STATUS OF MEASUREMENT ACCURACY IN LAKE WATER BALANCE STUDIES

A.K. BHAR
Scientist-E

National Institute of Hydrology, Roorkee-247 667

ABSTRACT

Water balance studies of lakes without error estimation can be very misleading and can give a false sense of security. The accuracy required for the computation and measurement of water balance components is more stringent for shorter time intervals. Case studies of error estimates for different components of water balance of lakes in India are rare, but experiences from elsewhere could be the guiding ones for adopting suitable techniques in future. Errors mostly emanate from a lack of understanding of the physical principles. Measurement of different components using imperfect instruments, inadequate sampling designs and poor data collection procedures, and regionalization of point data in a time space continuum are the major sources of errors. Also, there could be serious problems in accuracy if some terms in water balance are ignored e.g., evapotranspiration from the marshy zone associated with shallow lakes.

1. WATER BALANCE EQUATION FOR LAKES

The water balance equation for lakes for any time interval is basically a continuity equation. A lake represents a simple open system with respect to the mass balance of the water itself. Consequently, a fairly simple water balance equation can be set up (Fig. 1) as follows :

$$G = \underbrace{(I_r + I_p + I_g)}_{\text{Input}} - \underbrace{(O_r + O_e + O_g)}_{\text{Output}} \qquad \ldots(1)$$

Where, G = net change in storage of water in the lake,

I_r = Surface inflow

I_p = direct precipitation on the lake surface

I_g = groundwater inflow to lake

O_r = surface outflow

O_e = evaporation from lake water surface

O_g = groundwater outflow

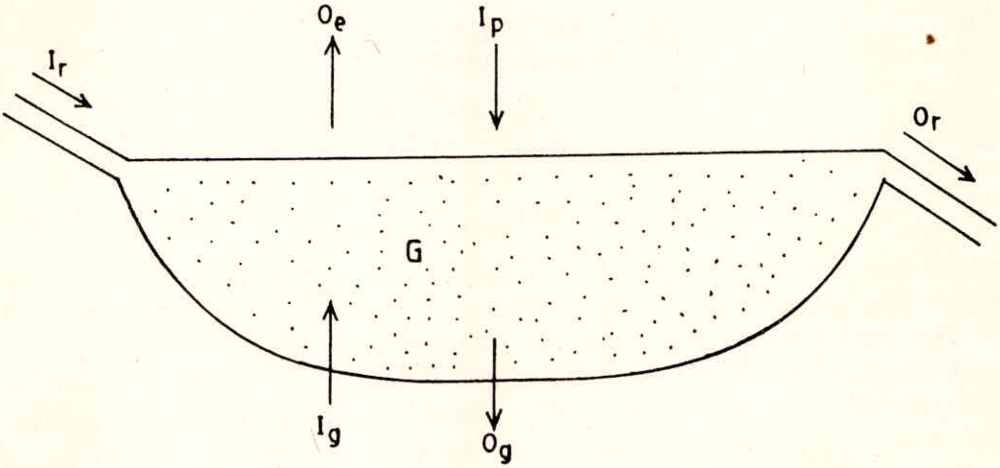

Fig. 1 Schematic diagram of the water balance of a lake

1.1 Discrepancy term (δ) in lake water balance

In practical applications of equation (1) there are errors involved in the estimates of the various components. If the variables are defined as measured or estimated values (as opposed to true values) these errors may be lumped in a discrepancy term δ and rewritten as

$$G = (I_r + I_p + I_g) - (O_r + O_e + O_g) \pm \delta \quad \text{... (2)}$$

It should be noted that δ represents the net effect of all the errors of estimate. Some of these may tend to cancel each other. In analyzing water balances a zero value of δ in equation (2) should, therefore, not be interpreted as an assurance that the estimates of individual components are all correct. The result may be fortuitous. On the other hand, a large value of δ compared to the magnitudes of other terms is an indication of serious problems in the analysis. For example, most shallow lakes involve significant marshy zones. In these lakes the water loss due to the air occur both from the open water surface and by evapotranspiration from the marshy zone. Thus the water balance equation should take into consideration the evapotranspiration from the marshy zone also and the modified water balance equation for shallow lakes similar to as suggested by Shih (1980) should be adopted for computation of the water balance.

