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WATER BALANCE OF A RESERVOIR

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1986-87

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ABSTRACT

The water accounting of reservoirs is necessary for their proper management. The purpose of water balance of a reservoir is to estimate the various components representing inflows, outflows and change in storage. Once these are determined, the continuity equation can be used to either test whether the components tend to balance out or to estimate an element of water balance which could not be determined. Although all the components of a water balance equation should balance themselves theoretically, a residual term is obtained in practice. This happens because the related measurements are susceptible to various sources of errors.

The water flows into the reservoir through streamflow, surface runoff, direct precipitation and ground water inflow. The main components of outflow are evaporation, discharge through spillway and outlets, turbines and seepage. Various techniques which can be used for determination of each of these individuals terms and change in reservoir storage are described in the report. As far as possible, independent methods should be used to determine the individual components so that the errors are not propagated.

LIST OF FIGURES

1.0 INTRODUCTION

The reservoirs are constructed to reduce the variability in the downstream. The aim is to change the natural availability in a beneficial way and provide assured water supply, mitigate floods, and generate hydroelectric energy. These are the most common purposes for which reservoirs are constructed in our country although benefits are also derived from other incidental uses.

It has been estimated that water bodies, excluding oceans, occupy 1.4% of world's total land area. The total full volume of 10000 major reservoirs of the world is about 5000 km^3 which is equivalent to about 11% of total annual runoff from the surface of the land. The total water surface area of reservoirs is estimated to be about 600,00 km^2. These figures give an idea as to how big the reservoirs are. The use of reservoirs in river regulation can not be ignored.

1.1 Importance of Water Balance of Reservoirs

The term 'water balance' in the context used here signifies quantitative assessment of various components of water balance equation of a reservoir. While studying water balance, it is indispensable to adhere to the law of conservation of mass. However, due to a large number of variables involved which defy an exact quantification, the water balance of a reservoir can not be watertight, errors occur while closing the water balance equation and these are to be appropriately considered.

Water, besides being essential for sustaining of life, is an important input resource in a number of economic activities. Due to its scarcity in many regions of the world and increasing depletion in other regions because of growing population, greater emphasis is being placed on better management of water resources. To take better reservoir operating decisions, it is required to have a complete quantitative understanding of the water cycle of a reservoir. Predictions of water balance components are also very helpful in design of reservoirs. A knowledge of these components can give a significant contribution to the study of extreme events and climate variability. These studies are also useful in estimation of components of water balance like seepage etc. whose direct determination is quite difficult.

1.2 Scope of the present work

In the present report, various components required for water balance study of a reservoir are discussed. Different methods to compute the individual components are discussed in detail. Requirement of data for a typical water balance computation is also given.

2.0 DATA REQUIREMENTS FOR RESERVOIR WATER BALANCE

The data requirement for computation of various components of a reservoir water balance is given below:

a) Catchment map for the reservoir with subbasins marked, showing location of raingauges, stream gauges, and gauges for other meteorological variables such as evaporation, temperature, wind velocity and direction etc.

b) Map of the reservoir area showing location of dam, hydromet stations, nearest upstream stream gauges at all the streams which directly enter into the reservoir.

c) Contour map of the reservoir area, on a contour interval of 1 m (preferably) and elevation-area-capacity tables,

d) Records of streamflow at all the stations on the streams which directly enter in the reservoir.

e) Precipitation data at the raingauges which are in the vicinity of reservoir and could be used to compute the direct precipitation input to the reservoir,

f) Evaporation data at the reservoir site,

g) Water level gauge data at all stations measuring reservoir water level,

h) Velocity and direction of wind in the reservoir area, incoming radiation, and sunshine hours,

i) Position of water table around the reservoir and soil permeability,

j) Spillway discharge tables showing discharge at different reservoir levels for various gate openings(if spillway is gated),

k) Discharge through undersluices at various reservoir levels,

l) If a power house also exists then following data is needed:

- Details of turbines
- power generated
- after-bay levels
- efficiency of turbines and generators
- head loss in penstocks and turbines

For all the data which involve time factor, it is required to have information for each time interval of computation and this data is needed for the entire duration for which water balance computations are to be performed.

3.0 COMPONENTS OF WATER BALANCE EQUATION FOR A RESERVOIR

The water balance equation for a reservoir is nothing but the mass balance or continuity equation. This equation states that the sum of inflow and outflow components and change in storage (with appropriate signs) must be zero over a given time interval. In the simplest form, the equation can be expressed as :

$$I_S + I_G + P - E - Q - L - \Delta S \pm \delta = 0 \qquad (1)$$

where,

I_S = Surface water inflow into the reservoir,

I_G = Ground water inflow into the reservoir,

P = Precipitation on the surface of reservoir,

Q = Release from the reservoir

E = Evaporation from the reservoir

L = Storage losses including seepage etc.

ΔS = Change in reservoir storage during the period of computation

δ = error term

The water enters in the reservoir through surface inflow and direct precipitation; the water that leaves reservoir comprises of releases through outlets and spillways, evaporation and losses due to seepage. The reservoir storage increases if the inflow exceeds outflow and decreases if the outflow exceeds inflow. All the components of water balance equation should be independently estimated. The term δ in the above equation (1) represents the net effect of errors involved in the estimation of different components. In practice it is quite likely that errors will be present while measuring or computing various terms involved in the water balance computation and the left hand side may not sum to zero. Thus a large value of δ represents significant error in estimating different variables involved in equation(1). However, a small value of δ does not indicate that the errors are small. The errors may be opposite in sign and thus may balance themselves. The components of water balance of a reservoir are diagramatically shown in figure 1.

The water balance equation(1) may be applied for any time interval. Mean water balance is a term specifically used for computations which are spread over an annual cycle e.g., a calender year or a water year. Sometimes this term is also used for seasonal water balances. The computations of mean water balance are simplest in nature. However, with the shortening of computational period, a more detailed accounting procedure is required. The additional factors which are to be included in the computations include bank storage during reservoir filling,water loss due to water and ice left on the banks when the reservoir is drawn down and return of this water to reservoir later on. The following equation was proposed to Vikulina (1970) for water balance computations for a short time interval(a month)

