply daily discharges but are average discharger over the previous D days (D-duration of flow duration curve). It is equivalent to the outcome of passing a moving average of D-days duration through daily data. Generally 1, 5, 7, 10, 30, 60, 90, 180 and 365 days are adopted as the standard values for D.
ii. Plot the flow duration curve from the data of discharge hydrograph derived at step (i) using the procedure described previously. Fig.3 illustrates the typical flow duration curves for different durations.

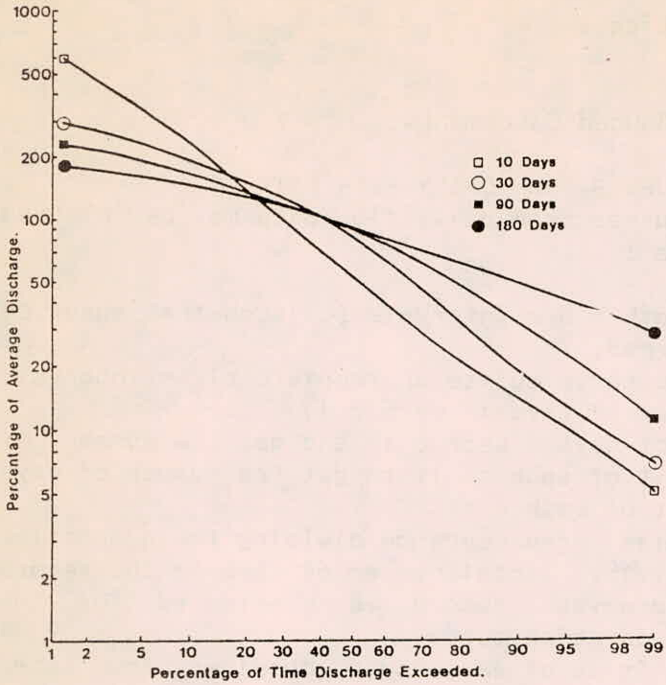

Fig. 3 Flow duration curves for different durations

Flow Duration Curves for Ungauged Catchments

This section describes how the flow duration curve of any duration can be constructed at an ungauged site. This method is based on the relationship between the flow duration curve and catchment characteristics. The latter include catchment rainfall, stream length and base flow index (BFI). The estimates for catchment rainfall and BFI can be easily obtained from the available flow data for the gauged catchments. The stream length can be derived from toposheet.

The procedure for estimating the curve for any duration D is divided into three components, ref. Fig. 4.

a. Estimate the 95 percentile from the 10 day flow duration curve, Q95 (10) expressed as % ADF. This locates point A on the diagram. The regression equations in the following form were developed to use in various regions of the U.K.

$$Q95(10) = a\sqrt{BFI} + b\sqrt{SAAR} + c \qquad (20)$$

BFI is estimated at the ungauged site from catchment geology, SAAR is the standard average rainfall in mm, and a, b, c are the regression coefficients. The estimates of Q95(10) for ungauged catchments can be obtained by substituting the corresponding values of BFI and SAAR in Eq. 20.

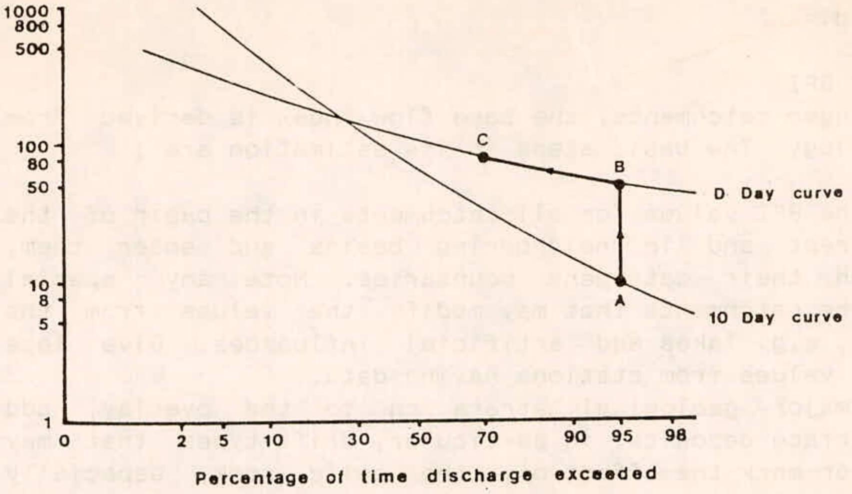

Fig. 4 Flow duration curve estimation for ungauged basins

b. Estimation of the 95 percentile for durations other than the 10 day duration Q95(D). This locates point B on the diagram. The process of obtaining Q95(D) is in two steps:
i. Obtain the gradient or rate of change of Q95(D)/Q95(10) with D, (GRADQ95). The gradient is obtained from the regression equation given in the following form :

$$\log(\text{GRA Q95}) = d\sqrt{\text{SAAR}} + e\sqrt{\text{Q95(10)}} + f \qquad (21)$$

where d, e and f are the regression coefficients.
ii. Calculate Q95(D) using the following equation :

$$\text{Q95}(d) = [1 + (D-10)\text{GRAD Q95}]\ \text{Q95}(10) \qquad (22)$$

here Q95(D) is expressed in % ADF units.
c. Estimation of a percentile other than the 95 percentile QP(D)
This located point c on the diagram. The process of obtaining flow duration percentiles other than 95 consists of multiplying Q95(D) by a factor that is read off a particular type curve from Fig 5. The type curve is determined solely by the value of Q95(D) using the Eq.23 :

$$\text{TC} = \text{nearest integer}\ [10 \log\{\text{Q95(D) as \% ADF}\}] \qquad (23)$$

Find the multiplying factor r, from Fig. 5 which is equal to QP(D)/Q95(D). An estimate of QP(D) can be obtained knowing Q95(D) from the previous step. Note that if only the 95% 10 day discharge for ungauged catchment is required then both steps (b) and (c) can be omitted. If the 95 percentile D day value is required, step (e) can be omitted.

