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WATER BALANCE OF LAKES

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PREFACE

A lake is easy to visualize because of its definite boundary. The knowledge of water balance of lakes is important to understand the interaction of lake and nearby catchment, nutrient budgeting and to plan proper use and conservation of lake water. However, little effort has gone into the understanding the processes and controls on water sources and sinks as they relate to lake water balance.

Water balance equation looks deceptively simple and a lake represents a simple open system with respect to the mass balance of the water itself. Proper measurement or realistic estimation of each component is a difficult technical problem. For example, the groundwater component especially for a closed lake if estimated as a residual could differ from an independent estimate by more than 100%.

With these things in view, this status report has been prepared to bring out various techniques and models to study water balance and its components, errors estimation, and shortcomings in the available hydrologic indices. The type of water balance and classification of lakes on the basis of of hydrologic characteristics suitable for Indian context has been identified. The hydrologic responses, behaviour and processes in a large and small lake important for water balance relationship have been highlighted for further testing. Indian lakes perhaps be categorised in general as small lake with respect to these characteristics.

This status report entitled "Water balance of lakes" is part of the work programme of Lake Hydrology Division of the Institute. The report has been prepared by Shri A.K.Bhar, Scientist-E.

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Director

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Abstract

Lake Water Balance relationships forms the basis for rational deterministic hydrological forecasting models and are necessary to harness, develop and manage lake water. Assessment of the causes of lake deterioration and the success of ameliorative strategies depend on nutrient budgeting and water budgeting is basic to calculate nutrient budgeting. The available models of lake water balance with concomitant nutrient budgeting are described. The various components of water balance, their web of interdependences and interactions, errors and difficulties involved for various types of lake are discussed at length. It has been found that the energy budget method is the most accurate method of calculating evaporation with least error. Groundwater component especially for a closed lake if estimated as a residual, could differ from an independent estimate of groundwater beyond permissible error. For surface water inflow, the non-channelized flow which are difficult to measure/estimate is the main source of error. Szesztay's classification of lakes on the basis of main water balance components is the only approach so far available to classify lakes on the basis of hydrologic indices and is recommended to be adopted for Indian lakes. Examples of water balances of lakes in equatorial tropics are included as the environmental conditions are close to Indian context. Differences of lake processes for large and small lake and their implications and effect in water balance of a lake is discussed and most of our lakes could be taken as small lakes for their hydrologic behaviour and for water balance study.

1.0 Introduction

1.1 General

A lake is easy to visualize because of its definite boundaries unlike other storages in the hydrologic cycle. Lakes contain over 95 % of the world's surface supply of fresh liquid water. But, lakes are transitory features of the earth's surface and each lake has a birth, life and death related to certain geological, hydrological and biological processes. Their life expectancy may vary from a short spell of two floods to millions of years. Lakes are pleasing aesthetically and important economically for recreation, domestic and industrial water supply, fishes, transport and serve as nuclei for community development. So, lakes often deteriorate due to these. Assessment of the causes of the lake deterioration and the success of management and restoration projects are essentially based on nutrient budgets. Water budgeting is basic to calculate nutrient budgeting. But, it seems that there are many intricate processes and controls relating to lake both as sources and sinks which need to be addressed and understood.

1.2 Need for water balance study

Water balance relationships form the basis for rational, deterministic hydrological forecasting models and are necessary for (UNESCO, 1981):

i) forecasts of lake levels for shoreline, property utilization and navigation.

ii) in the design, selection and operation of forecasting models,

iii) predicting environmental impacts i.e. preservation of living resources of a lake through the maintenance of water quality standards.

iv) to obtain valuable information base for effective management.

v) help in global studies of climate variability.

Water balance studies of lakes are of vital importance for the proper use, conservation and harnessing the lake water as water exchange in lake. The water exchange in lakes is much slower than in rivers. On a global basis and in terms of the total water of the earth, the lake water is ten times more than the river water. Incidentally, the average residence time for rivers and lakes are 2.1 years and 21 years respectively and these indicate the slower water exchange process in a lake than a river.

Following aspects should be taken care of while computing the water balance of a lake:

i) water inflow from rivers and drainage areas along the whole length of the water body perimeter

ii) peculiarities in the formation and fall out of precipitation on the water surface

iii) Water outflow to a river

iv) Peculiarities of water losses through evaporation from the water surface

v) Peculiarities in hydrology of watersheds

Lake has its hydrologic responses. It has its cause and effects relationship with the nearby catchment. Because of storage of large mass of water,it moderates flood and climate factor in the region. Smaller the lake, the more responsive it is to changes in energy inputs. Small lakes behave as a single system, but almost all large lakes respond as a complex of sub-basins, each of which may be significantly different in size, form and depth.

Lakes have an extremely large capacity to accept heat into storage and subsequently to give it back. This exert an influence on local climate and causes precipitation to be different than over land area (UNESCO, 1981). The available heat at the water surface to support evaporation depends less on short time fluctuations in radiation than in the stirring of the water or air.The great heat storage capacity keeps the surface cool and evaporation slow in spring and summer and maintains a warm surface and rapid evaporation in winter (Miller,1977). Apart from great volume, the size of the lake affects the evaporation of the catchment in dry sub-tropical area. If the lake water is to occupy more than 40 % of the catchment area, all runoff from the catchment would evaporate from the lake (Brouwer et al., 1975).

Lakes are most numerous in regions where stream arise and find their way to ocean basins. Stream hydrograph itself gets attenuated by the presence of these lakes. Other things being equal. a catchment with lake(s) will exhibit lower flood peaks,higher minimum flows and less sedimentation than a catchment without lake(s). Due to this, variability of downstream discharge of the river provide a more stable supply of water and reduce the incidents of floods and low flows (UNESCO, 1981). There are other regions in which streams are common but end in dry valley or in lakes without outlets, lakes are less common in these regions. In desert and semi-arid localities, streams are rare, and as would be expected, lakes are also less. But there could be lakes in such areas which are land locked and water escapes only through evaporation or seepage under conditions of high evaporation and low precipitation. Closed lakes are usually saline. Groundwater has a dominant role in framing the salt and water balance of closed lakes.

2.0 Water balance equation for lakes

2.1 General form of the water balance equation

The water balance equation for lakes for any time interval is basically a continuity equation. The water volume of a lake is not constant. According to the law of conservation of matter, there is equilibrium between inflow components, outflow components and the change of water volume for each time interval. This equilibrium is described by the water balance equation.

A lake represents a simple open system with respect to the mass balance of the water itself. A lake has an upper water surface exposed to the atmosphere and a lower surface boundary in contact with a solid mineral surface. Water may enter and leave through both of these boundary surfaces. Incoming streams and overland flow from ground surfaces draining into the lake represent point and line sources of water input, while an overflow channel represents an output point. Consequently, a fairly simple water balance equation can be set up (Fig. 1) as follows:

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

Where,

ΔS = net change in storage of water in the lake,

I_r = surface inflow

I_p = direct precipitation upon the lake surface

I_g = groundwater inflow to lake

O_r = surface outflow

O_e = evaporation from lake water surface

O_g = groundwater outflow

The above equation (1) based on inflow equals outflow plus or minus changes in storage is commonly used. But it can only serve the purpose adequately if all the components of water balance including groundwater are measured accurately. The relative magnitude of the water balance components vary from place to place and season to season. In most cases the groundwater contributions

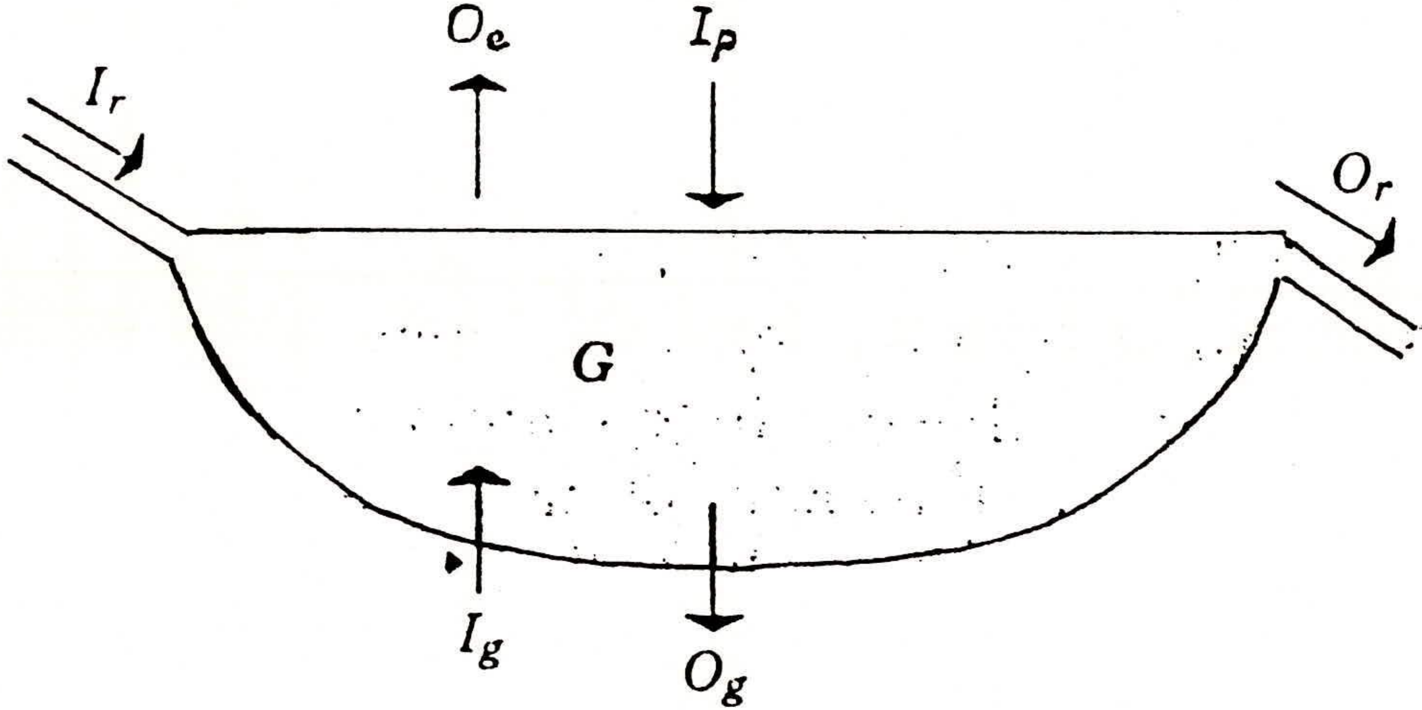

Fig. 1 - Schematic diagram of the water balance of a lake

are small compared to the other inflows and outflow components. In practical application of this equation 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

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

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.