$$Q_S + P - Q - E \pm Q_i = S \qquad (2)$$

where,

Q_S = temporary water losses by saturation of shores of the reservoir,

Q_i = temporary water losses by the ice left on the

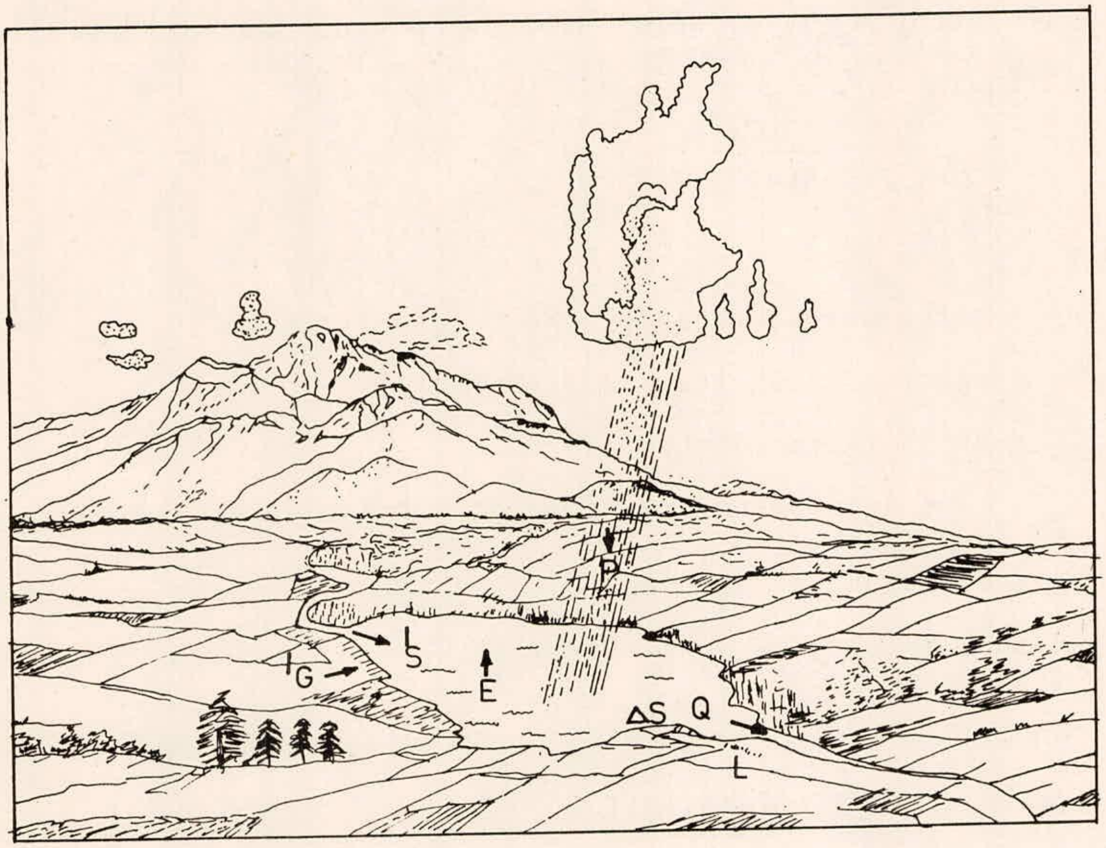

FIG.1 Diagramatic representation of components of water balance of a reservoir (adapted from Ferguson & Znamensky)

shores after the fall of level of the reservoir.

The accuracy of water balance components as well as the duration of the design interval are stipulated by the accuracy of determination of balance components. The most important components are the surface inflow and change in storage. Vikulina (1970) proposed the following equation to determine relative error B_e(%) of water storage changes compared to the inflows :

$$B_e = \frac{10^4 A_w \delta_h}{86400 I_s T} \qquad (3)$$

where,

A_w = water surface area of the reservoir in km^2

δ_h = error of mean level estimation(m)

I_s = discharge into the reservoir

T = time interval or duration of balance period(in days)

This equation can be used to determine the length of balance period such that B_e is less than ± 5%.

3.1 COMPUTATION OF COMPONENTS OF WATER BALANCE EQUATION

3.2 Estimation of Surface Inflow

Surface inflow is the most important component of income part of the water balance equation for reservoirs. It can be determined by direct measurement, can be computed using direct measurement of related variables or can be estimated indirectly. The total surface water inflow in the reservoir can be subdivided into two components : Contributions of the main rivers debouching in the reservoir and the runoff from the surrounding area which directly enters in the reservoir.

The site at which streamflow measurements are carried out is called a gauging site. The location of the gauging site may be little away from the reservoir to avoid the back-water effect and in such cases, the contribution of the area lying between the gauging site and the rim of the reservoir has to be considered to arrive at the correct figure. Most commonly the variables measured at the gauging site are river stage and discharge. If only river state is measured at the gauging site, discharge can be estimated using the rating curve at the site. A large number of methods are available to determine streamflow at a particular site. These methods include the velocity area method, slope area method moving boat method, dilution methods and ultrasonic method. These methods are described in great detail by Herschy(1978). Selection of a particular method largely depends upon the site and flow conditions, equipment available and accuracy requirements.

In case no measured data is available for the drainage basin surrounding the reservoir, techniques discussed below may be used to estimate inflow to the reservoir. These are described in greater detail in Ferguson and Znamensky(1981)

3.2.1 The Analogue method

In this method, the basin is subdivided into sub-basins based on factors which affect runoff such as topography,soil type and land use, precipitation etc. Now for each sub-basin which lacks measurements data, a search is made to find out the particular sub-basin which has similar characteristics and has sufficient observations available. The runoff from the ungauged sub-basin can be estimated using the unit discharges from the gauged subbasins. The procedure is repeated for all such subbasins which lack measurements and discharge in the reservoir and the summation of discharges of all such subbasins gives the inflow to the reservoir. In the situations where no sub-basin with adequate measuring stations is available, it may still be possible to use this method if a gauged sub-basin with similar hydromet and topographic characteristics is available in a neighbouring watershed. The indices which are important in comparing the subbasins are drainage density,mean slope soil type and land use. The formulae which could be used to determine discharge of ungauged basins are described in detail in Ferguson and Znamensky(1981).

3.2.2 The Water Balance Method

The water balance equation for an ungauged subbasin, which discharges directly in a reservoir, can be written as:

$$Q_u = P_u - E_u - \Delta S_u \tag{4}$$

where

Q_u = discharge of the ungauged subbasin

P_u = Precipitation over the ungauged subbasin

E_u = evaporation from the ungauged subbasin

ΔS_u = storage change in the ungauged subbasin which may be in the form of snow pack, soil moisture or ground water

For the long term water balance computations, the storage change is not very important parameter and in mean water balance computations, it may as well be assumed zero. In case the measurements of P_u and E_u are not available, it may be possible to use this method by correlating with physiographic characteristics such as slope,elevation etc. A number of studies have been cited in Ferguson and Znamensky(1981) where this has been successfully achieved.

3.2.3 Discharge Isoline maps

The runoff from the ungauged basins can also be computed using isoline maps. To draw the isoline maps, first of all normal runoff for each individual subbasin is computed. The data obtained are related to the center of gravity of the sub-basin. Now the hydrometric stations are marked on a map on which boundaries of each sub-basin are drawn and normal runoff values are marked at the center of each basin. Now, considering topographic and physiographic characteristics into account, lines are drawn connecting points with similar normal runoff values. The mean runoff for a basin area A is computed from

$$Q = \frac{1}{A} \sum_{i=1}^{n} a_i Q_i \qquad (5)$$

where

Q = normal runoff

a_i = sub area of the basin between two adjacent isolines with an average runoff depth Q_i,

n = number of subarea

3.2.4 Heat Balance method

The runoff from a basin may be considered to be the difference between precipitation and evaporation. The normal annual precipitation may be obtained from climatic maps and the normal annual evaporation may be computed by heat balance or by empirical formulae. It may be mentioned that for small basins, this method may give quite incorrect results.

3.3 Estimation of Precipitation

It has been estimated that precipitation falling directly over the reservoir surface forms approximately 17% of total water input to reservoirs in Asia, Unesco (1974). For a particular reservoir, naturally, the contribution of this component increases with increase in surface area of the reservoir. Precipitation is the most important meteorological parameter and apart from the water balance computations, it is extensively used in hydrology such as rainfall-runoff modelling, flood forecasting and reservoir operation.

The measurement of precipitation is carried out using the precipitation gauges which give the point values of precipitation. The precipitation, however, is not uniform over a particular area. Therefore some procedure is required to estimate total amount of precipitation falling over the given area using the point measurements available at a number of gauges scattered over the area. A large variety of instruments and techniques have been developed for gathering information on various phases of precipitation. On the instrument side, the most important ones are those measuring the quantity and intensity of precipitation although devices for measuring the raindrop size distribution and for the time of beginning and ending precipitation are also available (Linsley,et al.1975). The measurements of precipitation are expressed in terms of vertical depth of water which would accumulate on a level surface if the precipitation remained where it fell. The gauges which are commonly used to measure rainfall include weighing-type, Siphon-type and Tipping bucket raingauge. Of late, radar is also being increasingly used for estimation of precipitation.

