WATER BALANCE OF A RESERVOIR

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INTRODUCTION

Water, besides being essential for sustaining 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.

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 cannot be watertight. Errors occur while closing the water balance equation and these are to be appropriately considered.

Predictions of water balance components are also very helpful in design of reservoirs. Knowledge of these components can significantly contribute of 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.

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 sub basins marked, showing location of raingauges, stream gauges, and gauges for other meteorological variables such as evaporation, temperature, wind velocity and direction etc.,
b) Index map of the reservoir area showing location of dam, and other important hydro-projects,
c) Contour map of the reservoir area, on a contour interval of 1 m (preferably) and elevation-area-capacity tables,
d) Records of stream flow 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 under-sluices at various reservoir levels,
l) If a power house also exists then following data is needed:
   - Details of turbines
   - Power generated by each machine for each day/week/ 10-day
   - Tail race levels
   - Efficiency of turbines and generators and head loss in penstocks and turbines.

For all the time series data, 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.

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:

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

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, and δ = error term. The various terms can be expressed in volume or depth units.

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, to the extent feasible. The term δ in eq. (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 eq. (1). However, a small value of δ does not always indicate that the errors are small. The errors may be opposite in sign and thus may cancel themselves. The components of water balance of a reservoir are diagrammatically shown in Fig. 1.

The water balance eq. (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 calendar 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)

$$Q_S + P - E \pm Q_i = S \tag{2}$$

where, Q_S = temporary water losses by saturation of shores of the reservoir, Q_i = temporary water losses by the ice left on the shores after the fall of level of the reservoir.

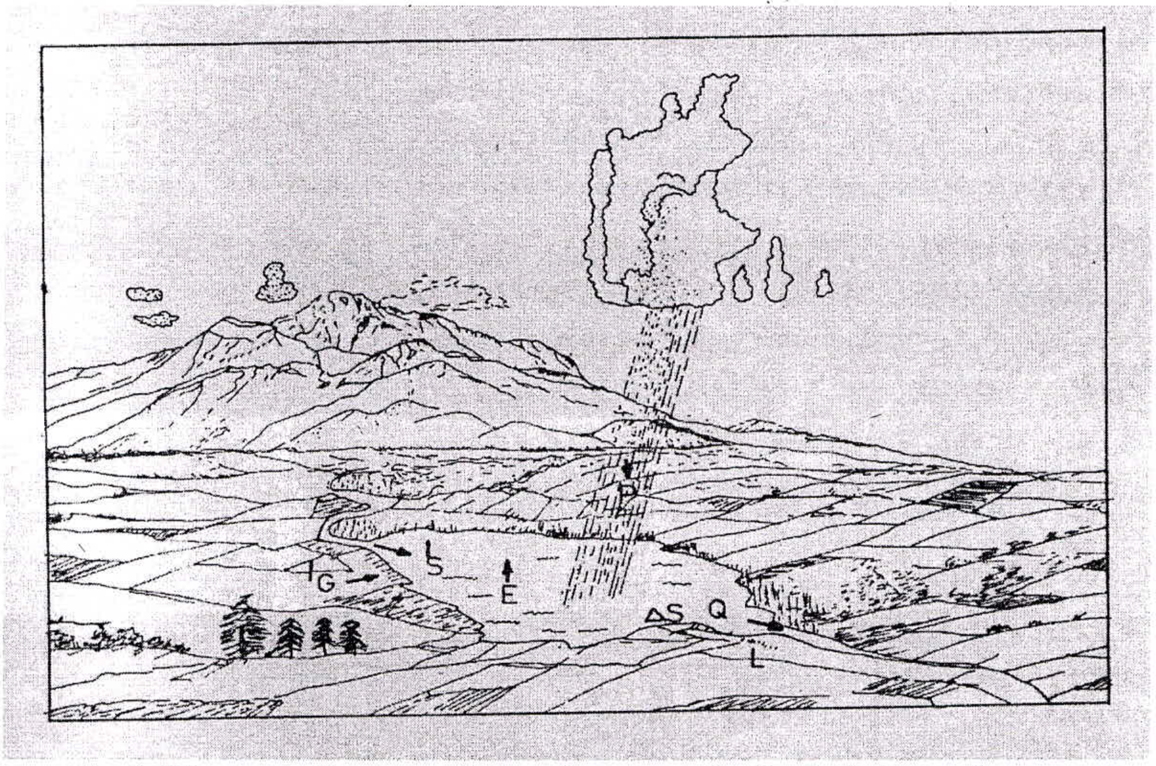

Fig. 1: Diagrammatic representation of components of water balance of a reservoir [adapted from Ferguson & Znamensky (1981)]

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 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:

$$B_e = \frac{10^4 A_w \delta_h}{86400 I_S T} \tag{3}$$

Where, A_w = water surface area of the reservoir in km^2, δ_h = error of mean level estimation (m), I_S = discharge in to 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%.