ESTIMATION OF BFI

For ungauged catchments, the base flow index is derived from catchment geology. The basic steps in its estimation are :

i. Assemble the BFI values for all catchments in the basin of the site of interest and in neighboring basins and enter them, together with their catchment boundaries. Note any special features of the catchments that may modify the values from the expected ones, e.g. lakes and artificial influences. Give less weight to BFI values from stations having data.
ii. Mark the major geological strata on to the overlay, add details of surface deposits, in particular, drift types that may differ from, or mark the effect of, the solid rock, especially deposits such as boulder clay overlaying chalk and sand or gravel on clay. The hydrogeological characteristics of the rock on the catchment scale are more important than the detailed stratigraphy.
iii. Collect information on local geology and hydrogeology. Note particularly details of thickness and permeability of the strata and whether there is a possibility that the river bed is incised into underlying rock units. The position of aquifer storage in relation to the base level of spring discharge determines whether the river is spring fed. Note fault lines in relation to the drainage network.
iv. Having collected the information about the flow and catchment geology, the BFIs from gauged catchments must be compared with their geology and this comparison used to estimate the BFI from the solid and drift geology of the ungauged catchment. Catchment having similar hydrogeological characteristics in terms of permeability and storage should be compared and in areas with similar geology . Variations in landscape are of importance. In this context the values of stream frequency and slopes are an objective way of making the comparisons.

The following situations may further be noted :
i. When dealing with medium and large streams the gradation in the BFI value when moving from upstream to down-stream allows one to interpolate a reasonable value, in well gauged basins the value is often obvious.
ii. Isolated catchments can be assessed analogy with gauged

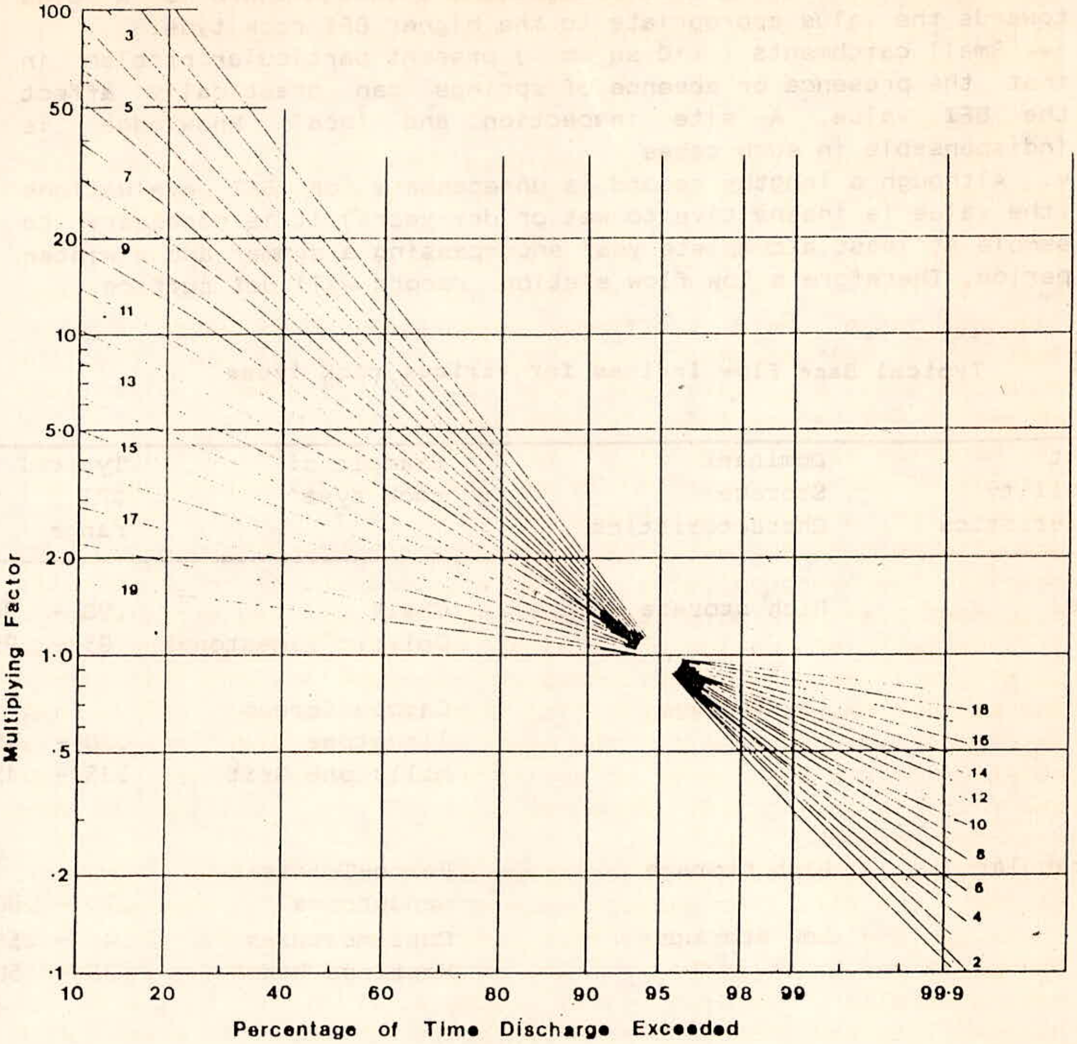

Fig. 5 - Type curves and frequency relationship for flow duration curve.