The precipitation gauges are subject to various errors. The individual error components may be small in magnitude but the cumulative effect is to yield a low value of observation. Among the errors, the most serious is the deficiency of measurements due to winds; other components caused by evaporation adhesion etc. are small. The deficiency increases with the reduction in raindrop size and thus it is greater for light rain. A number of shields have been developed and various agencies have recommended the use of wind shields particularly if the incidence of light rain or drizzle is high or a portion of catch is snow. The deficiency of catch varies from place to place and hence attention must be paid while applying corrections. The site for establishing a gauge should also be carefully selected. Preferably, the site should have level ground in its vicinity with bushes and trees serving as wind break. These however should not be too close to the gauge to affect the catch. The obstacles which serve as wind break should subtend an angle of at least 20^0 to 30^0 from the gauge orifice.

3.3.1 Precipitation network

A precipitation network can be considered as a system for collection of precipitation data with due consideration given to the needs as well as the economy. Typically purposes behind setting up a network are management of reservoirs for irrigation water supply and hydro-electric power generation, planning of water resources systems, agricultural planning and meteorology. The optimum density of network which is the number of gauges per unit area is determined based upon the purposes of measuring data. A relatively thinner network may be required for estimation of seasonal figures while a dense network will be needed for flood forecasting purposes. The World Meteorological Organisation,WMO(1974) has provided detailed recommendations for the optimum network for various climatic zones and type of terrain for general hydrologic purposes. The guidelines of Indian Standard Institution are also available in ISI 4987-1968.

In many instances, it may not be possible to establish an optimum network because of financial, physical or institutional problems. In such cases a minimum network is established. Guidelines are also available for installation of additional gauges in an existing network.

3.3.2 Analysis of precipitation data

Before any observed data is used in analysis, it is necessary to make checks regarding its consistency etc. so that any error which might have cropped up due to say, instrument failure or mistake by observer may be removed. Further, it must be ensured that the station has not been shifted during the period of analysis. The precipitation record may also have gaps, i.e. the values may be missing for one or more periods. One method which is popularly used to fill short data gaps is normal ratio method. In this method, the precipitation at the station x is estimated from the observations at three stations which are as close to station x as possible. The precipitation at station x is estimated by

$$P_x = \frac{1}{3} \quad \frac{N_X}{N_A} P_A + \frac{N_X}{N_B} P_B + \frac{N_X}{N_C} P_C \qquad (6)$$

where

N represents the normal annual precipitation, and P represents precipitation. Inconsistency in the observed data may be present due to change in the location of the station. Checks are available to test this type of inconsistency. A graphical method, called double mass analysis is in use since a long time. In this method, the consistency of the record at a station is tested by comparing its accumulated annual or seasonal precipitation with the concurrent accummulated values of mean precipitation for a group of surrounding stations. A change in slope of the line indicates a change in the precipitation regime at the base station. This type of change can not be attributed to meteorological causes because in that case, all the stations would be similarly affected.

3.3.3 Estimations of average precipitation over an area

The average depth of precipitation over a particular area is needed in a number of hydrological applications. The simplest method is to take arithmatic average of all the gauges located in that particular area. If the terrain is flat, gauges are uniformly spread over the area ,and the storm is quite uniform, this method may give quite accurate results.

One of the most popular method of estimation of areal average precipitation is the Thiessen Polygon method. The method is based upon the concept of proximal mapping. The nonuniform distribution of the gauges is accounted by providing a weighting factor to each gauge. To determine weights for the gauges, straight lines joining the gauges are drawn. Perpendicular bisectors of these lines lead to the formation of polygons around these gauging stations. It is assumed that the area enclosed in a polygon is represented by the station within it. This area can be measured and when expressed as a function of the total area, represents weight of that particular gauge. Weighted average precipitation for the area can be obtained by multiplying the observed precipitation at each gauge by the corresponding weight and then summing up. The weights remain unchanged unless there is change in the gauging network.

Due to simplicity, the method is very popular and widely used. One big limitation, however, is that the method is unable to consider orographic effects.

The average precipitation over an area may also be calculated using isohyets which are nothing but lines of equal rainfall. Once the location of station and the observed precipitation values are available, the isohyets can be drawn in the same manner in which contours are plotted. The average for an area can be computed by weighting the average precipitation between successive isohyets by the area between them, summing up these figures and then dividing by the total area. This is a linear interpolation method in which the effect of physiography may be taken into account.

3.3.4 Polynomial Interpolation

In this technique a polynomial function(either algebraic or trignometric) is fitted to the observed data. The interpolated value at any point (x_o,y_o) is given by

$$P_o^* = \sum_{k=1}^{m} a_k\, f_k\,(x_o,y_o) \qquad (7)$$

Where a_k is the k^{th} polynomial coefficient, $f_k(x_o,y_o)$ is the k^{th} monomial in terms of x_o and y_o and m is the number of monomials determined from the degree of polynomial function fitted. There are two approaches for polynomial fitting - least squares approach and Lagrange interpolation.

3.3.5 Least squares approach

This method provides the estimate of the variables as the average trend of the true process. This is an approximate method. Let p_i^* be the estimate of the variable at i^{th} point.Then

$$P_i^* = \sum_{k=1}^{m} a_k f_k(x_i,y_i) \qquad i=1,2....n \qquad (8)$$

where m is the number of monomials and $m < n$

Here the aim is to determine parameters a_k,k=1....m such that the sum of square of errors is minimized,i.e.,

$$\text{Min} \quad Z = \sum_{i=1}^{n} (p_i-p_i^*)^2 \qquad (9)$$

Taking derivatives of Z with respect to a's and equating to zero yields.

$$\sum_{i=1}^{m} a_i \sum_{j=1}^{n} f_k(x_j,y_j) f_i(x_j,y_j) = \sum_{i-1}^{n} p_i f_k(x_i,y_i) \qquad (10)$$

Solution of the system of equations(10) gives

$$a_k = \sum_{j-1}^{n} T_{kj} p_j \qquad k = 1,.....m \qquad (11)$$

where

$$T_{kj} = \sum_{i=1}^{m} H_{ki} f_i(x_j, y_j) \quad \begin{matrix} k=1\ldots m \\ i=1\ldots m \end{matrix}$$

and

$$H_{ki} = \sum_{i=1}^{n} f_k(x_j, y_j) f_i(x_j, y_j)^{-1} \qquad (12)$$

Substituting the value of a_k from equation (11) in equation(8)

$$p_i^* = \sum_{j=1}^{m} \sum_{k=1}^{m} T_{kj} f_k(x_o, y_o) \; p_j \qquad (13)$$

A noteworthy aspect of the least squares approach is that the estimate of the variable at the point of observation is different than the observed value.

3.3.6 Lagrange Interpolation

Unlike least squares, Lagrange interpolation is an exact interpolation technique. The coefficients a_k are determined by constraining the estimate to exactly match the observed values. This leads to the necessary conditions that the number of monomials is equal to the number of observation stations(m=n). Thus the linear system of equations given by (8) is written as

$$p_i^* = \sum_{k=1}^{n} a_k f_k(x_j, y_j) \qquad j = 1,2.... \qquad (14)$$

which upon solving yields

$$a_k = \sum_{i=1}^{n} B_{kj} p_j \qquad (15)$$

where B_{kj} is an element of the inverse of matrix formed from $f_k(x_j, y_j)$, k = 1...n and j = 1...n. If the interpolation is to be done over an area with fixed observation points and the polynomial is not changed then the elements B_{kj} have to be evaluated only once. This method is good as long as the variable p is sufficiently regular in space which is true for precipitation. The polynomials of high degree often yield sharp and unrealistic gradients and pose problems of ill conditioning of matrices.