ESTIMATING COMPONENTS OF WATER BALANCE EQUATION

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 sub-divided 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 sites at which stream flow is measured are called gauging sites. 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 determine correct inflow. 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 by using the rating curve at the site. Methods to determine stream flow at a particular site 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).

The Analogue method

In this method, the basin is subdivided into sub-basins based on factors which affect runoff such as topography, soil type, land use, precipitation, etc. For each sub-basin which lacks measurements data, a search is made to find out the particular sub-basin which has similar characteristics and sufficient observations. The runoff from the ungauged sub-basin can be estimated using the unit discharges from the gauged sub-basins. The procedure is repeated for all such sub-basins which lack measurements and discharge in the reservoir and the summation of discharges of all such sub-basins 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 neighboring watershed. The indices which are important in comparing the sub-basins are drainage density, mean slope soil, type and land use.

The Water Balance Method

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

$$Q_u = P_u - E_u - \Delta S_u \qquad (4)$$

Where Q_u = discharge of the ungauged sub-basin, P_u = Precipitation over the ungauged sub-basin, E_u = evaporation from the ungauged sub-basin, ΔS_u = storage change in the ungauged sub-basin 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 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.

Estimation of Precipitation

Precipitation falling directly over the reservoir surface forms significant water input to reservoirs. For a given reservoir, naturally, the contribution of this component increases with increase in surface area of the reservoir. Precipitation is the most important meteorological variable in water balance computations.

Precipitation is measured by 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). 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 rain-gauge. Of late, radar is also being increasingly used for estimation of precipitation.

Precipitation gauges are subject to various errors. 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 the use of wind shields is particularly recommended 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 wing 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° to 30° from the gauge orifice.

Precipitation network

A precipitation network can be considered as a system for collection of precipitation data with due consideration to the needs as well as the economy. Typical purposes behind setting up a network are management of reservoirs for irrigation water supply and hydro-electric power generation, planning of water resources system, 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 values while a dense network will be needed for flood forecasting. WMO (2008) has provided detailed recommendations for the optimum network for various climatic zones and type of terrain for general hydrological purposes. The guidelines of the Bureau of Indian Standards are 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.

Analysis of precipitation data

Before any observed data is used in analysis, it is necessary to check 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 the 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

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

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. A graphical method, called double mass analysis, is in used to test the consistency of the record at a station by comparing its accumulated annual or seasonal precipitation with the concurrent accumulated 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.

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 arithmetic 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 methods of estimation of areal average precipitation is the Thiessen Polygon method. The method is based upon the concept of proximal mapping. The non-uniform 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. This method is very popular and widely used. One 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 lines of equal rainfall. Once the location of station and the observed precipitation values are available, 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 and then dividing by the total area. This is a linear interpolation method in which the effect of physiography may be taken into account.

Distance Weighted Interpolations

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

$$
\begin{aligned}
w(d) &= 1/d \\
w(d) &= 1/(d+1) \\
w(d) &= 1/d^2 \\
w(d) &= 1/(d+1)^2 \\
w(d) &= e^{-\alpha d}
\end{aligned}
\tag{7}
$$

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 zero for large distance. 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.

Evaporation

The term evaporation is defined as the net rate of transfer of vapour 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.

Evaporation can be thought of as an energy exchange process. The most important factor in the process is radiation followed by wind speed and vapour pressure 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.

Estimation of Evaporation

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, sunk 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 these pans are difficult to install, 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 diameter 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%.

Energy Budget Method

In the energy budget method of 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. Along with 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

$$R_n - R_h - R_e - R_r + R_v = 0 \quad \ldots\ldots (8)$$

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 = increase in energy stored in the reservoir, R_v = net energy content of inflowing and out flowing water.

The units used in the above equation are calories per square centimeter. The term sensible heat transfer cannot 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:

$$E = \frac{(R_n + R_v - R_r)}{\rho H_v(1+R)} \quad \text{.......... (9)}$$

Where, E = evaporation in centimeters and ρ = density of water. The Bowen ratio can be computed by the following equation

$$R = \frac{0.61(T_o - T_a)p}{1000(e_o - e_a)} \quad \text{.......... (10)}$$

Where P = atmospheric pressure, T_o = water surface temperature, T_a = temperature of air, e_o = saturation vapour pressure corresponding to T_o, and 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

$$R_n = R_s - R_r + R_a - R_{ar} - R_o \quad \text{.......... (11)}$$

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, and 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 all wave radiation R_{ir} for the reservoir can be measured and the net radiation for the reservoir can be obtained from

$$\begin{aligned} R_n &= R_{ir} - \epsilon\sigma(T_o)^4 \quad \text{.......... (12)} \\ &= R_n + \epsilon\sigma(T_o)^4 - \epsilon\sigma(T_o)^4 \\ &= R_n + \epsilon\sigma(T_o - T_o)^4 \end{aligned}$$