Lakes can be divided into two main categories: open (exorheic) lakes with outflow and closed (endorheic) lakes without outflow. Lakes with intermittent (ephemeral) outflow during high storage constitute an intermediate category.

For large lakes it is often convenient to divide the surface inflow I_r into inflow from gaged streams (I_u) and lateral inflow from direct runoff or ungaged streams (I_{ug}) i.e.,

$$I_r = I_u + I_{ug} \qquad \text{........(3)}$$

For lakes with a surface area varying considerably during water level fluctuations, it is preferable to express the components of the water balance equation in volumetric measurements. For lakes with a nearly constant surface area, it is more convenient to express water balance components in units of depth of water relative to the mean surface area of the lake (UNESCO, 1981).

The water balance equation for open (exorheic) lakes for a period of zero net storage change can be written as

$$(I_r + I_p + I_g) = (O_r + O_e + O_g) \qquad \text{........(4)}$$

This equation can be applied to short period of time over which the measured storage change is zero, to a long period over which ΔS is negligible in comparison to other terms in the equation, or to long term mean annual water balances.

When, in addition, the underground components I_g and O_g do not contribute significantly to the balance they may be neglected and equation (4) becomes

$$(I_r + I_p) = (O_r + O_e) \qquad \text{........(5)}$$

The water balance equation for a closed (endorheic) lake when storage changes and subsurface flows are negligible can be expressed as,

$$(I_r + I_p) = O_e \qquad \text{........(6)}$$

When only an approximate computation of the water balance is required for the purpose of routine control of water inflow and outflow, a simplified water balance equation can be used for intervals when precipitation and evaporation are negligible,

$$\Sigma I = \Sigma O + \Delta S \qquad \text{........(7)}$$

where,

ΣI = sum of input components of the water balance equation

ΣO = sum of output components of the water balance equation

Equation (7) is suitable for small lakes with large inflow and outflow i.e. when there is a high rate of water exchange. Equation (7) becomes less reliable for larger (area) water bodies and shorter time periods, when the error in estimates of ΔS may exceed the total inflow.

2.2 Water balance equation for a long period

Equation (1) can be used to determine the water balance for a lake for any time interval. However, with the shortening of the balance period, computation should include a more detailed accounting of the water balance components. An example of the water balance computation for a short time interval (a month) is given by Vikulina (1970 vide UNESCO, 1981).

$$I_r + I_p - O_r - O_e \pm O_{ba} + O_{ice} = \Delta S \qquad ....(8)$$

where,

O_{ba} = temporary water loss by saturation of shores of lakes

O_{ice} = temporary water loss by ice left after fall of level of lakes

Underground inflows and outflows are assumed to be small and hence neglected.

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 upon the accuracy of the estimation of the basic water balance components, that is, 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)

$$B_e = \frac{10^4 A_w \delta \bar{h}}{86400\ Qt} \qquad ....(9)$$

where

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

$\delta\bar{h}$ = error of mean level estimation (m)

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

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

Equation (9) 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%, that is, within the limits of accuracy of hydrometric estimates of runoff. If B_e is less than 5% due to increase of inflow (e.g. during rainfall or snowmelt), then it is possible to reduce the length of the balance period.

Theoretically, the equations described above can be used to compute water balance in any lake without extensive marshy area. Practically, however, most shallow lakes involve significant marshy zones. In these lakes the water loss to the air occur both from the open water surface and by evapotranspiration from the marsh zone. Thus the water balance equation should take into consideration the evapotranspiration from the marsh zone also. Shih (1980) has suggested the following equation for the computation of water budget in time t (month) of a shallow lake:

$$V_t = V_{t-1} + I_t + A_t R_t - A_{wt} E_t - A_{mt} E\,T_t - O_t - SP_t \quad ....(10)$$

where,

V_t = storage at t

V_{t-1} = storage at (t-1)

I_t = inflow at t

R_t = rainfall at t

E_t = evaporation from water surface at t

$E\,T_t$ = evapotranspiration from marsh zone at t

O_t = outflow at t

SP_t = seepage at t

$A_t = A_{wt} + A_{mt}$, total surface area of lake at t

A_{wt} = the area of water surface at t

A_{mt} = the area of marsh zone at t

2.3 Water balance for closed lakes

Closed lakes are internal drainage area. Under congenial climatic conditions, runoff water accumulates in the deepest parts of these lakes and closed lakes are formed. Like fresh water lakes the closed lakes are supplied with water mainly through surface inflow and precipitation. But, this water is spent in different ways:- for a fresh water lake with an outlet it contributes to runoff and to a lesser degree to evaporation; in closed lakes without an outlet it evaporates entirely (UNESCO,1975). There are regions in which streams are common, but end in dry valley or in lakes without outlets, lakes are less common in these regions. In desert and semi-arid localities, streams are rare, and as would be expected, lakes are also less. But there could be lakes in such areas which are land locked and water escapes only through evaporation or seepage under conditions of high evaporation and low precipitation, closed lakes are usually saline. In such lakes, often groundwater plays an important role in framing the salt balance as in the for the Caspian Sea (Reid and Wood, 1976). Further about 250 cu.km. are drawn from it in the form of evaporation and as such it has a great influence on European water resources. In Asia closed salty lakes prevail in the steppe and semi-desert areas. In Australia, closed saline lakes are shallow and they dry up periodically. Such lakes are numerous; the largest among them are lakes Eyre and Torrens. Flow into these lakes is about 6.5 cu.km., but the potential from these lakes reaches 13 to 15 cu.km. Due to this reason, these lakes exist intermittently. These are filled up during years of abundant water and are transformed into salt marshes during the dry season.

In other closed lakes, substantial groundwater contribution does not allow the lake water to be saline, - i) Naivasha (highest rift valley lake in Kenya) lake has high potential evaporation rates but its water has not become saline indicating some sub-surface drainage, ii) Blue lake in the Karstic region of southeast Australia is recharged almost entirely from groundwater and provides municipal water supply . Levels of closed lake have been known for over 250 years as indicators of climate and these lakes occurs generally in climates where evaporation equals or exceeds precipitation. In case of precipitation exceeding evaporation, a closed lake must leak enough water into the groundwater system to keep the lake level below the surficial threshold. These lakes may also be sensitive to hydrologic shifts effected by non climatic factors like changes in land use. Groundwater exerts both local and regional controls on closed lake level changes. (Almendinger, 1990).

A water balance parameter characterising closed lakes is enunciated by Szesztay (1974 vide Kuusisto, 1985) as:

$$k_c = I/(E_1 - P_1) = r_c P_c/(E_1 - P_1) \quad ...(11)$$

Where,

I = total inflow, cu.m.

P_1 = precipitation on the lake, cu.m.

E_1 = evaporation from the lake, cu.m.

r_c = runoff coefficient

P_c = precipitation on the drainage basin, cu.m.

The values of k_c vary widely. For a lake situated in a highland depression with significant runoff and relatively low evaporation, k_c is about 0.23. For areas characterised by high evaporation and a low runoff coefficient, closed lakes can have k_c

values lower than 0.01. In the former case, the lake occupies a considerable portion of the total drainage area, in the latter case it may disappear during a prolonged drought.

The analysis of fluctuations of water level in the largest closed lakes of the Earth shows a definite drop in the last century. For example, the level of the Caspian Sea dropped about 300 cm from 1895 to 1960 and the level of the Great Salt lake by 350 cm in the period 1850-1960 (Kalinin and Klinge,1973 vide Kuusisto,1985). One reason for this has been the ever increasing utilization of water in their drainage basins. However, the decrease in the total volume of the largest closed lakes of the Northern Hemisphere was very sharp from 1910 to 1940, coinciding with a general warming of the climate. After 1940, the rate of decrease in lake volume has slowed down.

2.4 Measurement and estimation of water balance component and errors

The water balance equation apparently looks simple. But actual measurement of each term for a given lake is a most difficult technical problem. So, it will be appropriate to examine the errors that are involved in measurement and estimation of difficult water balance components. A rainguage might be placed at the lake of interest. But does it give a true picture of the amount of water falling on the lake's surface and drainage basin? How accurate are various stream gauging procedures? How often is overland flow, the non-channelized runoff considered in water balance studies? What is the proper justification of neglecting the lakes and groundwater interaction? Groundwater is seldom specifically mentioned in water balance studies of lakes. Further, the measurements should be representative for the lake being studied. For example, 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. Errors are not critically analysed in water balance studies inspite of the fact that it is very important. It is so because the residual term, whether it applies to groundwater or any other component, includes all errors of measured parameters.