3.3.7 Distance Weighted Interpolations

In the distance weighted interpolations the weights are only function of distances between the points of estimation and observation. The weights can be defined a priori. Most commonly the following weighting functions are used

$$\begin{aligned} w(d) &= 1/d \\ w(d) &= 1/(d+1) \\ w(d) &= 1/d^2 \\ w(d) &= 1/(d+1)^2 \\ w(d) &= e^{-\alpha d} \end{aligned} \tag{16}$$

where d represents distance and α is a constant.

This interpolator is an exact interpolator if the weights are equal to $1/d$ or $1/d^2$. Further as the distance goes on increasing, the weights go on reducing and approach to zero for large distances. . A major shortcoming of this technique is that the spatial interrelationship of the sampling points is not considered. The redundant information, when more than one observation stations are close to each other, is not properly considered in this method.

3.3.8 Multiquadric Interpolation

In this technique, the effect of each observation point is represented by quadric cones as a function of coordinates of these points and the summation of contribution of each cone gives the interpolated value. Mathematically

$$p_i^* = \sum_{i=1}^{n} a_i d_{oi} \tag{17}$$

where a_i is the multiquadric coefficient of ith station. The equation (17) is for each point and we have

$$p_j = \sum_{i=1}^{n} a_i d_{ji} \qquad j = 1....n \qquad (18)$$

Solving equation(18) the coefficients a_i are determined

$$a_i = \sum_{j=1}^{n} c_{ij} p_j \qquad (19)$$

where c_{ij} is an element of the inverse of matrix formed from d_{ij}, $i = 1...n$, $j = 1....n$. Substituting values of a_i from (19) into (17) yields

$$p_o^* = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} p_j \quad d_{oi} \qquad (20)$$

3.3.9 Optimal Interpolation

In this technique of interpolation, the weights are determined such that the variance of error is minimum:

$$\text{defining } \sigma_e^2 = \text{Var} \quad p_o - p_o$$

$$= \text{Var } p_o - \sum_{i=1}^{n} w_i p_i \qquad (21)$$

where Var stands for variance.

Expanding the RHS for this equation

$$\sigma_e^2 = \sigma^2 - 2 \sum_{i=1}^{n} w_i \text{Cov}(p_o p_i) + \sum_{i=1}^{n} \sum_{j=1}^{n} w_i w_j \text{Cov}(p_i p_j) \qquad (22)$$

where σ^2 = variance of p_o

$\text{Cov}(p_o p_i)$ = Covariance between p_o and p_i

Differentiating equation (22) with respect to the weights w_j, $j=1,2....n$ and equating to zero yields

$$\sum_{i=1}^{n} w_i \text{Cov}(p_i p_j) = \text{Cov}(p_o p_j) \quad j = 1....n \qquad (23)$$

Making use of homogeneity in the variances, the covariance terms can be substituted by

$$\text{Cov}(p_i p_j) = \sigma_i \sigma_j \rho(p_i p_j)$$

$$= \sigma^2 \rho(p_i p_j)$$

$$\text{and} \qquad \text{Cov}(p_o p_j) = \sigma^2 \rho \quad (p_o p_j) \qquad (24)$$

where $\rho(\ )$ is spatial correlation coefficient. A spatial correlation function must be defined to estimate these correlation coefficients which can be written as a function of distance assuming a homogeneous and isotropic spatial correlation structure. Hence equation(23) can be written as

$$\sum_{i=1}^{n} w_i \rho(d_{ij}) = \rho(d_{oj}) \qquad j = 1....n \qquad (25)$$

where d_{ij} is the distance between point i and j.

Solution of system of equations given by (25) yields weights $w_i, i = 1....n$.

The estimation of the variable will be unbiased if the sum of weights is unity, i.e.,

$$\sum_{i=1}^{n} w_i = 1 \qquad (26)$$

Incorporating equation(26) into equation(22) using Lagrange multiplier,

$$\sigma_e^2 = \sigma^2 - 2 \sum_{i=1}^{n} w_i \operatorname{Cov}(p_o p_i) + \sum_{i=1}^{n} \sum_{j=1}^{n} w_i w_j \operatorname{Cov}(p_i p_j)$$
$$+ 2\lambda \sum_{i=1}^{n} w_i - 1] \qquad (27)$$

where λ is the Lagrange multiplier. Multiplication by 2 is just for mathematical convenience. Differentiating ( ) with respect to weights and equating them to zero gives

$$\sum_{i=1}^{n} w_i \operatorname{Cov}(p_i p_j) + \lambda = \operatorname{Cov}(p_o p_j) \qquad j = 1...n \qquad (28)$$

which using isotropic correlations yields

$$\sum_{i=1}^{n} w_i \rho(d_{ij}) + \lambda = \rho(d_{oj}), j=1...n \qquad (25a)$$

$$\sum_{i=1}^{n} w_i = 1 \qquad (29b)$$

Upon solving (n+1) simultaneous equations(eqns.29a and 29b) the weights $w_i, i = 1...n$ and Lagrange multiplier λ are obtained.

The choices of correlation assuming homogeneity and isotropicity are :

(a) The reciporocal model $\rho(d) = q/(1+d/c_o)$,

(b) The square-root model $\rho(d) = 1/\sqrt{1+d/c_o}$, and

(c) The exponential model $\rho(d) = e^{-(d/c_o)}$

where c_o is called the characteristic radius and is to be estimated from the data.

3.3.10 The Technique of Kriging

For estimation of the areal averages of the variables which are considered to be realization of stochastic processes, Matheron(1971) proposed the theory of regionalized variables. A variable which characterises a phenomenon varying in space and/or time and shows a certain structure is called a regionalized variable. Thus the variables describing depth of rainfall, water level in observation wells, soil transmissivity are few examples of regionalized variables.

Given the values of the variable at n observation points, p_i, $i = 1,2...n$, the problem of Kriging is to estimate a quantity p_o^* which is a linear function of variables. Three types of problems may arise here:

a) To estimate the value of the variable at a point,

b) To estimate the value of the variable over a mesh of given area centered at a known point, and

c) To estimate the value of variable over a specified domain.

The first type of problems are called **point Kriging**; second and third types are called block kriging.

The third type is most generalized and the first two can be considered as special cases of the third type when the domain reduces to a point or a block. It is required to find the set of weights which give best possible estimation. For the estimation to be best possible, the weights must be

a) Unbiased, i.e. there should be no systematic cover or under estimation,

b) optimal, i.e., the variance between the observed and computed values must be minimum.