neighbors or by using the Table- 1 for various rock types and typical BFI values.

iii.The BFI value for catchments containing mixture of rock type can be estimated using area proportions although there is a bias towards the value appropriate to the higher BFI rock type.

iv. Small catchments (<10 sq km) present particular problem in that the presence or absence of springs can drastically affect the BFI value. A site inspection and local knowledge is indispensable in such cases.

v. Although a lengthy record is unnecessary for BFI evaluations (the value is insensitive to wet or dry years) it is necessary to sample at least a complete year encompassing a summer and a winter period. Therefore a low flow station record will not suffice.

TABLE 1 Typical Base Flow Indices for various rock types

Dominant Permeability Characteristics	Dominant Storage Characteristics	Example of rock type	Typical BFI range
Fissure	High storage	Chalk	.90 - .98
		Oolitic limestones	.85 - .95
	Low storage	Carboniferous limestone	.20 - .75
		Millstone Grit	.35 - .45
Intergranular	High storage	Permo-Triassic sandstones	.70 - .80
	Low storage	Coal measures	.40 - .55
		Hastings Beds	.35 - .50
Impermeable	Low storage at shallow depth	Lias	.40 - .70
		Old Red Sandstone	.45 - .55
		Silurian/Ordovician	.30 - .50
		Metamorphic-Igneous	.30 - .50
	No storage	Oxford Clay) Weald Clay) London Clay)	.15 - .45

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WATER BALANCE STUDY

INTRODUCTION

Water balance techniques, one of the main subjects in hydrology, are a means of solution of important theoretical and practical hydrological problems. On the basis of the water balance approach it is possible to make a quantitative evaluation of water resources and their change under the influence of man's activities.

The study of the water balance structure of lakes, river basins, and ground-water basins forms a basis for the hydrological substantiation of projects for the rational use, control and redistribution of water resources in time and space (e.g. inter-basin transfers, stream flow control, etc.). Knowledge of the water balance assists the prediction of the consequences of artificial changes in the regime of streams, lakes and ground water basins.

Current information on the water balance of river and lake basins for short time intervals (season, month, week and day) is used for operational management of reservoirs and for the compilation of hydrological forecasts for water management.

An understanding of the water balance is also extremely important for studies of the hydrological cycle. With water balance data it is possible to compare individual sources of water in a system, over different periods of time, and to establish the degree of their effect on variations in the water regime.

Further, the initial analysis used to compute individual water balance components, and the co-ordination of these components in the balance equation make it possible to identify deficiencies in the distribution of observational stations, and to discover systematic errors of measurements.

Finally, water balance studies provide an indirect evaluation of an unknown water balance component from the difference between the known components (e.g. long-term evaporation from a river basin may be computed by the difference between precipitation and runoff).

THE WATER BALANCE EQUATION

General Form of the Water Balance Equation

The study of the water balance is the application in hydrology of the principle of conservation of mass, often referred to as the continuity equation. This states that, for any arbitrary volume and during any period of time, the difference between total input and output will be balanced by the change of water storage within the volume. In general, therefore, use of a water-balance technique implies measurement of both storage and fluxes (rates of flow) of water, though by appropriate selection of the volume and period of time for which the balance will be applied, some measurements may be eliminated (UNESCO, 1971).

The water balance equation for any natural area (such as a river basin) or water both indicates the relative values of inflow, outflow and change in water storage for the area or both. In general, the inflow part of the water balance equation comprises precipitation (P) as rainfall and snow actually received at the ground surface, and surface and sub surface water inflow into the basin or water body from outside (Q_{SI} and Q_{UI}). The outflow part of the equation includes evaporation from the surface of the water body (E) and surface and sub surface outflow from the basin or water body (Q_{SO} and Q_{UO}). When the inflow exceeds the outflow, the total water storage in the body (ΔS) increases; an inflow less than the outflow results in decreased storage. All the water-balance components are subject to errors of measurement or estimation, and the water balance equation should therefore include a discrepancy term (η). Consequently the water balance for any water body and any time interval in its general form may be represented by the following equation:

$$P + Q_{SI} + Q_{UI} - E - Q_{SO} - Q_{UO} - \Delta S - \eta = 0 \qquad (1)$$

Other Forms of the Water Balance Equation

For application to a variety of water balance computations equation (1) may be simplified or made more complex, depending on the available initial data, the purpose of the computation, the type of body (river basin or artificially separated administrative district, lake or reservoir, etc.) and the dimensions of the water body, its hydrographic and hydrologic features, the duration of the balance time interval, and the phase of the hydrological regime (flood, low flow) for which the water balance is computed.