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

Aerodynamic Determination of Evaporation from Reservoirs

The determination of reservoir operation 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

$$E = (e_0 - e_a)(a + bv) \qquad \text{.......... (13)}$$

where e_0 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

$$E = 0.00304\,(e_0 - e_2)v_4 \quad e_2 \text{ and } v_4 \text{ over reservoir}$$
$$E = 0.00241\,(e_0 - e_8)v_8 \quad e_8 \text{ and } v_8 \text{ over reservoir} \qquad \text{.......... (14)}$$
$$E = 0.00270\,(e_0 - e_2)v_4 \quad e_2 \text{ upwind and } v_8 \text{ over reservoir}$$

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 USGS study in which the coefficients a and b of eq. (13) were determined after studying a number of reservoirs up to 120 km^2 in area. The coefficient a was found to be zero and b was given by

$$b = 0.00014\,A^{-0.05} \qquad \text{.......... (15)}$$

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

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.

$$E = \frac{1}{\Delta + r} = (R_n\Delta + rE_a) \qquad \text{.......... (16)}$$

Where Δ is the slope of the saturation - vapour pressure versus temperature curve at the air temperature T_a, E_a is the evaporation given by eq. (13) 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 (eq. 10):

$$R = r\frac{T_o - T_a}{e_0 - e_a} \qquad \text{.......... (17)}$$

Charts are available relating the reservoir evaporation with solar radiation, air temperature, dew point and wind moment.

In the derivation of equation (16), it is assumed that R_n represents exchange of radiation at water surface. E_a is based upon the aerodynamic equation and 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.

Water Budget method

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

Estimation of reservoirs outflow

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

$$Q = Q_{sp} + Q_{tb} + Q_{us} + Q_1 \qquad (18)$$

Where, Q_{sp} = discharge through spillways, Q_{tb} = discharge through turbines, Q_{us} = discharge through undersluices, Q_l = discharge through leakage from dam.

Discharge through spillway under sluices

The discharge through spillway can be computed either by using hydraulic formulae or by results of model testing. The discharge through spillway can be computed by

$$Q_{sp} = C_{sp} C_q b_{sp} \left(2gh_{sp}^{1.5}\right)^{1/2} \qquad (19)$$

Where, C_{sp} = submergence coefficient, C_q = discharge coefficient for spillway, b_{sp} = width of the spillway, and 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:

$$Q_{sp} = C(L - knH)(H + h_v)^{3/2} \qquad (20)$$

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 metric units, the value of c varies from 2.21 at the discharge head to 1.71 at very small heads. Along with spillways, usually reservoirs also have low level outlets for releasing water when the water level is low. These outlets behave as orifices and the discharge through them is given by:

$$Q_{or} = C_{or} eA(2gh)^{1/2} \qquad (21)$$

Where C_{or} is the submergence coefficient for semi-submerged or submerged orifices, e is a factor which accounts for jet contraction and difference between actual flow velocity and idealized flow velocity. A is the cross-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 consider the 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.

Discharge through turbines

Two methods of determining discharge through turbines are commonly used. Each of these is discussed below.

Discharge characteristics method

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

$$Q_{tb} = \frac{W_{tb}}{9.81 h_{tb} \eta} \qquad (22)$$

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 subtracting 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 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. Ferguson and Znamensky (1981) mention 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.

Leakage through dam

It consists of loss of water from the reservoir due to leakage through the body of the dam as well as through gates and spillways. It is not easy to relate these losses with a measurable 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% of the total discharge through the structure.

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 Darcy Law:

$$I_G = bdk\frac{h_1 - h_2}{l} \quad (23)$$

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 l apart (Fig. 2).

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. It can be expressed as a sum of four components (Ferguson and Znamensky 1981)

$$\Delta S = \Delta S_w + \Delta S_{rm} + \Delta S_{bs} + \Delta S_g \quad (24)$$

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.