The condition of minimum variance leads to equation (27) which is rewritten here

$$\sigma_e^2 = \sigma^2 - 2 \sum_{i=1}^{n} w_i \mathrm{Cov}(p_o p_i) + \sum_{i=1}^{n} \sum_{j=1}^{n} w_i w_j \mathrm{Cov}(p_i p_j) + 2 \lambda \left[\sum_{i=1}^{n} w_i - 1 \right] \qquad (30)$$

The theory of kriging assumes the increments of the variables to follow the weak stationarity of second order. Under this assumption, a random function is said to be stationary if the first two moments of its joint probability distribution at k arbitrary points are invariant under simultaneous translation of all the points. Now the semivariogram is defined as

$$\begin{aligned} \gamma(d_{ij}) &= \frac{1}{2} \mathrm{Var}\left[p_i - p_j\right] \\ &= \sigma^2 - \mathrm{Cov}(d_{ij}) \qquad i,j = 1,\ldots.n \end{aligned} \qquad (31)$$

where $\gamma(d_{ij})$ is the semivariogram which is function of the distance between i and j points. Making substitution in (30) from (21) results

$$\sigma_e^2 = \sigma^2 - 2 \sum_{i=1}^{n} w_i \left[\sigma^2 - \gamma(d_{oj})\right] + \sum_{i=1}^{n} \sum_{j=1}^{n} w_i w_j \left[\sigma^2 - \gamma(d_{ij})\right] + 2 \lambda \left(\sum_{i=1}^{n} w_i - 1 \right) \qquad (32)$$

which upon differentiating w.r.t. weights and equating to zero yields

$$\sum_{i=1}^{n} w_i \gamma(d_{ij}) + \lambda = \gamma(d_{oj}) \qquad j = 1, 2, \ldots . n$$

$$\text{and} \qquad \sum_{i=1}^{n} w_i = 1 \tag{33}$$

Solution of these (n+1) simultaneous equation yields n weights and the Lagrange multiplier. Substitutions from equation(24) and (25) into equation(32) give the variance of error of interpolation as

$$\sigma_e^2 = \sum_{i=1}^{n} w_i \gamma(d_{oi}) + \lambda \tag{34}$$

As mentioned above, the knowledge of variogram is required for interpolation using kriging. A number of models are available.

(a) Nugget type $\gamma(d) = C\ (1-\delta)$

(b) Monomial $\gamma(d) = g\ |d^b| \qquad 0 \leq b \leq 2$

(c). Spherical $\gamma(d) = \begin{cases} g\left[1.5\ |d|/a - 0.5|d|^3/a\right] & d \leq a \\ g & d > a \end{cases}$

(d) Exponential $\gamma(d) = g\left[(1-\exp(-|d|/a)\right]$

(e) Gaussian $\gamma(d) = g\left[(1-\exp(-|d|^2/a^2\right]$

where δ is Dirac delta and g and a are the constants to be determined.

3.4 Evaporation

The term evaporation is defined as the net rate of transfer of vapor to atmosphere. The degree of evaporation depends upon the nature of the evaporating surface and meteorological factors. The present discussion is limited to evaporation from free water surface.

The evaporation can be thought of as an enregy exchange process. The most important factor in the process is radiation followed by wind speed and vapour pressure of the air overlying the surface. The amount of evaporation also varies with latitude, season, time of day and condition of sky. It is difficult to categorically express the relative effect of the controlling meteorological factors, if radiation exchange and all other meteorological elements are constant over a shallow lake for a considerable time, the temperature of water and evaporation would become constant. If the wind speed is then suddenly doubled then the rate of evaporation would also be double for some time. However, this rate would start decreasing as the increased evaporation would extract heat from water at an increased rate than could be replaced by radiation and conduction and consequently water would achieve a lower equilibrium temperature.

The quality of water in a reservoir also affects evaporation although the change may be marginal. This reduction takes place because the dissolved solids reduce the vapour pressure of the evaporation, the temperature of water rises and this partially offsets the effect of reduction in vapour pressure. Moreover, any foreign material which affects the reflectivity property of water surface tends to affect evaporation.

3.4.1 Estimation of Evaporation

The instrument Pan Evaporimeter is most commonly used to estimate evaporation from water bodies. The pan is a shallow(and mostly) circular vessel exposed to atmosphere. The pans can be installed in three ways: on the land surface, sunked in ground and floating on water surface. The pans installed on or above the ground surface experience little higher evaporation since extra heat is absorbed by the side walls. This can be minimized by suitably isolating the pan. However, this effect must be suitably considered while estimating the evaporation from the reservoir using the pan evaporation measurements. The main advantages of surface pan are economy and ease of installation maintenance and operation.

By burying the pan, the objectionable effects due to radiation on the side walls are eliminated. But on the other hand these pans are difficult to instal, maintain, repair and observe. It is also difficult to detect the leakage which may take place from the pan. The heat exchange between pan and soil is appreciable. The height of vegetation adjacent to pan must also be limited.

The estimation of evaporation from a reservoir can be most nearly approximated by a pan floating on lake surface. However, the installation and maintenance expenses are quite large. Observation of data is very difficult and many times, splashing takes place which renders the records unreliable. Due to these reasons, these plans are not very common in use.

Among the various types of pans in use throughout the world, the most widely used is the US Weather Bureau Class A Pan. This pan is made of unpainted galvanized iron. Its shape is circular with diamater 122 cm. and depth 25.4 cm. It is recommended that this pan be mounted on a wooden frame so that air may circulate beneath it. The pan must be filled to a depth of 20 cm and it should be refilled when the depth of water falls to 18 cm. The water level can be measured using a hook gauge. The evaporation is computed as the difference between the water levels measured after accounting for precipitation .

The estimate of evaporation can be obtained by multiplying the pan evaporation by a coefficient called pan coefficient. The average value of pan coefficient for US Weather Bureau class A pan is 0.70. The value of this coefficient can vary regionally, it is low in arid regions and higher in humid. Many times, it is necessary to cover the pan with a screen to prevent loss of water due to drinking by animals and birds. The use of screen changes the pan coefficient. The change can be as much as 14%

3.4.2 Energy Budget Method

In the energy budget method determination of evaporation from the reservoir, the energy input and output from the reservoir is accounted and the residual is assumed to have been consumed for evaporation. Alongwith energy balance, a rough water balance is also required since water storage and inflow/outflow represent energy values.

The energy budget for a reservoir may be written as

$$R_n - R_h - R_r + R_v = 0 \tag{35}$$

where

R_n = Net radiation absorbed by the reservoir,

R_h = sensible heat transfer to atmosphere through conduction

R_e = energy used for evaporation

R_r = energy stored in the reservoir

R_v = net energy content of inflowing and outflowing water

The units used in the above equation are calories per square centimeter. The term sensible heat transfer can not be directly observed or computed. Let H_q represent latent heat of vaporization and R the ratio of heat loss by conduction to heat loss by evaporation or Bowen ratio. Thus the above equation can be written as :

$$E = (R_n + R_v - R_r) / \rho H_v (1+R) \qquad (36)$$

where

E = evaporation in centimeters

ρ = density of water.

The Bowen ratio can be computed by the following equation

$$R = 0.61 \quad (T_o - T_a) p / 1000.0 (e_o - e_a) \qquad (37)$$

where

p = atmospheric pressure,

T_o = water surface temperature

T_a = temperature of air

e_o = saturation vapour pressure corresponding to T_o

e_a = vapour pressure of air,

The above equation is valid for normal atmospheric conditions. The limiting values of the constant (0.61) in the above equation are 0.58 and 0.66 depending upon the stability of the atmosphere. If the correct value is assumed to be within these limits, the extreme error is likely to be within ± 4 % , Linseley et al.(1975) The estimation of evaporation very much depends upon accurate evaluation of net radiation. This can be expressed as

$$R_n = R_s - R_r + R_a - R_{ar} - R_o \qquad (38)$$

where

R_s = sun and sky short wave radiation incident upon the water surface

R_r = reflected short wave radiation

R_a = incident atmospheric longwave radiation,

R_{ar} = reflected longwave radiation

R_o = emitted longwave radiation

The radiation can be measured by radiometers which can be designed to measure either total incoming or net radiation.

Ideally, it is required to expose the radiometers at water surface at more than one point. Since it is difficult to take observations over a reservoir, many times the radiometers are exposed over a tank of water assuming that the emissivity and reflectivity of the water in tank and reservoir are the same. The incident minus reflected allwave radiation R_{ir} for the reservoir can be measured and the net radiation for the reservoir can be obtained from

$$R_n = R_{ir} - \varepsilon\sigma\,(T_o)^4 \tag{39}$$

$$= R_n + \varepsilon\sigma(T_o)^4 - \varepsilon\sigma(T_o)^4$$

$$= R_n + \varepsilon\sigma(T_o - T_o)^4$$

where T_o is the absolute temperature of the tank water surface, σ is the Stefan-Boltzmann constant which is equal to 11.71 x 10^{-8} Cal/cm^2 k^{4}d and ε is a constant which is equal to 0.97.