In large river basins, Q_{UI} and Q_{UO} are small compared with other terms and are therefore usually ignored, i.e. sub surface water exchange with neighbouring basins is assumed to be zero. There is no surface water inflow into a river basin with a distinct water shed divide (assuming no artificial diversions from other basins), and therefore Q_{SI} is not included in the water balance equation of a river basin. Thus, for a river basin equation (1) is usually simplified as follows:

$$P - E - Q - \Delta S - \eta = O \qquad (2)$$

where Q represents the river discharge from the basin.

On the other hand, depending on the specific problem, the terms of equation (1) may be subdivided. For example, in the compilation of water balances for short time intervals, the change in the total water storage (ΔS) in a small river basin may be subdivided into changes of moisture storage in the soil (ΔM) in aquifers (ΔG), in lakes and reservoirs (ΔS_L), in river channels (ΔS_c), in glaciers (ΔS_G) and in snow cover (ΔS_n).Thus in this case the water balance equation becomes:

$$P - E - Q - \Delta M - \Delta G - \Delta S_L - \Delta S_c - \Delta S_G - \Delta S_n - \eta = o \qquad (3)$$

where Q_{SI} represents the net surface water diversion from other basins.

Special Features of the water balance equation for different time intervals

The Water balance maya be computed for any time interval, but distinction may be made between mean water balances and balances for specific periods (such as a year, season, month or number of days), sometimes called current or operational water balances. Water balance computations for mean values and specific periods each have distinctive characteristics.

Mean water balances are usually computed for an annual cycle (calendar year or hydrological year), although they may be computed for any season or month.

The computation of the mean annual water balance is the most simple water balance problem, since it is possible to disregard changes in water storages in the basin (ΔS), which are difficult to measure and compute. Over a along period, positive and negative water storage variations for individual years tend to balance, and their net value at the end of a long period may be assumed to be zero.

The reverse situation occurs when computing the water balance for short time intervals, for which. The shorter the time interval, the more precise are the requirements for measurement or computation of the water balance component, and the more subdivided should be the values of S and other elements. This results in a complex water balance equation which is difficult to close with acceptable errors.

The term must also be considered a in the computation of mean water balances for seasons or months.

Special Features of the Water Balance Equation for Water Bodies of Different Dimensions

The water balance may be computed for water bodies of a any size, but the complexity of computation depends greatly on the extent of the area under study.

A river basin is the only natural area for which large-scale water balance computations can be simplified, since the accuracy of computation increases with an increase in the river basins area.a This is explaianed by the fact that the smaller a the basin area, the more complicated is its water balance, has it is difficult to estimate secondary components of the abalnce such as ground water exchange with adjacent basins; water storage in lakes, reservoirs, swamps, and glaciers; and the dynamics of the water balance of forests, and irrigated and drained land. The effect of these factors gradually; decreased with an increase in the river dbasin area on may finally be neglected.

The complexity of the computation of the water balance of lakes,reservoirs,swamps,ground water basins and mountain-glacier basins tend to increase with increases in area. This is due to a related increase in the technical difficulty of accurately measuring and computing the numerous important water balance components of large water bodies, such as lateral inflow and variations in water storage in large lakes and reservoirs, precipitation on their water surface, etc.

Closing of the Water Balance Equation

To close the water balance equation it is essential to measure or compute all the balance elements, using independent methods wherever possible. Measurements and computations of water balance elements always involve errors, due to shortcomings in the techniques used.a The water balance equation therefore usually does not balance, even if all the components are measured or computed by independent methods. The discrepancy of water balance (n) is given is a residual term of the water balance equation, and included the errors in the determination of the components considered, and the value of components not taken into account by the particular form of the equation being used. A low value of n may indicate only that its component parts tend to balance out.

It is is impossible to obtain the value of a balance component by direct measurement or computation, the component maya be evaluated as a residual term in the water balance equation. In this case, the term includes the balance discrepancy, and therefore contains an unknown error, which may even be larger than the value of the component. Similar considerations apply when measured values asof one component are used to estimate the values of another component through an empirical or semi-empirical formula. The value so estimated will include errors due to the imperfections of the formula and in the measured component, and the overall error is again unknown.

Units for the Components of the Water Balance Equations

The components of a water balance equation maya be expressed as a mean depth of water over the basin or water body (mm), or as a volume of water (m^3), or in the form of flow rates (m^3/sec). The last form is convenient for many water management computations, but is usually computed from a balance which has been derived for a specific time interval.

As the computation of the water balance usually begins with the computation of mean precipitation over the basin, the other compOonents are usually also expressed as depths of water. In the recommended units, transformations between depth and volume are simple, e.g.

$$V = 1\ 000\ A\ S$$

where S is a storage expressed as a mean depth (mm), V is the same storage expressed as a volume (m^3) and A is the area of the basin or water body (km^2).

METHODS OF COMPUTATION OF THE MAIN WATER BALANCE COMPONENTS

Basic Data

Records of precipitation and runoff from the network of stations are the basic data for computation of the water balance components of river basins for longs-term periods. These records are published in hydrological and meteorological year-books, bulletins etc.

To compute the water balance for individual years, season, or months, it is necessary in addition to have data on water storage variations in the basin. These are sobtaianed from snow surveys, observations of soil moisture, water-level fluctuations in lakes and ground water fluctuations in wells.

The compute the water balance of small areas with specials features in the water balance (mountain glacier basins, large forest areas, irrigated land, etc.), it is necessary in most cases to organise a special programame of observations, eg. observation of glacier ablation, interception of precipitation, soil moisture, etc.

To compute evaporation it is desirable to have data from evaporation pans or tanks and meteorological data on temperature, humidity, wind, cloudiness, and radiation.