Errors can be broadly classified into those of measurement and regionalization (interpretation). Measurement errors result from trying to measure a quantity at a point using imperfect instruments and inadequate sampling design and 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, that is, are the proper instruments and the proper equations and techniques being used to regionally extend the point data?

By being unaware of the proper design of data collection systems and not evaluating or mentioning measurement errors, a water budget estimated by imprecise methods looks as good on paper as one determined by using the best available theory, instruments and analysis techniques. Water budgets determined by poor methodology, without 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 period be analysed. More data over longer time periods tend to decrease the errors (Winter, 1981). Various incongruities that may occur in the measurement and estimation of the water balance components are described in the subsequent sections.

2.4.1 Precipitation

Factors affecting precipitation over a lake are different from those affecting it over surrounding land areas. A lake may be affected by the topography of the adjacent land, specially if there is a steep rise from the shore of the lake. Local storms accompanied by high winds are greatly influenced by the relief of the surrounding land area. Further lakes in deeply incised valleys, crater, rift valley, fjord lakes could be subjected to severe local storms with extremely high wind passing along the entire length of water surface, e.g. lake Baikal, a rift valley lake. But despite relative short duration of such winds they may have considerable impact on local shore erosion, sediment transport and deposition. Excessive heating of the land surface in warm weather leads to the formation of convective precipitation (Kuusisto,1985).

Studies indicate that lake precipitation is lower than the precipitation over surrounding land areas. Average annual precipitation on lake Balaton (600 sq.km) was 17% lower during 1921-58 than over the adjacent land area. For the largest lake in Finland, lake Suursaimaa, the corresponding difference for annual values was 6% over period of 18 years (Kuusisto,1978 vide Kuusisto,1985). Several studies on lake precipitation using island rain gage and radar data collected over the Great Lakes have shown that lake rainfall as compared with land basin rainfall is generally diminished in the summer (when cooler lakes act to stabilize conditions) and is increased in the winter and fall (when the lakes add moisture and heat to enhance over lake instability). Precipitation into a lake is usually measured by the rain gages 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. Rain gauges on rafts have also been used. Care should be taken when regionalizing point precipitation values from the surroundings of a lake.

Besides, areal variability of precipitation over a lake can also be considerable. One portion of a lake might get systematically low or high precipitation rates due to the topography of the surrounding land.

Besides human errors in reading the scale in a precipitation gage, errors could be made for gages that use dipsticks due to (i) water may creep up the stick if the stick is immersed for an extended time (ii)the water displaced by the stick, which makes the reading more by about 1 % .For heavy rains, the tipping bucket gages measures the rainfall lower by 5 % due to mechanics of operation. Weighing bucket type gages suffer from decreased sensitivity with increased volume of water in the gage. Rain gages with wind shields catch about 20 % more water than gages without wind shield (Linsley et al.,1958).

There are problems of regionalization of point rainfall data. Linsley, et al. (1958), show the areal average determined by the arithmetic mean to be 18 % more and that determined from the Thiesson method to be 9 % more than the one determined by isohytel method, respectively. Usually, the sampling error 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 % and placement of gages could contribute error in the range of 5-15 % for long term data and as high 75 % for individual storms. Differences as high as 20 % in the catches have been observed between gages with and without wind-shield. Areal averaging of point precipitation data can be as high as 60 % for individual storm depending on storm type, duration and gage 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 gages at the lake will have least error. But in case of a large lake, more than one gage is necessary to keep areal variability to a minimum. Gages near the lake provide the next best option if these are read after each precipitation event.

2.4.2 Evaporation

Evaporation plays an important role in the water regime of a lake and yield from a lake could be seriously affected by the evaporation loss. It has been estimated that the average annual evaporation from lake Mead above Hoover dam is about 6 ft. Lakes from which water leaves only by evaporation are termed as closed lakes.

Because evaporation is basically an energy exchange process, solar radiation is the most important factor governing evaporation. It directly affect the temperature of the evaporating surface. As such, the temperature at the water surface is very significant for the estimation of evaporation. There are number of physical processes which transfer heat energy within the water mass. They vary in importance from climate to climate, from lake to lake and from season to season. They determine the vertical and horizontal temperature distributions in the water body and affect essentially its chemical and biological characteristics. Water temperature and vapour pressure are not independent of wind speed. The vapour pressure of a water body increases with temperature. Equal temperature increases of water surface and overlying layer may not increase rate of evaporation. Depending upon the size of the water body, the water temperature may lag behind air temperature. However, evaporation is not dependent on air temperature alone.

The effect of wind on the evaporation also depends on the size of the water body. Large water bodies may require high velocity and turbulent air movement for maximum evaporation. Wind stir up the air and remove the lowest moist layers adjacent to the lake water surface and to mix them with upper driven layer. So, wind affects the evaporation from the lake and quantity of available water. However, the relationship between wind speed and evaporation holds good only to a certain point, beyond a certain critical value, any further increase in wind speed leads to no further increase in evaporation. Actually, wind does not cause evaporation from the lake, but by "clearing the air" it permits a given rate of evaporation to be maintained. Evaporation of water from lake is greatest in warm, dry conditions because of saturation deficit is large (Ward, 1967). Winds upto 25 miles/hr may be needed to increase evaporation. In the long run, a 10 % change in the wind speed will change the evaporation 1 to 3 % only.

A body of water with a flat surface has greater vapour pressure than one with a concave surface but less than one with a convex surface under the same conditions. When a solute is dissolved in water, its effect is to reduce the vapour pressure of the solution. The reduction of vapour pressure reduces the rate of evaporation. The rate of evaporation decreases with increase in specific gravity (Singh,1989). Although the subject of evaporation from a free water surface as in a lake has been studied for at least two hundred years, the methods of measurement and estimation used are still inadequate.

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. A study was conducted in 1951-52 on evaporation from Lake Hefner (Lake surface area:8.7-9.7 sq.km). As the natural drainage area above the lake is only 30 % larger than the lake at full level, the natural inflow is usually much less than the direct rainfall on the lake surface. Water balance computations were made daily for the study period and required precise measurements or estimates of all the terms in Eq.(1) except evaporation were taken. It was observed that the error in the computation of the monthly evaporation from the water balance was less than 5% and the errors were somewhat larger for daily values. The relative success of this method at the lake was due to the reason that the evaporation was a major component in the balance, outflow from the lake was about 10% greater than evaporation and the inflow term was generally much less except during filling up of the lake or after a rain storm. But this type of situation cannot be expected for all lakes and the water balance method is found to be not practicable (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. Besides these, periodic temperature surveys of the entire water body are needed. If advective energy cannot be neglected, the temperature and amount of the different components of the water balance should also be measured or estimated. Lake Toba is in north Sumatra, Indonesia and is largest fresh water lake in Indonesia. A detailed study (Sene et al., 1991) has been done on this tropical lake perhaps for the first time to estimate evaporation on the basis of 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 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% of its water budget (Simon and Mero, 1985). The energy budget method is considered most accurate for the estimation of the evaporation. The method can estimate the annual evaporation within 10% or less error and the seasonal evaporation within about 13% error (Winter,1981). A comparison of lake evaporation measured/ estimated from shore pan, lake pan and energy balance method for Perch lake, a shallow (mean depth 2m) lake of 0.45 sq.km in the Canadian shield was made. It has a dense forest cover around it. The shore sited pan with proper exposure tallied well (3% lower) with the estimate of evaporation from the energy balance method. However, the lake pan estimate was about 40% higher than the energy balance values. This over estimation by the lake pan could be attributed to the effects of wetting of and the evaporation from the walls caused by the waves rocking the pan. Pan wall temperatures could be considerably higher than water temperatures, leading to rapid evaporation from the wetted areas (UNESCO, 1984).

In comparative methods, evaporation pans are the most commonly used to measure evaporation. But,the lakes have considerably different wind and thermal regimes than pans located on the land. Floating pan can only partly overcome this disadvantage. Neuwirth(1973 vide Winter,1981) reported another example of variation in pan design. At Lake Neusiedl, Austria, a GGI-3000 pan was floated in the lake water using a platform. To ensure that water temperature in the pan was close to that of the lake, a larger pan was fixed around the evaporation pan, and lake water was continuously pumped through the outer pan. The outer pan served a second purpose by reducing splash in, a common problem with floating pans. Evaporation from the rinsed GGI-3000 pan was compared with a class A pan at midlake, the data from which were modified by Webb's (1966 vide Winter, 1981) method. Individual monthly totals for a six -month period differed by 14 percent to 22 percent. The idea of using a submerged pan in the lake centre to provide direct estimate of lake evaporation is conceptually attractive, but there are some very difficult practical problems to overcome in the operation and maintenance of such an installation (UNESCO,1984).

An insulated evaporation pan ,when used in conjunction with a modified form of the energy budget equation (Kohler and Parmele, 1967 vide Winter,1981), is considered by the National Weather Service to give improved evaporation estimates compared to the class A pan. To use this technique,incoming and reflected solar radiation data are also needed. In the studies being done at the Institute of Hydraulics and Hydrology, Poondi, to find a material for floating evaporimeter whose thermal conductivity is equivalent to that of water (0.556 W / m C) and at the same time non leaky and light in weight, 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 Poondi reservoir. The unit has the 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).

In addition to the problem of designing the ultimate evaporation pan an even more perplexing problem is the relationship between pan evaporation and lake evaporation. Although floating pans are supposed to get rid of some of the difficulties. it has been the aim of evaporation researchers to find pan to lake evaporation from land based evaporation pans because these are easiest to install service and maintain and a considerable pan-evaporation data base already exists in many places.