3.4.3 Aerodynamic Determination of Evaporation from Reservoirs

The determination of reservoir evaporation using aerodynamic concept is based upon turbulent transport concept. A number of empirical equations have been developed relating evaporation with atmospheric elements. The general form of these equations is

$$E = (e_o - e_a) \quad (a+bv) \tag{40}$$

where e_o is the vapour pressure of the water surface, e_a is the vapour pressure of the over running air at some height, and a and b are coefficients. Linsley et al (1975) report some of the equations collected in a study

$$\begin{aligned} E &= 0.00304\,(e_o - e_2)v_4 && e_2 \text{ and } v_4 \text{ over reservoir} \\ E &= 0.00241\,(e_o - e_8)v_8 && e_8 \text{ and } v_8 \text{ over reservoir} \quad (41) \\ E &= 0.00270\,(e_o - e_2)v_4 && e_2 \text{ upwind and } v_4 \text{ over reservoir} \end{aligned}$$

where E is reservoir evaporation in inch per day, small e's represent vapour pressures in inches of mercury, v's are wind speeds in miles per day and numerical subscripts designate heights above water surface in meters.

It has been observed that the vapour pressure of the air increases downwind across an open water surface and thus the concepts based upon turbulent transport conclude that evaporation decreases with downwind . Linsley et al(1975) have quoted a study conducted by USGS in which the coefficients a and b of equation (40) were determined after studying a number of reservoirs upto 120 km^2 in area. The coefficient a was found to be zero and b was given by

$$b = 0.00014\,A^{-0.05} \tag{42}$$

for E in inches and A the reservoir area in acres.

3.4.4 Combination methods

The combination methods of estimating evaporation make use of both aerodynamic and energy budget equations. The following equation has been derived assuming a thin free-water surface, i.e. without heat storage or conduction from below.

$$E = \frac{1}{\Delta + r} = (R_n \Delta + r E_a) \qquad (43)$$

where Δ is the slope of the saturation-vaopur-pressure versus temperature curve at the air temperature T_a, E_a is the evaporation given by equation (40) assuming the water surface temperature $T_o = T_a$, R_n is the net radiation exchange, and r is the psychrometeric constant in the equation of Bowen ratio (equation 37):

$$R = r \frac{T_o - T_a}{e_o - e_a} \qquad (44)$$

Charts are available relating the reservoir evaporation with solar radiation, air temperature, dewpoint and wind movement.

In the derivation of equation(43), it is assumed that R_n represents exchange of radiation at water surface. E_a is based upon aerodynamic equation and the correct value of E is obtained when used with the observed vapour pressure of the water surface, and Δ at T_a is good approximation of its average value between T_a and T_o.

3.4.5 Water Budget method

This method of estimation of reservoir evaporation is based on determining the various components of water balance(except evaporation and error term) and then computing evaporation from equation(1). This method, although simple, is quite inaccurate because errors in measuring all other components will be encompassed in evaporation. The estimation of various components of water balance equation is dealt separately in different sections.

3.5 Estimation of reservoir Outflow

The total outflow from a reservoir is sum of discharge through spillway, turbines, undersluices and leakage through dam:

$$Q = Q_{sp} + Q_{tb} + Q_{us} + Q_1 \tag{45}$$

where

Q_{sp} = discharge through spillways

Q_{tb} = discharge through turbines,

Q_{us} = discharge through undersluices

Q_1 = discharge through lakage from dam

3.5.1 Discharge through spillway undersluices

The discharge through spillway can be computed either by using hydraulic formulae or by using result of laboratory model testing. The discharge through spillway can be computed using following formula.

$$Q_{sp} = C_{sp} \; C_q \; b_{sp} \sqrt{2g} \, h_{sp}^{1.5} \tag{46}$$

where

C_{sp} = submergence coefficient,

C_q = discharge coefficient for spillway,

b_{sp} = width of the spillway

h_{sp} = head over crest of spillway outside the zone of the draw down

Under the free flow conditions, the discharge of an ogee spillway is given by :

$$Q_{sp} = C \, (L - kn \, H) \, (H + h_v)^{3/2} \tag{47}$$

Where C is the coefficient of the weir, L is the clear crest length , n is the number of end contractions, H is the head over spillway, and h_v is head due to velocity of approach. In the metric units, the value of c varies from 2.21 at the discharge head to 1.71 at very small heads.

Alongwith spillways, reservoirs are also provided with low level outlets for releasing water when the reservoir water level is low. These outlets behave as orifices and the discharge through them is given by :

$$Q_{or} = C_{or} \; e \; A \sqrt{2gh} \qquad (48)$$

where C_{or} is the submergence coefficient for semisubmerged or submerged orifices, e is a factor which accounts for jet contraction and difference between actual flow veolocity and idealized flow velocity, A is the corss-section area of the orifice, and h is the head at the orifice measured from the center of orifice. The discharge coefficients can be obtained by hydraulic considerations or they can be determined from laboratory model tests or field calibrations. While conducting the

model tests, one should properly considerthe situations like characteristics of approaching flow, lateral discharge estimation will arise if the actual field conditions are not considered or the discharge coefficient is wrong.The project authorities prepare tables giving discharge through gated spillways for various gate openings. Linear interpolation is sufficient for intermediate values.

3.5.2 Discharge through turbines

Basically, these are two methods of determining discharge through turbines. Each of these is discussed below.

3.5.2.1 Flowmeter method

This method, as the name suggests, makes use of flow-meter to measure discharge passing through a turbine. It uses the following equation to compute discharge.

$$Q_t = C_f \frac{\Delta M_f}{t} \tag{49}$$

where M_f is the difference in the flowmeter readings for the time period t and C_f is the flowmeter constant. To avoid errors in discharge estimation, the flowmeter calibration should be checked at specified time intervals.

3.5.2.2 discharge characteristics method

This method makes use of the relation between generated power and turbine discharge. These two are related by:

$$Q_{tb} = \frac{W_{tb}}{9.81\ h_{tb}\eta} \tag{50}$$

where W_{tb} is the power generated in kilowatt, h_{tb} is the effective water head in meters, Q_{tb} is discharge through turbine and η is combined efficiency of turbine and generator. The effective head is obtained after deducting the head losses from the total head. The total head is obtained by subracting the water level of forebay from the level of lower pool. Head loss takes place because of friction and bends in penstocks and losses at entrances and exists. Since the hydropower plants are mostly used for peaking purposes, the discharge through turbines will have considerable fluctuation during a day and hence measurements may have to be taken at a shorter time interval.

The term η in equation(50) represents combined efficiency of turbine and generator and is obtained by multiplying the individual efficiencies.

In case the plant consists of more than one turbine then the total discharge can be obtained by summing the discharge through all turbines. It has been mentioned by Ferguson and Znamensky(1981) that the estimation of discharge from turbines are generally on the lower side and the error in daily discharge may be of the order of 3-5%. A major source of error in such cases is the incorrect estimation of head losses. Errors may also crop in because of unstable operation characteristics, wearing of elements etc. and hence the results should be periodically checked with other methods.