1.2 Time interval of lake water balance

Equation (1) can be used to determine the water balance for a lake for any time interval. All of the above components of the water balance should be estimated independently on the basis of required data. The shorter the time interval, the more stringent is the requirement of accuracy for the computation or measurements of the water balance components. The accuracy of the computation of the water balances of lakes and the minimum allowable balance period are dependent on the accuracy of the estimation of the basic water balance components, viz., surface inflow and outflow and water storage in the lake. The relative error, $B_e(\%)$, of water storage changes compared to the infow is expressed as (UNESCO, 1981):

$$B_e = \frac{10^4 \, A_W \, \delta \bar{h}}{86400 \, Qt} \quad \text{... (3)}$$

Where, A_w = Water surface area of lake or reservoir (km^2)

δh = error of mean level estimation (m)

Q = discharge into the water body ($m^3 \, a^{-1}$)

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

Equation (3) can be used to determine the length of the balance period that will ensure that the relative error, B_e, is not more than 5 percent, i.e., within the limits of accuracy of hydrometric estimates of runoff. If B_e is less than 5 percent due to increase of inflow (eg during rainfall or snowmelt), then it is possible to reduce the length of the balance period.

2. CLASSIFICATION OF ERRORS IN THE MEASUREMENT OF BALANCE COMPONENTS

Errors emanate due to our lack of understanding of the controlling physical principles. Errors are of two types: (i) Measurement errors (ii) Errors due to regionalization of point data. Measurement errors result when we try to get a measurement of a quantity at a point using imperfect instruments and inadequate sampling design and data collection procedures. Errors due to regionalization result from estimating quantities in a time space continuum from point data.

The tendency at present is to distribute the error term by equating percentages to equal quantities of water. But a large percentage error in a small quantity may represent an insignificant volume in a large quantity of water. It is important that errors associated with different time periods be analysed. More data over longer time periods tends to decrease the errors (Winter, 1981). Some of the incongruities that may occur in the measurement and estimation of the water balance components are described in the subsequent sections.

2.1 Precipitation

Factors affecting precipitation over a lake are different from those affecting it over surrounding land areas. Studies indicate that lake precipitation is lower than the precipitation over surrounding land areas.

Precipitation into a lake is usually measured by the rain gauges located near and around the lake. This conventional method gives rise to unavoidable serious wind errors. If there are islands or islets in the central part of the lake, opportunities increase for more accurate lake precipitation estimates.

Also, there are problems of regionalization of point rainfall data. Linsley, et al. (1958), showed that the areal average determined by the arithmetical mean to be 18 percent more and that determined from the Thiesson method to be 9 percent more than the one determined by the isohytel method respectively. Usually, the sampling errors tend to decrease with increasing network density, duration of precipitation and size of area. In general, the instrument error could be to the tune of 1–5 percent and placement of gauges could contribute errors in the range of 5–15 percent for long term data and as high 75 percent for individual storms. Differences as high as 20 percent in the catches have been observed between gauges with and without wind-shield. Ariel averaging of point precipitation data can be as high as 60 percent for individual storms depending on storm type, duration and gauge density. These observations are generally based on studies in relatively flat terrain. Errors in measuring precipitation in mountainous areas can be expected to be considerably larger.

In lake studies, hydrologists are interested to determine the amount of precipitation falling directly on the lake rather than throughout the watershed. Use of gauges at the lake will have least errors. Gauges near the lake provide the next best option if these are read after each precipitation event.

2.2 Evaporation

Three groups of methods exist for the study of evaporation from water surfaces (Winter, 1981).

1. *Balance methods*: the application of energy and/or water balance.
2. *Comparative methods*: the use of evaporation pans or tanks, followed by the use of pan or tank coefficients.
3. *Aerodynamic methods*: eddy correlation, mass transfer and gradient methods.

Use of the balance method requires the measurement of all other components of the respective balance equation except the component related to evaporation. But, the water balance method is found to be impracticable (UNESCO, 1984).