Maps and Atlases

When there is an absence or shortage of observational data on precipitation runoff or evaporation in a river dbasin, regidsonal maps and atlases of means values of these elements maya be useful (Nordenson, 1968; GUGK; Solkolov, 1961; Sokolov, 1968). With the help of these isonline maps it is possible to determine the mean values of precipitation, runoff and evaporation for any area by planimetering.

The principal methods for preparing these maps are described standard text. At this point it should be noted that for water-balance computations the maps .of annual precipitation, evaporation and runoff must be co-ordinated, i.e. precipitation, minus evaporation and runoff, all evaluated by isoline maps evaporation and runoff, all evaluated by isoline maps must be equal to zero in conformity with the equation for the mean water balance of a river basin (GUGK and USSR Academy of Sciences, 1964):

$$\overline{P} - \overline{E} - \overline{Q} = 0 \qquad (4)$$

The co-ordination of the three maps is performed on the basis of an evaluation of the reliability of each map. Usually, the runoff map is the most reliable (with the exception of arid areas with aphemeral streams, once the data on discharge at a gauging section automatically integrate the depth of runoff for the basin. Runoff maps are therefore usually used for correction, as well as coordination, of precipitation and evaporation maps.

(Refer Publication entitled Methods for Water Balance Computations, edited by A.A. Sokolov, T.G. Chapman, the UNESCO Press; 1974)

TYPICAL WATER BALANCE STUDY

In this study an attempt has been made to establish the water balance of India by estimating components of atmospheric water balance, hydrologic water balance, ground water balance and water use balance using available information and data. Some components have been evaluated indirectly as residual terms in balance equations. It has been found that out of 165 million hectare of cropped area of the country (23 percent already under irrigation) the irrigation facilities could be extended to a maximum of 73 percent and the remaining cropped area would remain under rainfed cultivation.

In the present study the components of the following interlinked mean water balance equations on an annual basis have been estimated for the country using data available from reports of irrigation Commission and India Meteorological Department .and other relevant data.

1) Atmospheric Water Balance
2) Hydrological Water Balance
3) Water Use Balance
4) Ground water Balance

ATMOSPHERIC WATER BALANCE

The atmospheric water balance equation for the country can be written by considering inflow equal to outflow plus change in storage as below :

$$V_I + E_T + V_{AI} = P + V_O + V_{AE} + \eta$$

Here V_I represents inflow of water vapour from land routes and sea routes, E_T is the total evapotranspiration and V_{AI} is the initial water vapour present in the atmosphere, P is total precipitation, V_o is the outgoing water vapour, V_{AE} is the water vapour present at the end of period under consideration, and η represents discrepancy of water balance. The term η is a residual term of the water balance equation and includes the errors in the determination of the components considered as well as the values of components not taken into consideration. (Fig. 1.)

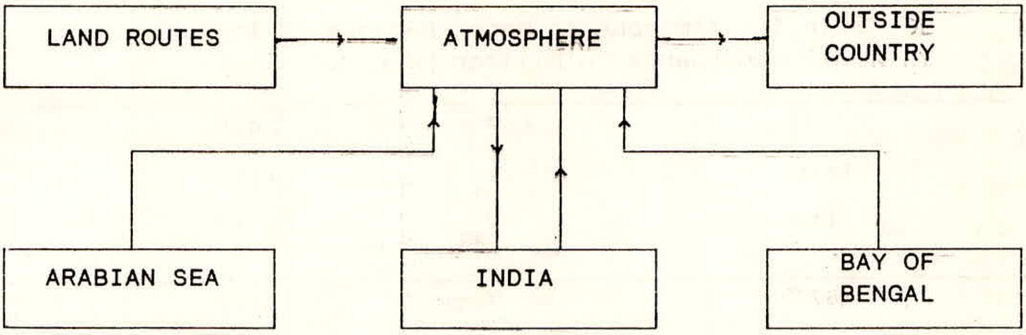

Fig. 1: Atmospheric Water Balance

On the basis of observations by India Meteorological Department the average annual values for inflow of water vapour from Arabian Ocean has been estimated as 77- million ha. metres and from Bay of Bengal as 370 million ha. metres of water. The inflow of water vapour from land routes mostly during non-monsoon months has been estimated as 300 million ha. metres of water which also includes winter rains in South. This has been arrived at by considering, available information of non-monsoon rainfall of 100 million ha. metres and possibility of 33 percent of water vapour precipitating as rain during non-monsoon moths. The water vapour present at the beginning and end of year has been assumed to be same and it has been estimated from available data of IMD as equivalent to 40 mm of precipitable water over the total area of the country. This cores as 13 million ha. metres of water. The estimate of total precipitation and total evapotranspiration have been obtained by IMD on the basis of data of raingauge network and evaporimeter network over the country. The average annual rainfall for the whole area of India has been estimated as 119.4 cm. depth which is equal to 392 million ha. metres of water. The data for snowfall is not available for a reliable estimate, however, the total precipitation, P including rain as well as snow has been estimated as 400 million ha. m. The total evapotranspiration has been estimated on the basis of detailed estimate of water use balance (as discussed later) at 254 million ha.m.

Substituting the estimated values of V_I, E_T, V_{AI}, P and V_{AE} in the equation of atmospheric water balance, the outgoing water vapour V_o has been estimated as 1264 million ha.m. which includes the discrepancy term η . The results of atmospheric water balance are given in Table 1.