3.5.3 Leakage through dam

This component of outflow consists of loss of water from the reservoir on account of leakage through the body of the dam as well as through gates and spillways. It is not easily possible to relate these losses with a measureable quantity. For example the losses through the gates or valves of undersluices depend upon their design, installation and maintenance. A simplifying assumption which is usually made in practice is that these losses linearly vary with the reservoir level. In general, the amount of water lost due to these reasons varies between 0.5% to 4% f the total discharge through the structure.

3.6 Computation of Groundwater flow

A reservoir also experiences subsurface flow from or towards the aquifers though the magnitude is very small compared to the surface water inflow. The amount of this flow depends upon the physiographical features and soil characteristics in the vicinity, and the position of water table. Assuming homogeneous condition, the flow can be computed by the Darcey Law:

$$I_G = b \quad d \quad k \quad \frac{h_1 - h_2}{1} \tag{51}$$

where,

b = base width of flow

d = depth of flow

k = horizontal permeability coefficient (m/day)

h_1, h_2 = water levels at two sections across the under-ground current at a distance 1 apart (ref. fig.2)

3.7 Estimation of change of storage

The change of storage component of water balance equation represents the change in the reservoir storage during the period of computation. As explained by Ferguson and Znamensky(1981) this term can be expressed as a sum of four components.

$$\Delta S = \Delta S_w + \Delta S_{rm} + \Delta S_{bs} + \Delta S_g \tag{52}$$

where,

ΔS_w = change in storage in reservoir.

ΔS_{rm} = change in channel storage of all those streams which directly debouch in the reservoir between the gauging site which lies just upstream of reservoir and the rim of reservoir.

ΔS_{bs} = change in storage in the banks of the reservoir.

ΔS_g = change in storage because some ice is left on the reservoir banks during winter which melts and flows back in summer.

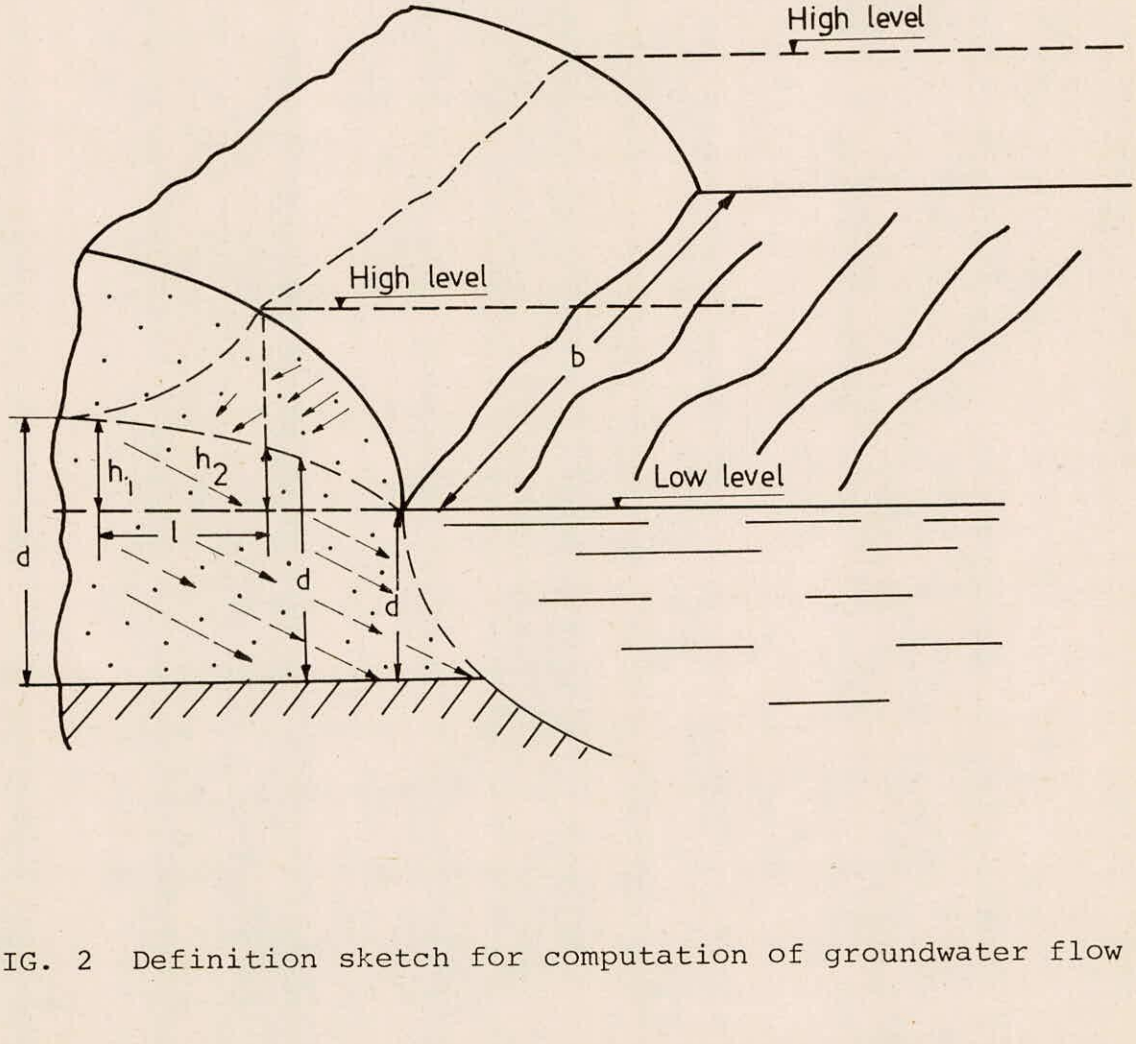

FIG. 2 Definition sketch for computation of groundwater flow

Out of these four, the first component is most important. The last component may have to be considered only for very few Indian reservoirs.

3.7.1 Estimation of volume of Stored Water

To estimate the volume of water stored in the reservoir at any time, it is necessary to estimate the stage of the reservoir. The stage can be used to determine volume by using stage-volume curve. To prepare this curve, first of all, a detailed surveying is done for the reservoir area and a contour map with a small contour interval is prepared. Using this map, the surface area of the reservoir at any particular elevation can be easily determined. The volume of water between any two successive contours is the average area at these countours multiplied by the contour interval. Thus starting at the bottom of reservoir, it is easy to prepare elevation-area-capacity curves or table. These figures keep on changing with time because of instability of shores and deposition of sediments. Hence, to maintain the required degree of accuracy in the computations, it is necessary to undertake reservoir surveys from time to time to have uptodate information.

The water level gauges are installed to measure the mean water level of the reservoir. The main points to consider while installing these gauges are the shape of the reservoir the types of fluctuations that it experiences due to winds etc. and the ease in installation observation and maintenance of these gauges. Generally, it is required to locate the gauges along both banks (in the upstream direction from dam) of a reservoir. Special care must be taken of the area where the reservoir influences the stage of the river unless the storage in this zone is less than 5-10% of the total accumulation.

When wind blows over a reservoir, it applies shear stress on the water surface and thereby it tries to carry water along with it. This leads to a redistribution of water in reservoir, there will be greater storage in the down wind direction and lesser water in the upwind direction. Changes in the wind direction and/or magnitude of wind leads to fluctuations in the water level. The following equation(Ref.figure 3) can be used to compute the change in stage due to wind.

$$\Delta h_w = (3+\bar{d}_w) \frac{u^2 l}{d_m} (\mathrm{Cos}\,\lambda)\, 10^8 \qquad (53)$$

where u is the wind speed in m/s, l is the distance in meters between two points for which h_w is to be computed, d_m is the mean depth of reservoir in meters between these two points. λ is the angle between wind direction and the line joining these two points, and d_w is the mean wave height.