The energy balance equation requires the measurement of incoming short wave and long wave radiation, air temperature, dew point, wind velocity and surface water temperature. Lake Toba is in north Sumatra, Indonesia and is largest fresh water lake in Indonesia. A detailed study (Sene et., 1991) has been done on this tropical lake perhaps for the first time to estimate evaporation on the basis on energy budget method. The investigators have indicated the applicability of energy budget method with the assumption that the average energy for evaporation is equal to the net radiation. It is estimated that the annual average evaporation from the lake is about 1.5 m. Lake Kinneret (average area = 160 sq.km) in Israel and in which the river Jordan falls is a major contributor to the Israeli water supply scheme. Evaporation from this lake is quite high and has been estimated to be 30 percent of its water budget (Simon and Mero, 1985). The energy budget method is considered most accurate for estimation of the evaporation. The method can estimate the annual evaporation within 10 percent or less error and the seasonal evaporation within about 13 percent error (Winter, 1981).

In comparative methods, evaporation pans are most commonly used to measure evaporation. But the lakes have considerably different wind and thermal regimes than pans located on land. Floating pans only partly overcome this disadvantage.

In the studies being done at the Institute of Hydraulics and Hydrology, Poondi, to find material for hydraulics and hydrology, Poondi, for floating evaporimeter whose thermal conductivity is equivalent to that of water and at the same time non-leaky and light in weight, a perspex sheet which is akin to glass but at the same time non brittle, non-leaky and workable was chosen for the fabrication of floating evaporimeter installed at the Poondi reservoir. The unit has a sliding arrangement which follows the water surface and could be fixed at the desired location. A graduated gauge of requisite least count when fixed to the frame-work shall enable the observation of water level fluctuations at the site of evaporation through the transparent perspex sheets (Makwana, 1992).

The ratios of annual lake evaporation to pan evaporation are found to be consistent from year to year and region to region but exhibit considerable variation from month to month. Pans should not be used to estimate evaporation for shorter time periods.

However, Lake Hefner data indicates that reasonable values for monthly coefficient can be determined by adjusting the annual coefficients on the basis of the average monthly values of vapour pressure. However Butler (1957) suggested a method of computation of a reasonable value for class A evaporation pan coefficient for a given month.

$$C = \left[\frac{(e_o - e_z)\ Lake}{(e_o - e_z)\ pan} \right] * 0.69 \qquad \text{... (4)}$$

where, c = pan coefficient for a given month,

e_0 = Vapour pressure of saturated air at the temperature of the water surface for the given month,

e_z = corresponding average vapour pressure of air at some specific height (usually 2 m) above the water surface.

Aerodynamic methods are based on the work of Dalton who, in 1802, suggested that evaporation is proportional to the vapour pressure gradient between the evaporating surface and the air, with a coefficient which is strongly dependent on wind velocity, usually referred to as wind function.

Jobson (1972) collected data during a 15 month period at Lake Hefner. He studied the effects of averaging of meteorological data for periods of three hours, one day in one month on estimation of evaporation. He inferred that the value of the wind function is independent of the time interval over which the meteorological data have been averaged provided that the data are averaged for the value of the coefficient and becomes dependent on the averaging time and the computed evaporation will be systematically in error.

All the methods of determining or estimating evaporation have a common problem. Estimated errors in selected terms of a given equation, or in evaporation itself, were generally compared with other methods of evaporation, which in themselves contain errors.

2.3 Streamfow and Surface Outflow

The surface inflow into a lake can be subdivided into inflows from rivers and creeks and inflows from numerous small basins surrounding the lake. Part of the latter components consist of non-channelized overland flow which is often overlooked or ignored. Little studies have been made to ascertain the importance of their role in lake behaviour. There will always be parts of the lake's watershed that cannot be gauged by stream gauging techniques (Fig. 2.).