The rate of evaporation from a pan is greater than that from large water bodies. So a suitable pan coefficient is used to convert the pan observation to get an estimated value of evaporation for a lake. The most commonly used coefficient to estimate lake evaporation from class A pan data is 0.7. Kohler and others(1959 vide Winter,1981) had calculated evaporation from lakes by converting measured evaporation from pans by applying a coefficient. Bleney had studied the effects of high altitude on evaporation from pans and determined suitable coefficients. Studies by Bigelow has shown that the location of pans relative to the water of a reservoir has significant effect on the calculated evaporation. He concluded that evaporation from natural lakes is about five eighth of that measured from an isolated pan placed outside the vapour blanket. Further studies by Rohwer, Kohler, Mansfield showed that the evaporation coefficient ranges anywhere between 0.2 to 1.5 and this factor is dependent upon the size, depth and location of pan. In the Experimental Lake Area (ELA) in the northwestern of Ontario, Canada, the annual average lake evaporation is about 0.7 times the lake evaporation.

It is essential that the coefficient of evaporation be measured under all different conditions, which is not practically feasible in large water storage systems. 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. Pan should not be used to estimate evaporation for shorter time period. Linsley et al.,(1958), pointed out that the ratio should only be applied to annual data and only if effects of wind (advected) energy into the lake and the heat transfer through the pan are considered. It may be thus possible to estimate lake evaporation within 10-15 % by applying a coefficient to pan data with due consideration to lake depth and climate regime.

It is widely recognized that the coefficient should be lower for lakes in arid regions than for lakes in humid climates. A value of 0.52 was obtained for the Salton Sea, California and 0.81 for Lake Okeechobee, Florida (Hounam, 1973 vide Kuusisto, 1985). The annual average Class A pan coefficient to be 0.69 for lake Hefner, Oklahoma. This is in fair agreement with the results of other investigations indicating that the evaporation pan method of determining annual lake evaporation may be accurate to within perhaps 10 or 15 percent, provided care is taken in measuring pan evaporation and selecting the coefficient to be used. In cold climates where lakes are ice covered in winter, the Class A pan coefficient for the open water season also tends to be large (Jarvinen, 1978). In addition to the regional variation of pan coefficients, there is a remarkable seasonal variation for many climates. Figure 2 shows this variation in some lakes. The monthly evaporation pan coefficients vary more widely and with a greater range of probable error than the annual coefficients. The coefficients tend to be smaller than the annual average in the winter and spring and larger in summer because of the lag between lake water temperature and the pan water temperature. Since the temperature lag is greater for deep lakes, it is expected that the monthly variation in the coefficients is greater for deep lakes for a climate which has large seasonal variations in temperature. From studies made on seven Australian lakes, it was inferred that the effect of heat storage on lake evaporation is less in tropical climates than in subtropical climates and monthly pan coefficients show much smaller variation in the former than in the latter and depth seems to be the most important parameter in determining the variability of monthly lake to pan coefficients for subtropical lakes (Garrett and Hoy, 1978).

Obviously the use of constant value for each month can lead

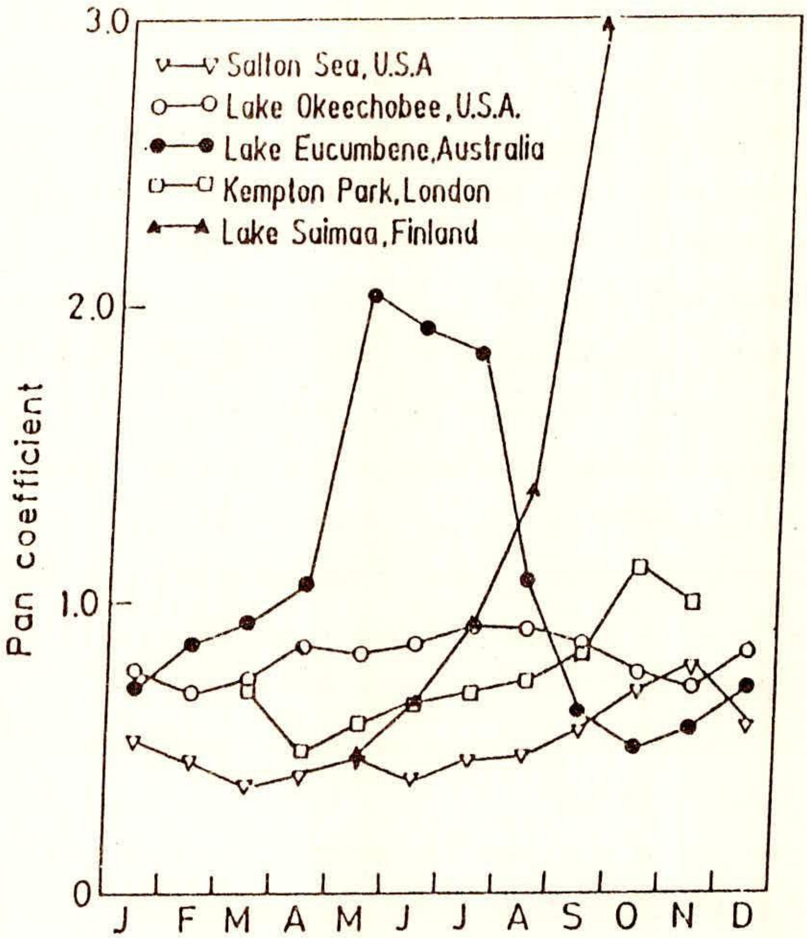

Fig. 2 Monthly values of Class A pan coefficients for some lakes in different climatic conditions. Data are from Hounam (1973) and Kuusisto (1978).

to serious errors. 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 the method of computation of a reasonable value for class A evaporation pan coefficient for a given month.

$$C = \left[\frac{(e_o - e_z)_{Lake}}{(e_o - e_z)_{pan}} \right] * 0.69 \qquad ....(12)$$

where, C = pan coefficient for a given month,

e_o = vapour pressure of Saturated air at the temperture of the water surface for the given month,

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

The 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.

$$E = f(v)(e_s - e_a) \qquad ....(13)$$

Where,

$f(v)$ = proportionality coefficient, which is often called the wind function,

e_s = saturation vapour pressure at surface water temperature and

e_a = vapour pressure of the air

Jobson (1972) collected data during a 15 month period at Lake Hefner. He studied the effect of averaging of meteorological data for periods of three hours, one day and one month on estimation of evaporation.He inferred that the value of the proportionality coefficient in the above mentioned semi empirical mass transfer formula is independent of the time interval over which the meteorological data have been averaged provided that the data are averaged for no more than one day. Averaging for one month is undesirable because the value of the coefficient becomes dependent on the averaging time and the computed evaporation will be systematically in error.

The general form of the wind function is usually expressed as follows

$$f(v) = a + Nv^{n} \quad ....(14)$$

where

a,n = constants for a given water body

and N = mass transfer coefficient.

Generally,"n"is assumed to be unity and "a" is often taken as zero, if wind velocity has been measured over the lake near the centre. The mass transfer coefficient accounts for many factors such as wind profile, size of the lake, atmospheric stability and air pressure. Harbeck (1962 vide Kuusisto, 1985) obtained the following empirical relationship between N and lake area A

$$N = 0.169 / A^{0.05} \quad ....(15)$$

where,

N is in $mmd^{-1}mb^{-1}ms^{-1}$ and A in sq. km

The mass transfer coefficient, N, is a constant for a specific lake. It accounts for various factors like wind profile, size of the lake,roughness of water surface, atmospheric stability, barometric pressure, density and viscosity of air. Errors in evaporation estimated by mass transfer method are related to estimates of the mass transfer coefficient (N) and measurement of wind speed and air and water temperature. Errors of only a few degrees in measurement of water temperature can lead to errors as great as 40 % in estimates of evaporation.

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

2.4.3 Streamflow and surface outflow

The relative magnitude of the surface inflow and precipitation to the lake depends upon the ratio of the basin area to the water body area. An increase of this ratio leads to an increase of inflow to lakes relative to precipitation (UNESCO,1981).

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 component consists of non-channelized overland flow which is often overlooked or ignored. Little studies have been made to ascertain the importance of its role in lake behaviour.But its importance especially in influencing the lake water chemistry and consequently the lake water quality can not be easily overlooked. The surface water affects the water quality depending on the chemical and biological properties of the sediments,organic matters and other debris it contributes to the lake. The non-channelized flow travels in several routes ranging from overland runoff (sheet wash flow) to water flowing at various depths just below the land surface called as interflow (Winter, 1981). This water is important and constitute the only source of surface water for lakes which have no inflowing streams. It is often convenient to subdivide the total surface water inflows into two components:- i) main inflow and ii) lateral inflow. Main inflows refer to the total contribution of the larger gauged rivers and lateral inflow is the total direct runoff into the lake from the surrounding land area including the contribution of the small ungaged stream (UNESCO, 1981). It is debated that there is always some drainage area that contribute directly to the lake as overland flow. But, the matter is somewhat controversial (Winter, 1981).

Winter (1977) highlighted the factors that control the exchange of water between lake and sources of surface water :-i) surfacewater inlets and outlets, ii) lake area, iii) drainage basin area, iv) ratio between drainage area and lake area. According to structure of the water balance, lakes with outlets have different influences on the flow of the rivers in whose basins they lie. In the temperate regions of Europe and North America, lakes contribute to an increase in river flow because the precipitation falling on their surfaces is greater than the evaporation from them. This increase is relatively unimportant and varies between 5 to 10% of the inflow. But in the equatorial and southern hemisphere, with few exceptions, lakes with outlets have a negative influence on river flow, lowering it considerably because of intense evaporation from the water surfaces. This decrease in different African river basins that are regulated by lakes represents 30 to 90 % ; in South America the lake influence is even stronger and produces a lowering of the flow by 4 to 5 times. Asian lakes with outlets occupy an intermediate position between northern and southern regions of the globe. The lakes in Asian region have no effect on the river water capacity because for most of the fresh water lakes evaporation from and precipitation on the water surfaces of the lakes are equal(UNESCO, 1978).