Table 1 : Atmospheric Water Balance of India
(All components in million ha.m. of water)

V_{AI}	13	P	400
V_I	1410	V_o	1264
E_T	254	V_{AE}	13
Total	1677	Total	1677

HYDROLOGIC WATER BALANCE

The equation for hydrologic water balance of the country for average annual conditions can be written as:

$$P + I = Q_S + E_T + Q_g + \Delta S + \eta$$

where P represents total precipitation and E_T represents total evapotranspiration in million ha.m. of water as explained under atmospheric water balance, I represents total inflow as surface water (I_s) and ground water (I_g), Q represents total outflow as surface water to oceans and other countries (Q_s) as well as ground outflow (Q_g), S represents change in soil moisture storage.

All the acomponents of water balance equation are in million ha.m. of water and the term η represents the discrepancy of water balance. A diagrammatic representation is shown in Fig. 2.

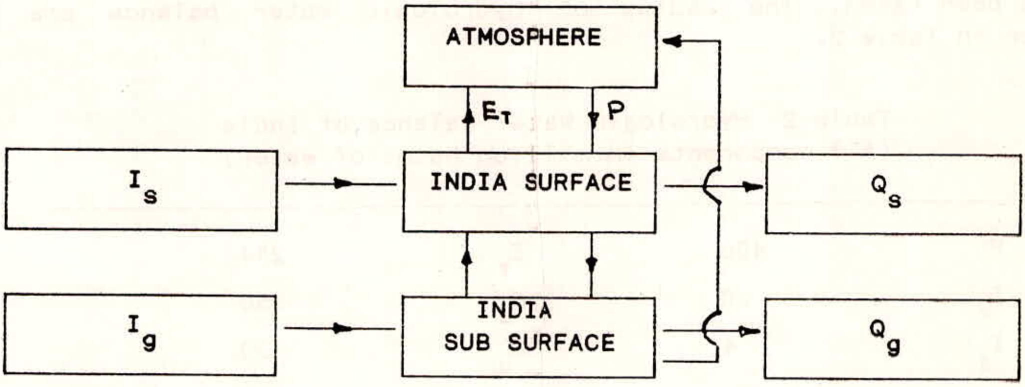

Fig. 2- Hydrologic Water Blanace

The surface water inflow (I_s) from the country comes in the rivers Brahamputra, Tista, Kosi, Kamla, Bagmati, Gandak, Ghaghra, Gomati and other small streams. This flow has been estimated as 20 million ha.m. on the basis of Irrigation Commission Report (1972). Nag and Kathpalia (1972) ahave also arrived at similar figure. For evaluating ground water inflow I_g adequate data is not available. However, it dhas been assumed as 20 percent of surface water inflow I_s, i.e. 4 million ha.m. The surface water outflow Q_s has been estimated as 150 million ha.m. on the basis of data compiled by Irrigation Commission (1972) for 18 river basins of the country. Nearly similar estimation was made by Nag and Kathpalia (1975) and Ghaturvedi (1975) considering actual utilisation of water in river basins. The average annual run-off for the country has been estimated as 1881.12 million ha.m. out of which 38.64 million ha.m. is at present actually being utilised leaving about 150 million ha.m. as surface water outflow (Q_s). Chaturvedi (1973) has estimated potential utilisation for the country as 66.6 million ha.m. The ground water outflow has been assumed to be about 13 percent of the surface water outflow on the basis of general pattern and thus Q_g has been estimated as 20 million ha.m. The values for total precipitation P and total evapotranspiration E_T were estimated for atmospheric water balance also. The change in storage has been assumed as zero for average conditions. The discrepancy term η is included in estimates of I_g and Q_g for which approximate values have been taken. The results of hydrologic water balance are given in Table 2.

Table-2: Hydrologic Water Balance of India
(All components in million ha.m. of water)

P	400	E_T	254
I_s	20	Q_s	150
I_g	4	Q_g	20
Total	424	Total	424

WATER USE BALANCE

The quation of water use balance for the irrigated land for average annual conditions can be written as :

$$E_{TI} = (R_s + D_s - N_s)\alpha + (T_p - N_g)\beta + P_E$$

where E_{TI} represents evapotranspiration from irrigated crops, R_s represents diversion from river sources, D_s represents supply from detention storage, T_p represents withdrawal by tusbewells and other wells, P_E represents effective precipitation which is consumptively used by irrigated crops, N_s represents non-irrigation use of surface water and N_g for ground water. All these components are in million ha.m. of water. The term α is consumption use efficiency for surface water and β is for ground water. On the basis of experiments in U.P. after accounting for losses in canals, distributories and water courses, and for field application efficiency, α has been estimated as 33 percent for unlined canals. For ground water after accounting for losses in water courses and field application efficiency, β has been estimated as 50 percent Kathpalia (1971) has discussed various factors involved in estimating α and β. A diagrammatic representation of water use balance equation is shown in Fig. 3.