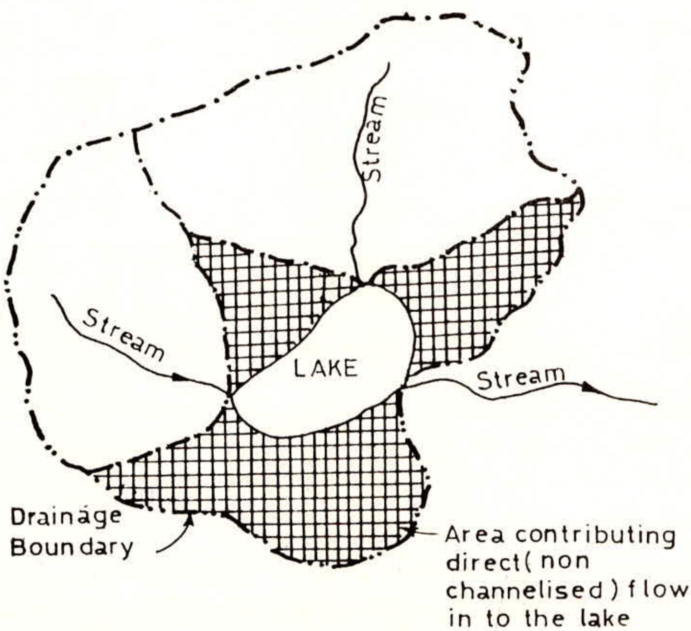

***Fig. 2** Lake and drainage basin showing area contributing to non-channelised surface inflow (after Winter 1981)*

The limited accuracy of the gauged data at times leads to large errors in evaporation estimates. Kriging method have been successfully used for point by point estimation of surface level for Lake Winnipeg in Manitoba, Canada. The method is useful for obtaining an overview of the water level for the entire surface of the lake and through an examination of the sequential daily water surface profile. Unusual and unrealistic behaviour of the profile can be identified to exclude the suspect gauge readings (Zrinji and Burn, 1992).

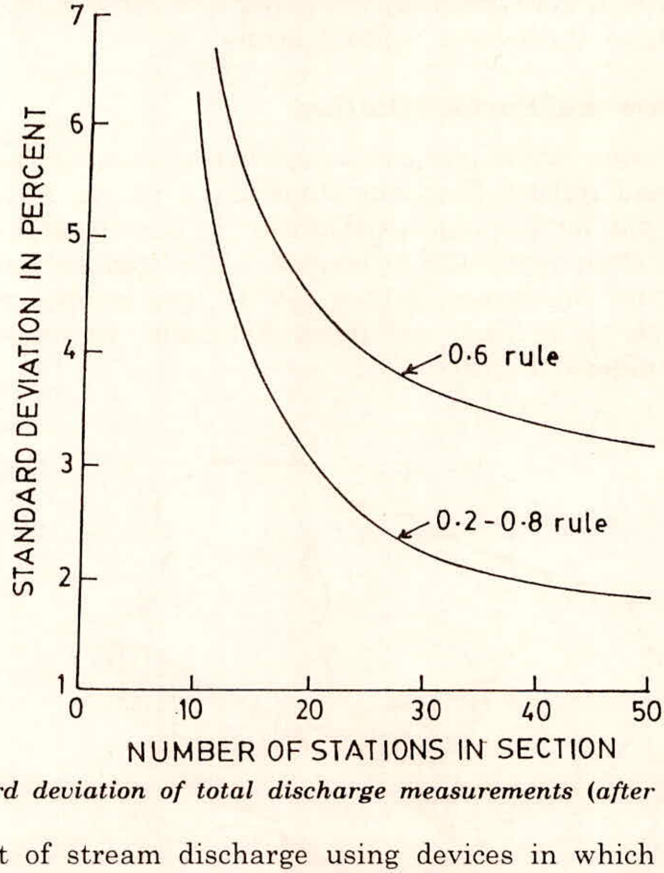

Fig. 3 Standard deviation of total discharge measurements (*after Winter 1981*)

Measurement of stream discharge using devices in which the flow is routed through them, such as weirs and flumes, can usually be done within 5 percent error, if recording instruments are used to continuously monitor water stage.

Accuracy of current meter discharge measurements are dependent on: (1) the velocity meter, (2) number and distribution of velocity measurements, (3) time of exposure of the meter, and (4) measurement of the cross sectional area of the channel. Tests of velocity meters indicate that errors are generally less than three percent at low velocities and less than one percent at higher velocities. Comparative calibration of meters between pre and post field use have shown that their ratings change by less than ten percent. Errors related to estimating velocity distribution, which is related to the number of point measurements in both the vertical and horizontal direction, can be about five percent. Errors related to exposure time of the meter can also be about five percent. Considering all these factors, figure 3 can be used to summarize the overall errors to be expected in a current meter discharge measurement.