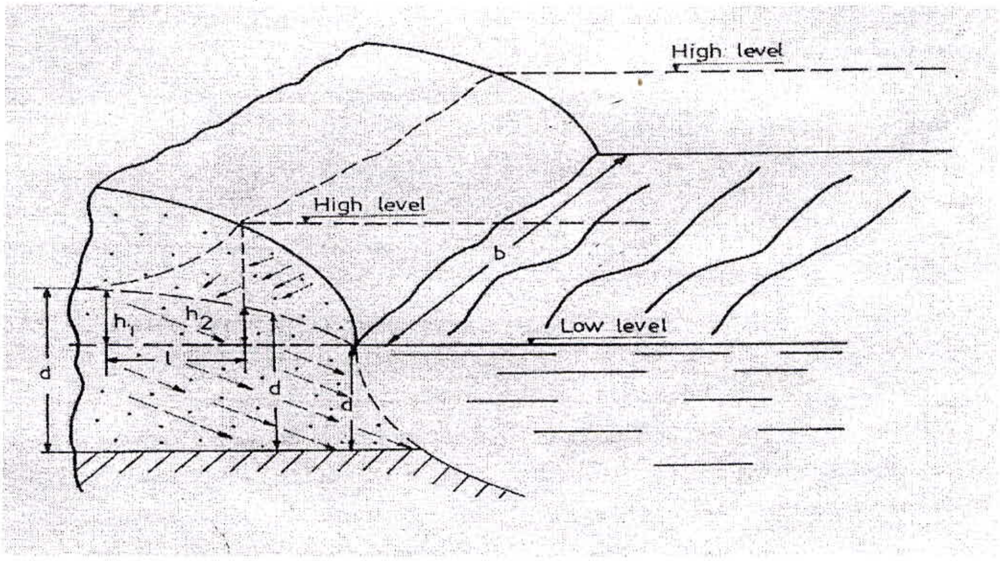

Fig. 2 Definition sketch for computation of groundwater flow

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

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 contours 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 up-to-date 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. 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 lead to fluctuations in the water level. The following equation (Fig. 3) can be used to compute the change in stage due to wind.

$$\Delta h_w = \left(3 + \bar{d}_w\right)\frac{u^2 l}{d_m}(Cos\lambda)10^8 \qquad (25)$$

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 (25), the changes in water volume in a sub area 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 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.

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 this 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 sub area but this requires individual elevation-storage curves for each sub area.

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 sub area with the total area for reservoir. These weights are then multiplied by the corresponding stage to determine mean weighted water level. Mathematically,

$$h_m = h_1 \frac{A_1}{A_R} + h_2 \frac{A_2}{A_R} \ldots\ldots\ldots\ldots\ldots h_n \frac{A_n}{A_R} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(26)$$

Where h_m is the mean stage, $h_1 \ldots h_n$ 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 surface area of complete reservoir.

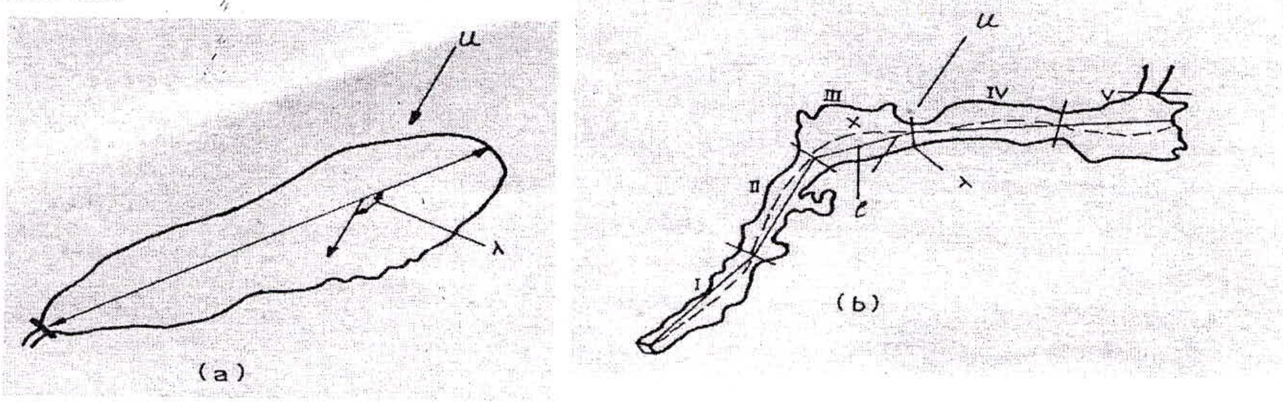

FIG. 3(a): Computation of fluctuation of water level in a reservoir, 3(b): Computation of fluctuation of water level due to wind in a reservoir when wind directions are changing

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 be used for determination of volume of stored water.

The other components of equation (24) 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).

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 δ_1, δ_2, … δ_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

$$\delta < \sqrt{\delta_1^2 + \delta_2^2 + ... + \delta_n^2} \qquad (27)$$

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 varies widely, percentage errors in them will also vary over a large range. This variation also depends 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 sensitivity 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 rainy season, 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.

CONCLUSIONS

From the review of literature on the various methods to determine the different components of water balance of a reservoir, 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 should be considered while deciding about the accuracy of a particular measurement.
c) The above point 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) In India, extra attention must be paid for estimation of reservoir inflow from the ungauged basin and seepage losses from the reservoir.

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