Continuous observations of discharge should be carried out in as many inflowing rivers as possible. However, the necessary regionalization of these point discharges over the ungaged catchments may lead to serious errors. The variations of the specific discharges of the gaged rivers together with physiographic evaluation, offers a limited possibility for assessing the accuracy of the estimated total inflow. The limited accuracy of the gaged data at times leads to large errors in evaporation estimates. Kriging method has been successfully used for the 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 sequential daily water surface profile. Unusual and unrealistic behaviour of the profile can be identified to exclude the suspect gage readings(Zrinji and Burn,1992).

Errors in measuring stream discharge are related to instrumentation and the methods used to distribute discharge data both in time and in space. Measurement of stream discharge using devices in which 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 3 percent at low velocities and less than 1 percent at higher velocities. Comparative calibration of meters between pre and post field use have shown that their ratings change by less than 10 percent. Errors related to estimating velocity distribution, which is related to the number of point measurements in both the vertical and horizontal directions, can be about 5 percent. Errors related to exposure time of the meter can also be about 5 percent. Errors related to exposure time of the meter can also be about 5 percent. Considering all these factors, figure 3 can be used to summarize the overall error to be expected in a current meter discharge measurement. In general, if many verticals are used, the error can be kept to less than 5 percent, but if few are used and exposure times are short, the error can be between 5 and 10 percent, or even higher.

Errors related to determination of temporal distribution of stream discharge can be great, well over 100 percent, if occasional miscellaneous measurements are averaged. If correlation techniques are used to extend records, errors in the regression have been shown to vary widely, and caution should be used. 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 gaged to ungaged watersheds has been shown to be in error by as much as 70 percent. Use of multiple regression to estimate low flow stream 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.

Estimation of surface water input to a lake by regionalization from gaged to ungaged watersheds should be done with caution, and should not be considered an accurate technique for balance type studies.

Lake hydrologists must be aware of overland type flow into a lake, because there will always be parts of the lake's watershed

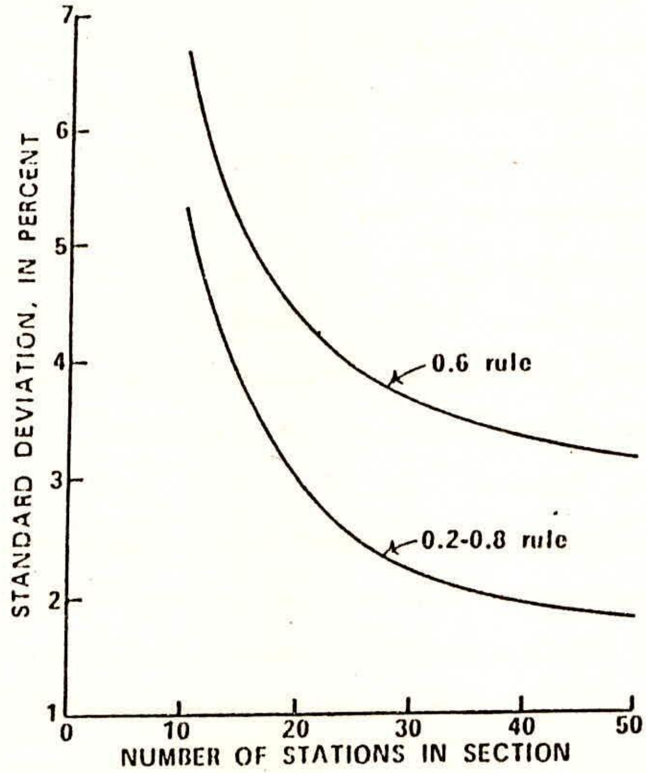

Figure 3 Standard Deviation of Total Error of Discharge Measurements (modified from Carter, 1973).

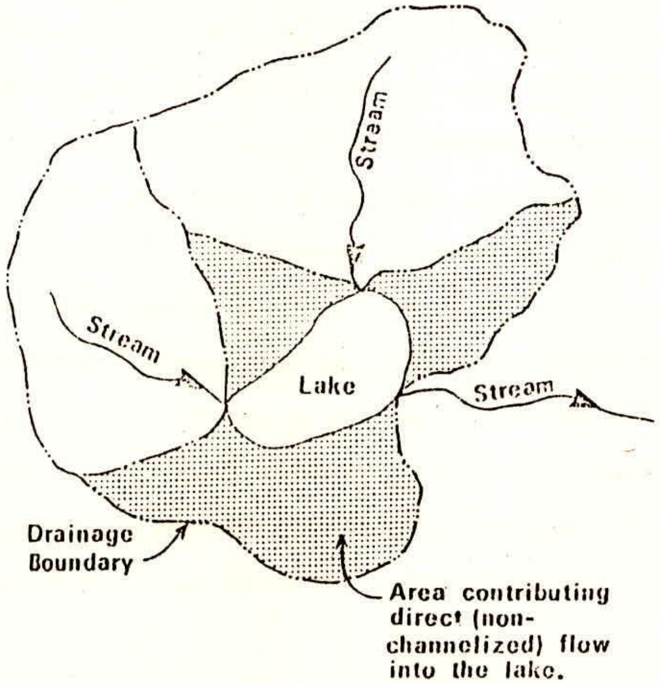

Figure 4 Example Lake and Drainage Basin Showing Area Contributing to Nonchannelized Surface Inflow.

that cannot be gaged by stream gaging techniques(Fig.4). This non channelised flow is important for lakes which have no inflowing streams. Lack of understanding of overland flow remains one of the serious drawbacks to water balance studies of lakes; it should receive increased attention.

2.4.4 Groundwater

Lakes are three- dimensional depressions in the landscape that generally intersect the water table, and the groundwater flow patterns around and below a lake may be complex (Almendinger, 1990).

Until recently, the ground water component of the lake system has been ignored or considered unimportant relative to other components of the hydrologic system. The interaction of lakes and groundwater is the least understood component of lake hydrology. Groundwater flow is next to impossible to measure directly and must be estimated from a knowledge of local gradients of the water table and aquifer properties (Strahler and Strahler, 1973).

Understanding the interaction of lakes with groundwater requires an understanding of the dynamic character of the distribution of hydraulic head in the groundwater system. This distribution of head is controlled to a large extent by the distribution of recharge, which, in turn, is directly related to infiltration and water movement through the unsaturated zone. Therefore, the entire continuum from infiltration to redistribution in the unsaturated zone to movement into and through the groundwater zone to movement through the bed of a surface water body needs to be studied (Winter, 1983).

Groundwater flow is of utmost importance in lakes which do not have inlets and outlets like seepage lakes in which water passes out as ground water discharge lowering the watertable because of which these lakes may come across extreme drop of water level and occasional complete emptying also (Reid and Wood, 1976). Seepage lakes not only lose water by ground water but are recharged by ground water only (Thurman, 1985).

The interaction between a lake and an aquifer is different to that of a spring, river or canal because the area of contact between the lake and the aquifer is much larger. Consequently the flow patterns in the vicinity of the lake tend to be more complex, so that water may flow from the aquifer into the lake in one region whereas in another region the same lake water may be transmitted from the lake back into the aquifer.

Anisotropy of the geologic materials within the groundwater system is one of the most difficult parameters to obtain. It is seldom the subject of field investigations. Lack of knowledge of the relative distribution of zones of high and low hydraulic conductivity can lead to serious misinterpretation of the interaction of lakes and groundwater.

3.0 Relative importance of the water balance components in lake classification

Water balance of a lake depends upon the relative importance of the various inputs and outputs to and from the lakes. In arid zones, lakes often have no outlets and water is lost by evaporation. For most larger lakes the major input is rivers and streams but the largest African lake-Victoria usually gets 75 % of its input from rainfall on its surface. By contrast there could be some small lakes which are totally supplied by groundwater.

The volumes of water in a lake, and the level of its surface, depends on how the inputs and outputs of water balance. If there is a good balance, the water level fluctuates very little.

However, because of year-to-year changes in rainfall and other climatic factors, some fluctuation is expected. The degree to which fluctuation affects the lake level depends on the size of the lake and the rate of water addition and removal. For lakes receiving most of their water from streamflow, this can be represented in terms of the time it would take to replace the water in the lake; that is, the time necessary, at the present rate of inflow, to fill the lake to its present volume. Mathematically the replacement, or filling, time for water is defined as ;

$$\tau_w = V/F_i \qquad ....(16)$$

where,

$_w$ = replacement time for water.

V = volume of water in the lake.

$_i$ = rate of streamflow addition.

Low values of τ_w mean that short-term fluctuations in input are rapidly witnessed by lake level changes whereas high τ_w values mean that the lake level (volume) is relatively impervious to rapid input changes. Not surprisingly, low τ_w values are characteristic of small lakes and ponds and high τ_w values of large lakes. Large lakes are able to adjust their level to long-term averages of inputs and outputs. Values of τ_w for most lakes lie between 1 and 100 years.

If a lake maintains a constant volume, because inputs and outputs are equal, it is said to be in steady state with respect to its water content. In this case the replacement time can also be viewed as a residence time of water in the lake. This is the average time a water molecule spends in the lake before being removed through the outlet. The concept of residence time is used extensively in the literature on both limnology and oceanography, but it is sometimes forgotten that it only makes sense when there is a steady state. Otherwise, more general concepts, such as that of replacement time, are preferable.