To compute the mean water level in presence of these fluctuations it is necessary to determine the location of equilibrium axes where the water level fluctuations due to wind generated shear are minimum. Once the change in water storage has been determined using the equation (53), the changes in water volume in a subarea can be determined by multiplying by the corresponding areas. The equilibrium axis is determined at the division of sub-areas of positive and negative change of water volume. The direction of this axis is perpendicular to the wind direction. The position of this axis should be found for eight main directions i.e, N,NE,E.... The point where the longitudinal axis of the

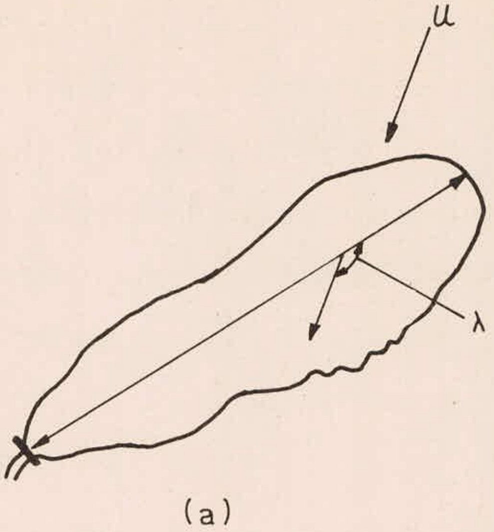

FIG. 3(a) Computation of fluctuation of water level in a reservoir

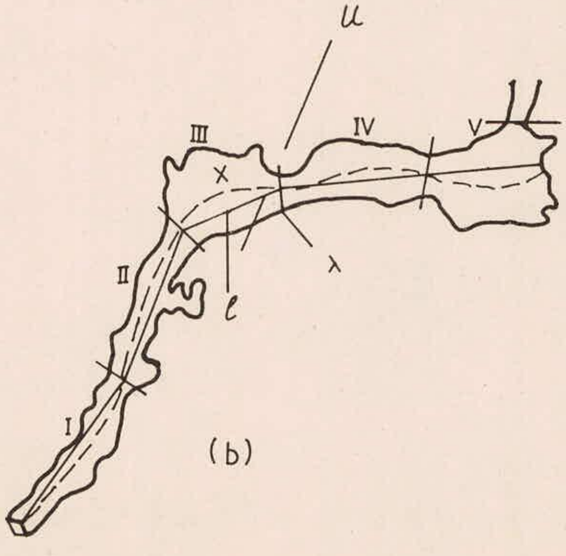

FIG. 3(b) Computation of fluctuation of water level due to wind in a reservoir when wind directions are changing reservoir crosses the equilibrium axis perpendicular to a given wind direction is the best location for a stage gauge. At these points the stage will be closest to mean reservoir level. It has been recommended to locate the gauges near the equilibrium axis when the stage gradient due to wind effects exceeds 15-20 cm.

3.7.2 Setting the gauge datum

For ease of computations, consistency of results and because of several other reasons, it is necessary to reduce all the gauges to a common datum. In India, the Survey of India has established very large number of bench marks. by levelling from the nearest bench mark. Thus the datum of a particular gauge can be expressed in terms of mean sea level.

For large reservoirs, it may be difficult to carry out levelling because of inhospitable territory. The technique makes use of the fact that the surface of still water is horizontal. Using this property, information is transferred from one place to another. The best time to do this exercise is the low flow period when the discharge from the reservoir is quite small. Automatic stage recorders are installed many times to achieve better accuracy. Further, adjustments are made using long term observations to weed out cycles of smaller frequency.

3.7.3 Calculation of mean reservoir level

The mean water level of a reservoir at any time is used to determine the volume of water stored in the reservoir at that instant. Using this information at the beginning and end of a time period the change in storage can be worked out. Several methods are available for this purpose which could be used depending upon the slope of the water surface and degree of knowledge of morphometric characteristics of the reservoir. If the water surface of the entire reservoir is more-or-less horizontal, the mean water level can be used to determine the storage. Otherwise volume may have to be determined for each subarea but this requires individual elevation-storage curves for each subarea.

The mean weighted water level can be computed in a manner which is similar to Thiessen polygon method for rainfall estimation. In this method the weights for each area are determined by dividing the area of each subarea with the total area for reservoir. These weights are then multiplied by the corresponding stage to determine mean weighted water level. Mathematically,

$$h_m = h_1 \frac{A_1}{A_R} + h_2 \frac{A_2}{A_R} \ldots\ldots\ldots h_n \frac{A_n}{A_R} \qquad (54)$$

where h_m is the mean stage, $h_1 \ldots\ldots h_n$ are the stages at the gauges 1,...n respectively. A's are the partial area of the reservoir associated with these gauges and A_R is the surfac area of complete reservoir.

A graphical method known as smoothed graph method is quite helpful for reservoirs where long term stage fluctuations take place due to wind. The water level fluctuations at all gauges are plotted on a graph. The points where the stage curves intersect are connected with a smooth curve from the zone of reservoir influence upon the river stages to the dam. This line shows the position of the water stage undisturbed by the fluctuations due to wind. The mean stage can then be used for determination of volume of stored water.

The other components of equation(52) are not very significant. Their magnitude is either very small or negligible in most of the cases. The determination of these components is described in Sokolov (1974) and Ferguson and Znamensky (1981).

4.0 ERRORS IN WATER BALANCE COMPUTATION

From the theoretical point of view, the various components of water balance equation should sum up to unity. However, it is not possible to exactly estimate or measure the various components and thus the term δ was introduced in equation (1) to take care of the residual error. To avoid the propagation of errors, it is necessary to estimate the individual components of the water balance equation independently. The errors in individual components may be positive or negative and hence they may also tend to balance. Therefore, a small value of the error component does not indicate that the errors in estimation of individual components are small. The purpose of error analysis is to assess the correctness of the estimates and their sensitivity.

If the error in estimating individual water balance components are $\delta_1, \delta_2, \ldots\ldots\ldots \delta_n$ then it is recommended that the maximum value of error should not exceed the square root of sum of error of individual components, or

$$\delta < \sqrt{\delta_1^2 + \delta_2^2 + \ldots\ldots\ldots \delta_n^2} \quad \ldots (55)$$

If this criterion is not satisfied then it is required to reevaluate the estimation procedure and measurements of individual components. Since the magnitude of different components vary widely, percentage errors in them will also vary over a large range. This variation also depends upon

upon the time period of computation. As this period increases the magnitude of error in various terms which represent inflow and outflow to and from the reservoir also increases. However, the error in the term representing change of storage tends to reduce with increase in time period. The aim of any water balance study is to minimize the errors associated with different components of water balance equation. This requires an assessment of the sensivity of various water balance components. This will depend upon duration of computation period, climatic conditions, physiographic factors and season of year. Different components may become significant in different seasons of year. For example, during summer months, inflows to the reservoir may be very small and evaporation quite large while during the monsoon period, the situation may be just reverse. Hence, the existing measurement network may have to be expanded in many cases. This requires a careful study and a final decision should be based upon the network analysis for required degree of accuracy and the finances available.

5.0 CONCLUSIONS

The various methods which are used to determine the different components of water balance of a reservoir have been described. From the review of literature the following points emerge:

a) As far as possible, independent methods should be used to determine the individual components of the water balance equation.

b) The relative magnitude of components of water balance equation varies from season to season and this fact should be considered while deciding about the accuracy of a particular measurement.

c) The above point 'b' is also important in determining the number and location of additional stations to be established if the existing network is to be strengthened This would also depend upon the purpose of carrying out water balance computations.

d) It is felt that in India, extra attention must be paid for estimation of reservoir inflow from the ungaged basin and seepage losses from the reservoir.

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