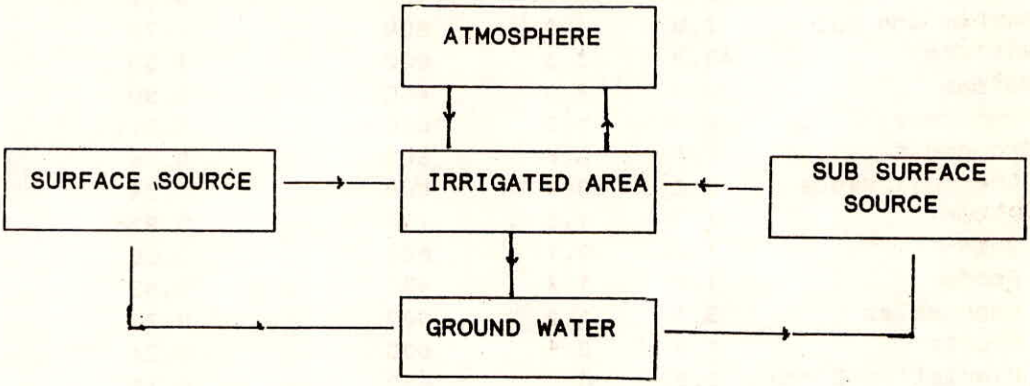

Fig. 3- Water Use Balance

The components E_{TI} has been estimated by using the data compiled by National Commission on Agriculture (1976). The details of computation are given in Table 3.

It has been assumed that consumptive use of irrigated crops is equal to the irrigation water requirement and the component E_{TI} has been estimated as 32 million ha. m. Nag and Kathpalia (1975) have estimated non-irrigation use for industrial, domestic and other purposes as 3 million ha.m. The estimated non-irrigation use from surface water sources (N_g) is 1 million ha.m. and from ground water sources (N_g) is 2 million ha.m. It has been estimated that the water diverted from rivers (R_s) is 15 million ha.m. on the basis of data compiled by Irrigation Commission (1972). The storage capacity created in the country up to 1970 has been estimated as 15 million ha.m. out of which 10 million ha.m. (D_s) is released for irrigation and non-irrigation uses and the rest is lost by evaporation.

Table- 3: Consumptive Use by Irrigated Crops

S. No.	Crop	Area (million ha) Sown	Irrigated	Water require-ment(mm)	Irrigation Water requirement (mill.- ha-m)
(1)	(2)	(3)	(4)	(5)	(6)
1.	Rice	37.4	14.9	1200	17.90
2.	Wheat	18.2	9.8	400	3.92
3.	Barley and Oat	2.6	1.3	600	0.78
4.	Millets	43,2	2.5	600	1.50
5.	Pulses	23.1	2.0	450	0.90
6.	Sugarcane	2.6	1.9	1850	3.515
7.	Groundnut	7.5	0.6	600	0.36
8.	Other oil seeds	6.2	0.4	600	0.24
9.	Cotton	7.7	1.3	720	0.936
10.	Jute	1.2	0.1	600	0.06
11.	Fodder	7.0	1.4	450	0.63
12.	Vegetables	3.1	1.2	600	0.72
13.	Fruits	1.2	0.4	600	0.24
14.	Plantation Crops	2.2	0.4	450	0.18
15.	Tobacco	0.4	0.1	600	0.06
16.	Miscellaneous Crops	1.5	0.2	600	0.12
Total		165.1	38.5		32.06

The National Commission on Agriculture (1976) has estimated 6.10 million open wells in the country in 1971. During fourth plan there were 21 thousand state tube wells having electric pumps and 782 thousand private wells were used for irrigation with diesel or electric pumps. Assuming reasonable running time of 2000 to 3000 hours per annum for state tube wells and 500 to 1000 hours per annum for private wells; and their average discharges as 1,35,000 litres/hour and 30,000 litres/hour respectively, the total draft from ground water (T_p) has been estimated as 13 million ha.m. per annum. The component P_E representing the portion of rainfall consumptively used by crops over irrigated area of 38.5 millions hectares has been estimated as 14 million ha.m. by Nag. and Kathpalia (1975). The results of water use balance for irrigated land are given in Table 4.

Table- 4: Water Use balance of India (irrigated land)
(All components in million ha.m. of water)

E_{TI}	32	$(R_s+D_s-N_s)\alpha$	10
		$(T_p-N_g)\rho$	8
		P_E	14
Total	32	Total	32

WATER USE BALANCE FOR OTHER AREA

The equation for water use balance considering all areas can be expressed as :

$$E_T = E_{TI} + E_I + E_F + E_{TU} + E_W + E_{Tg} + E_R + \eta$$

where E_T represents total evapotranspiration, E_{TI} represents evapotranspiration from irrigated lands, E_I represents immediate evaporation from land surfaces, E_F represents transpiration from forests and vegetation, E_{TU} represents evapotranspiration from unirrigated crops, E_W represents evaporation from water bodies, E_{Tg} represents evapotranspiration from ground water, E_R represents evaporation from remaining areas and η is the discrepancy term. All these components are expressed in million ha.m. of water.

The component E_{TI} has been estimated in water use balance of irrigated areas as 32 million ha.m. The component E_I has been estimated as 70 million ha.m. of water by National Commission of Agriculture (1976) by considering meteorological data of rainfall. This has been found by considering on an average total number of rainy days per year as 130 and 55 days out of them as having rainfall 2.5 mm or less which gets evaporated immediately. It has been estimated that about 71 million ha. of land is under forests and assuming that in half of this area the evapotranspiration is occurring at potential rate of 1.55 m. per year, the component E_T comes to 55 million ha.m. The area under unmitigated crops has been estimated as 126 million ha. and assuming that 3.55 m. of effective rainfall is used consumptively (Nag and Kathpalia, 1975) the component E_{TU} comes as 45 million ha.m. The evaporation from water bodies E_v occurs at potential rate throughout the year and it has been estimated as 5 million ha.m. on the basis of evaporimeter data. The National Commission on Agriculture (1976) has estimated water logged areas as 6 million ha. from whcih evapotranspiration occurs at potential rate of 1.55 m. per year giving the component E_{Tg} as 9 million ha.m.