A lake classification based on the water balance can help to detect man-made or natural changes in water levels. One group of questions is related to predicting the trends and expected long-term variations of water level; the other group includes the prediction of the extremes of water level within relatively short periods.

Szesztay (1974 vide Kuusisto, 1985) has presented a water balance classification based on three simple criteria:

(1) The inflow factor (i): the percentage of inflow (I) of the sum of inflow and lake precipitation (P).

(2) The outflow factor (o): the percentage of outflow (O) of the sum of outflow and lake evaporation (E).

(3) The magnitude of the mean annual flux (F): the sum of inflow plus precipitation (F_i) or the sum of outflow plus evaporation (F_o).

The subdivision of the i-and o-axes into three equal parts defines nine classes of lakes (Figure 5). So lakes belonging to the square I-O are characterized by the dominance of inflow and outflow. They have generally a highly unstable water balance: they also usually have a high value of the annual flux F. Lakes in the opposite corner, type P-E, are climate-controlled - their water levels tend to follow climatic fluctuations. Lakes belonging to classes P-OE, P-O and IP-O can only occur in humid regions; they are lakes with relatively small catchment areas. Closed lakes are obviously located on the ordinate axis; most man-made lakes are in the I-O class.

Some additional parameters are needed to combine the water

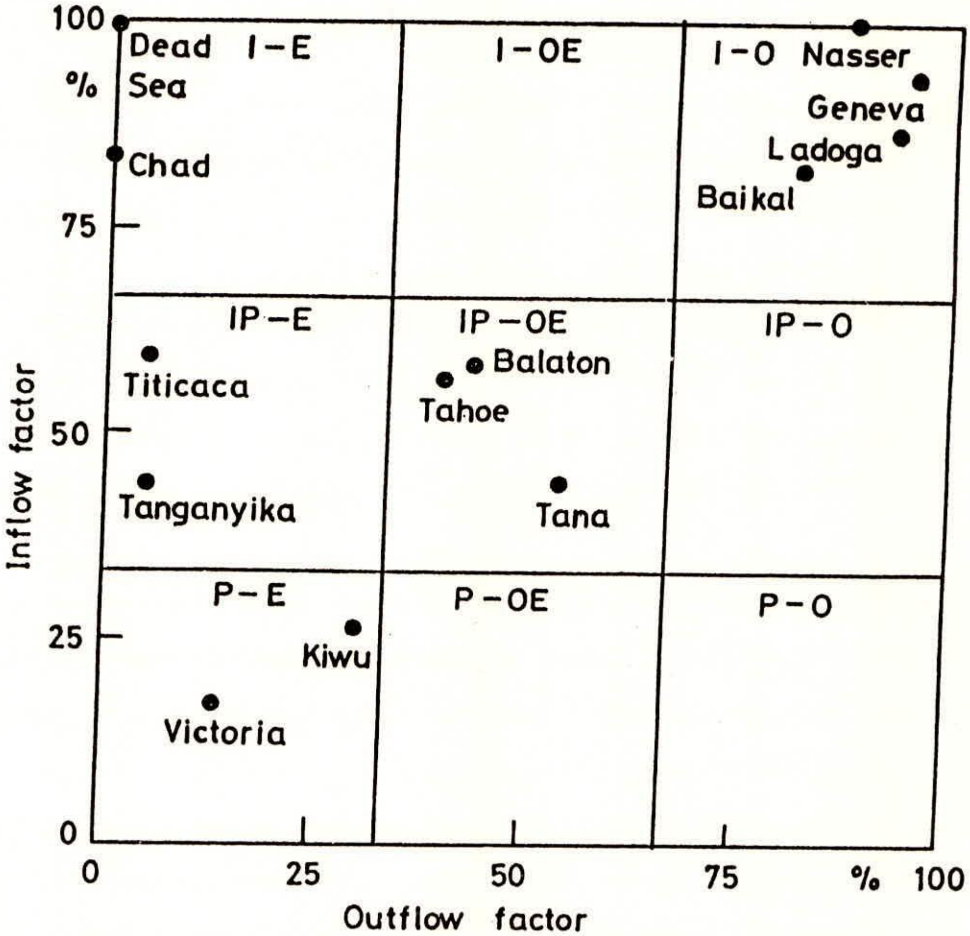

FIG. 5 - CLASSIFICATION OF LAKES BY WATER BALANCE CRITERIA (AFTER KUUSISTO, 1985)

Table 1 Water balance of the major lakes of the world (after Vikulina et al.,1976;Unesco 1978)

Lake	Observation period	Volume km^3	Inflow $km^3 a^{-1}$	Precipitation mm	Outflow $km^3 a^{-1}$	Evaporation mm	Inflow factor	Outflow factor	Retention time a
Caspian Sea	1940-1966	78200	289	246	10.8	994	0.76	0.03	204
Michigan and Huron	1959-1966	8200	142	780	161	750	0.61	0.65	33
Superior	1959-1966	11600	47.6	760	69.7	470	0.43	0.64	107
Victoria	1925-1959	2700	17.9	1630	21.9	1570	0.14	0.17	21
Aral Sea	1959-1969	1020	49.5	173	0	1050	0.82	0	15
Tanganyika	long-term	18900	25.8	1000	3.0	1690	0.44	0.05	322
Baikal	1901-1970	23000	60.3	405	59.5	416	0.82	0.82	317
Nyasa	long-term	7720	34.2	1220	6.3	2130	0.48	0.09	107
Great slave	long-term	1070	136	350	141	166	0.93	0.97	7.4
Erie	1959-1966	545	190	860	182	920	0.90	0.88	2.6
Ontario	1959-1966	1710	210	900	210	800	0.93	0.94	7.6
Balkhash	1911-1966	112	15.7	154	0	1020	0.85	0	6.0
Ladoga	1932-1958	908	69.1	606	73.7	344	0.87	0.92	11
Chad	1954-1962	44	45.8	378	0	2260	0.85	0	0.9
Eyre	long-term	-	4.2	150	0	dries up	0.77	0	-
Maracaibo	long-term	-	19.6	977	4.9	2080	0.60	0.15	-
Onega	long-term	295	15.9	575	18.0	350	0.74	0.84	14
Rudolf	long-term	-	16.0	750	0.0	2610	0.71	0	-
Titicaca	long-term	710	7.7	625	0.6	1500	0.60	0.05	55

balance components with the characteristics of the lake:

1. The ratio of the mean annual flux F to the volume of the lake:

$$R_f = F/V \quad ....(17)$$

The reciprocal of this ratio is often considered as the mean retention time of the water in the lake. However, the practical applicability of this concept depends on the stratification and mixing processes in the lake.

2. The ratio of the mean annual inflow to the volume of the lake.

$$R_i = I/V \quad ....(18)$$

This ratio is more appropriate than R_f in, for example, studies of sedimentation and the nutrient balance of the lake.

3. The range of storage, either absolute (ΔV) or relative(ΔV_r)

$$\Delta V = V_{max} - V_{min} \quad ....(19)$$

$$\Delta V_r = (V_{max} - V_{min}) / V \quad ....(20)$$

where,

V_{max} = maximum water volume during a period, e.g. one year

V_{min} = minimum water volume during the same period

V = mean water volume.

Table 1 shows some characteristics of the water balance of major lakes of the world. The Caspian Sea has the largest inflow, Lake Ontario the largest outflow. Most of the tropical African lakes are concentrated in the equatorial region. The Great Lakes area in the south eastern part of Africa has Lake Victoria, Lake Tanganyika, Lake Nyassa and others. The greatest African lake and the third largest in the world -Lake Victoria is the rainiest among the large lakes. It also has the lowest inflow factor. Correspondingly, the Great Slave Lake with the lowest evaporation has the highest outflow factor. The two deepest lakes of the world, Baikal and Tanganyika, have the longest retention times. Lake Tanganyika is said to be one of the natural lakes with the best natural balance where inflow corresponds to evaporation.

Water balance of some of the important African lakes being in the tropical area seem to be relevant to the context and is given in Table-2 below. These estimations / balances have been arrived at by various investigators and is reported by Balek (1977).

Table 2. Water Balance of Important African Lakes

Lake	Area Sq.Km	Inflow* mm	Ppt* mm	Outflow* mm	Evaporation* mm
Victoria	66400	241	1476	316	1401
Kyoga	1800	3825	1270	3127	1968
Albert	5300	4717	868	4151	1434
Edward	915	880	1360	800	1440
Nyasa	30800	472	2272	666	2078
Tanganyika	32890	1609	950	141	2418
Kariba	5250	8440	686	7038	2088

* related to lake area

The basic balance values calculated vary considerably. The inflow and the outflow were measured with reasonable accuracy but the precipitation and evaporation are rather uncertain values.

4.0 Mathematical models for lake water balance and components

In the tropics particularly the lakes are only a temporary feature of the surface. Most tropical lakes have been formed by the action of the rivers, wind and by earth movement and tectonic activity. They disappear through a process of natural eutrophication involving the the filling up of the lakes with nutrient containing sediments. The process of cultural or man-made eutrophication is much faster than the slow rate of natural eutrophication. Many among these nutrients are beyond the control and most frequent are carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur (Balek, 1983).

Water quantity and quality considerations are directly linked. Water balance study are basic necessity for doing nutrient budgeting which in turn helps to assess the causes of lake deterioration and to devise successful strategies for lake amelioration. Conceptually, the nutrients budgeting is similar to the water budgeting- an accounting of inputs, storages, and outputs.

4.1 Box model

One way of quantitatively treating rates of addition and removal is by means of box modelling. In box modelling one assumes that a portion of a lake or the whole lake is so well stirred that it is homogeneous in composition and can be treated as a uniform "box". Rates of addition (or removal) to each box are slow enough, relative to mixing, that high concentrations of added substances do not build up around each source. The concentration of a given substance in a given "box" is controlled by the relative magnitude of inputs and outputs. If inputs balance outputs there is a steady state and concentrations do not change with time. This is analogous to to the situation of steady-state water content.