Stage discharge relationship curves can vary widely in quality. If a good relationship is developed, the error in estimating discharge is probably less than 5 to 10 percent.

Regionalization of stream discharge information from gauged to engaged watersheds has been shown to be in error by as much as 70 percent. Use of multiple regression to estimate low flow steam discharge based on basin characteristics has been shown to be in error by greater than 100 percent in many studies, but as little as 10-15 percent in others.

3. DISCUSSIONS AND CONCLUSIONS

Errors can be broadly classified into those of measurement and regionalization (interpretation) errors. Measurement errors result from trying to measure a quantity at a point using imperfect instruments and inadequate sampling designs and poor data collection procedures. Regionalization errors result from estimating quantities in a time space continuum from point data. Both types, in turn, are influenced by our understanding of the controlling physical principles. The measurements should be representative for the lake being studied. For example, the temperature profile of the lake should be taken in the middle of the lake. Temperature profile of a lake is important with respect to heat balance vis a vis thermal regime, evaporation, internal oscillation and mixing of a lake. The lake level measurement should be made at the end of a lake and should be free from any wind effect.

The errors are particularly more serious if one or more components are calculated as a residual term. Water budgets determined by poor methodology, with estimates of errors, can be very misleading and can give a false sense of security about how well the budget is known (Winter, 1981). It may be pointed out that there is a tendency at present to distribute the error term by equating percentages to equal quantities of water. But, a large percentage error in a small quantity may represent an insignificant amount of water in contrast to a small percent error in a large quantity of water. It is also important that errors associated with different time periods be analysed. More data over longer time periods tend to decrease the errors (Winter, 1981).

Errors in measuring and estimating hydrologic components interacting with lakes can have a significant impact on calculations of water balance of lakes. The errors are particularly serious if one or more components are calculated as the residual term, and the errors in the measured components are not considered in interpretation of that residual term.

If a hydrologic component, such as ground water, is calculated as the residual of the budget equation, it must be appreciated that the residual can be on only one side of the equation, and that it is a net value. Therefore, especially for flow through situations, the residual value can seriously underestimate actual quantities of water moving through the lake bed.

When estimating errors in calculations of hydrologic components, it is important to evaluate the errors in interpretation of point data, such as ariel averaging technique, as well as the errors in gauging. A rain gauge or evaporation pan might be fairly accurate but if it is a number of kilometers from the lake, care must be exercised in adjusting the gauged value to the lake of interest.

Accuracy of water budgets decreases as shorter time frames are considered. Therefore, errors associated with annual estimates of a hydrologic component should not be applied to shorter term values.

References

1. Butler. S.S., (1957),"Engineering Hydrology," Prentice Hall, New Jersey, USA.
2. Jobson, H. E., (1972), "Effect of Using Averaged Data on the Computed Evaporation," Water Resources Research, Vol.8, No. 2, pp.513–518.
3. Linsley, R.K.,M.A. Kohler and J.l.H. Paulhus, (1958), "Hydrology for Engineers," McGraw-Hill, New York, pp. 340.
4. Makwana, M.M., (1972), "Evaporation from Water Bodies and Its Control," Water Science Educational Series No. 2, NIH, Roorkee.
5. Shih, S.F., (1980), "Water budget computation for a shallow lake-Lake Okeechobee, Florida," Water Resources Bulletin, American Water Works Association, Vol. 16, No. 4 Aug.,80.
6. Simon, E. and F. Mero, (1985), "A Simplified Procedure for the Evaluation of the Lake Kinneret Evaporation," J.of Hydrology, vol. 78.
7. UNESCO, (1984), "Methods of Computation of the Water Balance of Large Lakes

and Reservoirs–Vol. II : Case studies," Publication No. 31, Edited by Ferguson et al.

8. Winter T.C. (1981), "Uncertainties in Estimating the Water Balance of Lakes," Water Resources Bulletin, Vol. 17, No. 1, pp 82–115.

9. Zrinji, Z and D.H. Burn, (1992), "Applications of kriging to surface level estimation," Canadian J.Civil Engineers, vol. 19,no.1.