The component E_T representing total evapotranspiration was estimated under hydrological water balance as 254 million ha.m. The remaining component E_R representing evaporation from remaining areas works out to 38 million ha.m. which includes discrepancy term η

GROUND WATER BALANCE

The equation for ground water balance for average year may be written as:

$$R_R + R_F + R_I + I_g = T_P + E_{Tg} + S_E + S_g + Q_g + \eta$$

where R_R is recharge due to rainfall, R_F is Flood flow recharge when the river is in high stage, R_I is the recharge due to irrigation, I_g is the groundwateer inflow from outside, T_p is the withdrawl by wells, E_{Tg} is evapotranspiration from waterlogged areas S_E is effluent seepage, S_g is not charge in ground water storage, Q_g is ground water outflow and η is the discrepancy term. All components are expressed in million ha.m. of water. The various components are shown in Fig. 4.

The component R_F for all rivers has been estimated as 5 million ha.m. by C.W.C. The component R_I representing recharge due to irrigation can be directly obtained from water use balance data as difference between water from surface and ground water sources and water used consumptively (for irrigation). The component has been estimated as 17 million ha.m. The component I_g has been taken as 4 million ha.m. and component Q_g as 20 million ha.m. in hydrological water balance. Nag and Kathpalia (1975) have estimated effluent seepage S_E as 45 million ha.m. by considering base flows of rivers. The change in ground water storage S_g has been assumed as zero in the absence of any other

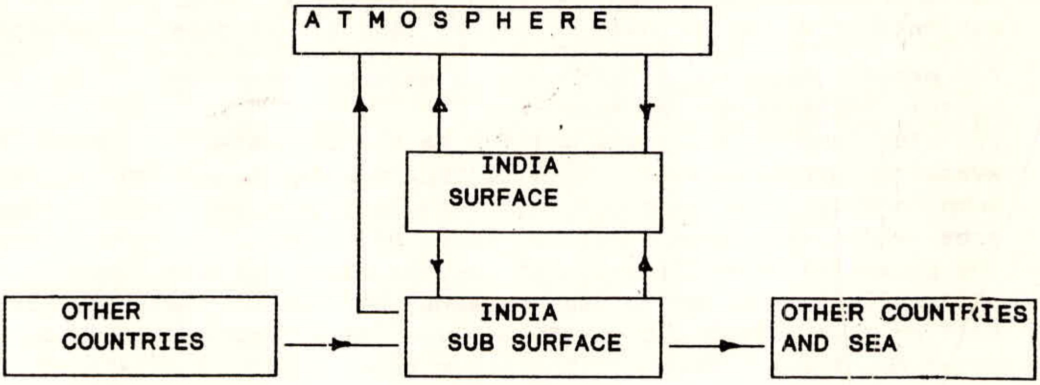

Fig. 4 - Ground water Balance

data. This should be reasonable for long term data. By knowing all components of ground water balance the remaining component R_R representing recharge due to rainfall has been evalued as 61 million ha.m. This includes discrepancy term η also.The results of ground water balance are given in Table. 5.

Table -5: Ground Water Balance of India
(All components in million ha.m. of water)

R_R	61	T_P	13
R_F	5	E_{Tg}	9
R_I	17	S_E	45
I_g	4	Q_g	20
Total	87	Total	87

CONCLUSIONS

(1) The atmospheric water balance for India indicates that out of a total of 1677 million ha.m. of water available as water vapour per annum only 400 million ha.m. precipitates over the country. The outgoing water vapour V_o has been estimated only indirectly. It is necessary to collect relevant radiosonde data so that an estimate of V_o can be made directly. Additional data is necessary for other components of atmospheric balance equation. So that better estimates can be made.

(2) The land is using 254 million ha.m. of water to meet the evapotranspiration need. Some control can be exercised on this component by lowering ground water table elevation in water logged areas which will save 9 million ha.m. of water for other uses. The potential of utilisation of surface water for the country is 66.6 million ha.m. while the present utiliation is only 38.64 million ha.m. Thus out of 150 million ha.m. going to sea and other countries a further 28 million ha.m. could be developed.

(3) In the hydrologic water balance inflow and outflow of ground water has been estimated only approximately. Further data of ground water observations is needed in order to have better estimates.

(4) At present 38.5 million ha. of cropped area out of total of 165 million ha. cropped area i.e. 23 percent is getting assured irrigation. A s indicated above further development of 64 million ha.m. of water is possible, which includes 9 million ha.m. saying from water logged area, 28 million ha.m. from surface water and 27 million ha.m. from effluent seepage. Nag and Kathpalia (1975) are of the opinion that further development in surface water could be 45 million ha.m. Thus the further development is pôssible to a maximum extent of 81 million ha.m. of water which could irrigate an additional 50 percent of cropped area bringing 73 percent of cropped area under assured irrigation. The remaining 27 percent would remain under rainfed irrigation.

(5) The ground water balance equation indicates that 45 million ha.m. of water is being released as effluent seepage which could be developed. Assuming 60 percent of this water to be utilisable cosumptively, the balance 18 million ha.m. will constitute return flow to ground water reservoir.

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