The simplest kind of box model is that of a single box representing a whole lake. In this case we have input of a dissolved substance from streams (groundwater and rainwater inputs are neglected), output by a surface outlet, precipitation and removal to bottom sediments, and addition via dissolution, or bacterial regeneration, of suspended and sedimented soils (Figure

6). Rates of these processes can be represented as;

F_i = rate of water inflow from streams (volume per unit time).

F_o = rate of water outflow through outlet.

M = total mass of the dissolved substance in the lake.

R_p = rate of removal via precipitation and sedimentation to the bottom (mass per unit time).

R_d = rate of addition via dissolution of solids (mass per unit time).

C_i = concentration of the dissolved substance in streamwater (mass per unit volume).

C = concentration in lake water.

t = time.

Assuming steady state with respect to water (constant volume lake) the rate of change of mass with time in the lake $\Delta M/\Delta t$ is;

$$\Delta M/\Delta t = C_i F_i - C F_o + R_d - R_p \qquad ....(21)$$

If there is a steady state also with respect to the dissolved substance, $\Delta M/\Delta t = 0$, then

$$C_i F_i - C F_o + R_d - R_p = 0 \qquad ....(22)$$

Finally, if dissolution represents redissolution of the same material that was previously precipitated and sedimented to the bottom, then

$$R_s = R_p - R_d \qquad ....(23)$$

where,

R_s = rate of burial in sediments (mass per unit time).

Using Equation (22) one can calculate, for example, from a knowledge of measured water flow, rainfall, and sedimentation rates, the maximum allowable input concentration (C_i) of a pollutant, P, to a lake, if the lake concentration of the pollutant (C) is not to exceed a certain level. Suppose the water inflow rate (F_i) to the lake is equal to 100 m^3/sec (appropriate for a small river) and rainfall (minus evaporation) averaged over a year is 50 m^3/sec. Then the outflow rate (F_o) should be 150m^3/sec in order to maintain constant lake volume. Let the sedimentation rate (R_p) be 250 mg P/sec, and assume that the lake concentration (C) may not exceed 5μg P/l (which equals 5 mg P/m^3 and is sufficiently low that it should inhibit eutrophication) Then upon substituting in Equation (22) and letting $R_d = 0$, the maximum allowable concentration of a pollutant , C_i, could be estimated (10 mgP/cu.m).

Replacement time is that time necessary to replace the mass of a dissolved substance, via the present rate of stream addition, if all of the substance were suddenly removed. It gives a measure of the sensitivity of lake concentration C to changes in input concentration, C_i or water inflow, F_i. The replacement time of a dissolved substance is defined as;

$$\tau_r = \frac{\text{Mass in lake}}{\text{Rate of stream input to lake}} = M/C_i F_i \qquad ....(24)$$

Further, the replacement time for water(τ_w)is expressed by the ratio of volume of water in the lake and rate of streamflow addition (V/F_i).So, Eq.24 could be written using M= CV as,

$$\tau_r = (C/C_i)\tau_w \qquad ....(25)$$

If the lake is at a steady state with respect to the dissolved substance of interest (and water), the τ_r (and τ_w) can be viewed as residence times as well as replacement times. In other words, for steady state the value τ_r represents the average time spent by a dissolved species in the lake prior to removal either via sedimentation or through the outlet.

If, on the other hand, the lake is not at steady state, and an attempt is being made to lower the lake concentration, C, of a pollutant by reducing the input concentration, C_i, it can seen from Eq.26 that lakes with short water-replacement times are more responsive to efforts to reduce pollution i.e., the replacement time of a dissolved substance, τ_r, is directly proportional to the water replacement time, τ_w.

An additional concept, that of relative residence time, (Stumm and Morgan, 1981 vide Beruer et al., 1987) is very useful. Relative residence time is the residence time of a given dissolved substance relative to that of water:

$$\tau_{rel} = \tau_r / \tau_w = C/C_i \qquad ....(26)$$

Relative residence time is an indication of the type of behaviour to be expected for a given substance. A relative residence time of 1 indicates that the substance does not react chemically in the lake ($R_d = 0; R_p = 0$) and it simply accompanies water as it passes through the lake. Dissolved Cl^- or Na^+ are examples. In this case the substance acts as a tracer of water motion. If τ_{rel} is less than 1, the substance tends to undergo removal via sedimentation in the lake ($R_p > 0$) indicating its chemical reactivity. (An example is dissolved Al). If τ_{rel} is greater than 1, the substance tends to be trapped in the lake while the water that brought it in is removed. This can take place if the substance is cycled within the lake, that is, it is precipitated and sedimented to the bottom ($R_p > 0$), then redissolved ($R_d > 0$), then reprecipitated, and so on. This is characteristic of elements involved in biological processes, for example, P, N, Si, and Ca, and such biological cycling within the lake can result in a relative residence time of each of these

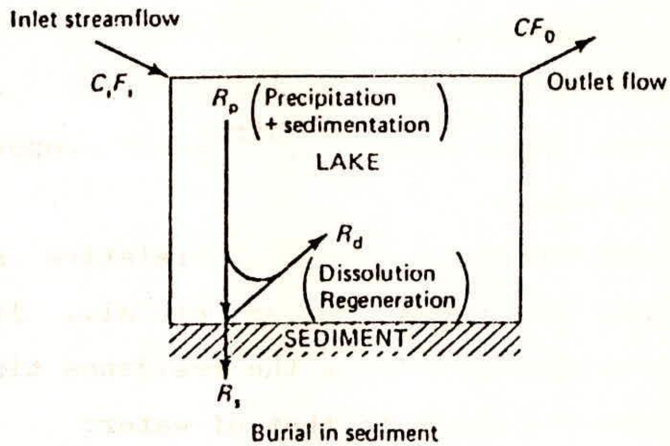

Fig. 6. One - box model for lakes

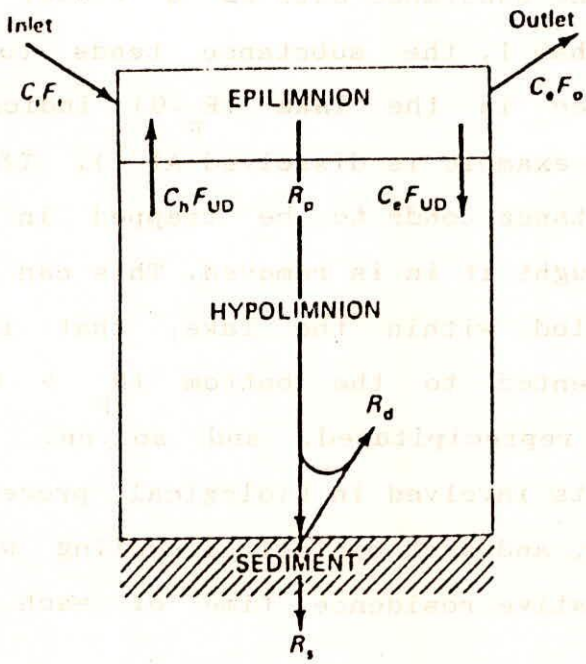

Fig. 7. Two - box model for lakes

elements appreciably greater than 1.

Simple one-box models, although applicable to all lakes to express their average properties, are most accurate as representations of shallow lakes that do not undergo stratification. For the more usual case of stratified lakes, a two-box model is more appropriate (Imboden and Lerman 1978 and Stumm and Morgan vide Beruer and Beruer, 1987) One box is used to represent the epilimnion and the other box the hypolimnion. This is shown in Figure 7. In the two-box model we have fluxes between the reservoirs (boxes) as well as inputs and outputs for the whole lake. There is input of dissolved material by streams to the epilimnion and output via an outlet. There is exchange of water containing the dissolved substance of interest between hypolimnion and epilimnion which is represented by up and down arrows. Finally there are chemical reactions; in this case these include removal of the substances from the epilimnion via precipitation and transfer downward by sedimentation, injection of a portion to solution in the hypolimnion, and burial of the remainder.

Mathematical representation of the rates in a two-box lake model is similar to that presented above for a one-box lake. Besides the parameters defined for the one-box model we also have the following:

F_u = rate of water transfer from hypolimnion to epilimnion

F_D = rate of water transfer from epilimnion to hypolimnion

R_p = rate of removal, by precipitation and sedimentation from epilimnion

R_d = rate of addition, via dissolution, to hypolimnion

M_e = mass dissolved in epilimnion.

C_e = concentration in epilimnion (mass per unit volume)

M_h = mass dissolved in hypolimnion

C_h = concentration in hypolimnion (mass per unit volume)

If we have steady state with respect to water for both boxes (constant volumes of the epilimnion and hypolimnion, V_e and V_h, with time), then

$$F_U = F_D \qquad ....(27)$$

and the either rate can be referred to as as F_{UD}

Using the above definition, the rates of change of mass in solution for each box $\Delta M_e/\Delta t$ and $\Delta M_h/\Delta t$ by summing inputs and outputs:

$$\Delta M_e/\Delta t = C_i F_i - C_e F_O + (C_h - C_e)\, F_{UD} - R_p \qquad ....(28)$$

$$\Delta M_h/\Delta t = R_d - (C_h - C_e)\, F_{UD} \qquad ....(29)$$

If, in addition we have steady state, both with respect to the dissolved substance and its solid precipitated form, and dissolution represents redissolution of sedimenting solids, we have,

$$C_i F_i - C_e F_O + (C_h - C_e)\, F_{UD} - R_p = 0 \qquad ....(30)$$

$$R_d - (C_h - C_e)\, F_{UD} = 0 \qquad ....(31)$$

$$R_p = R_d + R_s \qquad ....(32)$$

These equations provide information on rates of processes from measurements of other rates and concentrations and, in this way, the equations are most useful.

4.2 Water balance study of Lake Colac in Australia for eutrophication study

Environment Protection Authority, Victoria (Australia) undertook a one year multidisciplinary study on Lake Colac in 1975 (Walker, 1978).

Lake Colac is a large, shallow lake located in a rich agricultural area of western Victoria, about 120 km south-west of Melbourne. In addition to its natural susceptibility to eutrophication due to its shallowness, agricultural practices in the catchment, dairy product wastes and treated domestic sewage from a community of about 10,000 people, substantially contribute to the over-enrichment of Lake Colac. The Lake has a catchment area of 20,402 ha. and is kidney shaped in outline. It has a surface area of approximately 2,970 ha. and has a full capacity of 71,250 Ml, the mean depth of the Lake is therefore 2.4 m.

There are four categories of sources of water (and pollutant) entering the Lake; precipitation, tributary inflow, wastewater discharge and overland flow. Two mechanisms transport water from the lake; evaporation and diversions, and groundwater may act as an input and output. The approximate contribution of each component is an indication of its relative importance in determining the Lakes characteristics.

Water balance were calculated for the 11 months, May, 1975 to March, 1976. The time interval was set at 1 month. In addition to quantifying all the relevant water balance components in Lake Colac, the study also assisted in assessing the effect of these components on the water quality of the Lake. An important characteristic that influences the water quality of an inland lake is the lakes flushing rate. A crude water quality model for lake flushing rate requiring minimum knowledge of lake characteristics and inflow and outflow hydrology has been suggested (Viessman et al., 1977). This rate, F, may be determined from,

$$F = \frac{\text{Annual Inputs}}{\text{Lake Volume}} = 0.90 \text{ yr}^{-1} \qquad ....(33)$$

Consequently, during the study period, almost all water in the Lake was renewed. This study period was one of high rainfall (977 mm compared with an average of 720 mm), and therefore during a period of average climatic conditions complete flushing of the Lake may require closer to two years. The importance of each component in the annual water balance is best demonstrated by Table 3.

Table 3.Water table contribution

	STUDY PERIOD			TYPICAL YEAR		
	Ml.	% in	% out	Ml.	% in	% out
Rain - P	27282	47	-	20000	62	-
Trib - R	28550	49	-	10000	31	-
Eff - W	1386	2	-	1400	4	-
G (net)	1000	2	-	1000	3	-
Evap - E	-26150	-	43	-26000	-	100
O'flow - D	-35357	-	57	0	-	0
Total	- 3289	100	100	6400	100	100

[P= volume of rain falling directly on lake, R= total tributary inflow, W= total wastewater inflow, E= volume of water lost by evaporation, G= volume of groundwater entering or leaving the lake D= volume of water lost by diversions out]

Clearly direct rainfall and subsequent tributary inflow are the major volume inputs, with effluent and groundwater inflows contributing the remainder. The output volumes, however are shared almost equally between evaporation and overflow.

The overflow mechanism is to a large extent proportional to the volume of rainfall and runoff occurring between September and November. Since its construction in 1953, the overflow has operated during 13 of the 24 years. Hence, it is important to consider the zero overflow situation in an average or below average rainfall year. Using average annual rainfall, evaporation, effluent and groundwater volumes and estimating tributary volumes from the rainfall-loss method, the contributions for a 'typical' year have been listed in Table 3.

The water balance study was one component of this multidisciplinary study of eutrophication and nutrient sources of Lake Colac. The high evaporation rate was found to be an important factor in controlling eutrophication. Evaporation concentrates the same mass of pollutant into a smaller volume with a subsequent rise in pollutant concentration. Especially during the summer period when hot and sunny conditions may assist entrophication.

Although the overflow mechanism assists in the removal of nutrients from the Lake; this process normally occurs in spring when nutrient levels in the Lake are lower because the relatively good quality rainfall and tributary inputs are at their maximum. If the overflow is delayed until summer to export water of higher nutrient concentrations, the actual greater mass of nutrient in the Lake (due to delayed release) and the natural evaporation may result in higher nutrient concentrations.

4.3 Simulation of lake-watershed systems

Lakes on the Canadian prairies are important water resources. However, problem related to excess salinity, contamination or declining water levels have significantly impaired the development of these lakes. A practical lumped response watershed model has been developed to study lake-watershed system (Crowe and Schwartz, 1981) in a Canadian prairie setting. The model can simulate both lake levels and the concentration of a single chemical component of the lake water as a function of time. It is designed to be used when only a relative estimate of the various hydrologic components of the watershed is required. Only a limited amount of basic physical, climatic, hydrological and hydrochemical data is necessary for the simulation. Generalised flow chart of the lake-watershed model is given in Fig.8.

Following results were obtained from the model study of a hypothetical lake-watershed system with characteristics similar to prairies in Canada.

1. The water level and salinities of the lake depended on the general lake morphometry.

2. Variations in groundwater chemistry over a part of the watershed do not significantly alter the salinity of the hypothetical prairie lake. For this lake, the groundwater contributions are - 15 % of the total inflow to the lake. Large increases or decreases in the quality of groundwater over the entire watershed will, however, alter the salinity of the lake.

3. The unsaturated zone primarily controls the amount of water percolating to the groundwater zone and hence, indirectly influences the amount of groundwater that is discharged to a lake. Decreasing the unsaturated zone moisture capacity in the test watershed causes increased surface runoff and groundwater discharge, which results in higher lake levels and salinity.

4. Increasing the proportion of this hypothetical watershed that is impervious, for example by urbanization, causes precipitation to flow directly to the lake, decreasing the lake salinity, increasing fluctuations of lake levels, and generally increasing the lake stage.

5. Precipitation and potential evaporation exhibit a greater influence on lake levels and salinity in a small watershed (less than 100 sq.km.) than does groundwater discharge. The opposite is true in a large lake - watershed system.

The model has been applied successfully to recapitulate a 6 year history of lake levels and 2 year record of lake salinity at

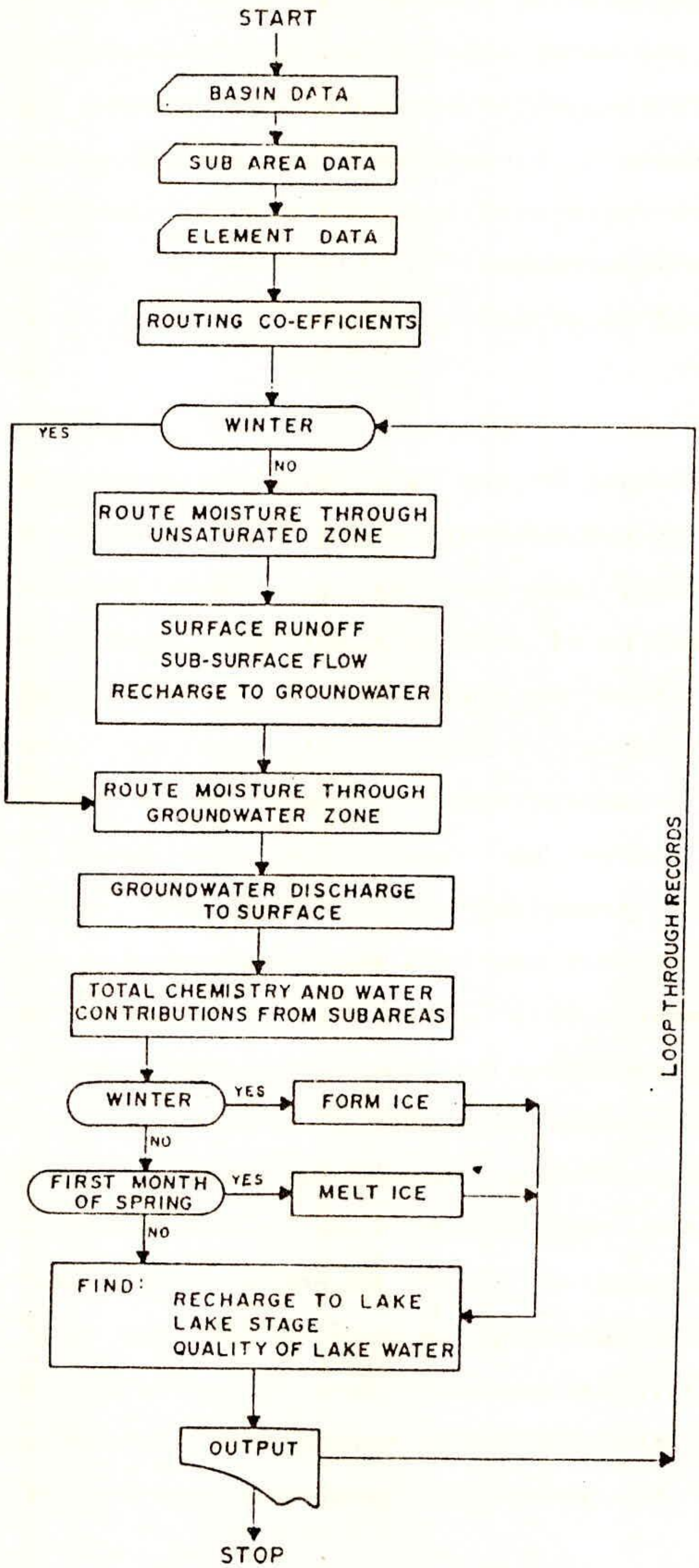

Fig. 8. Generalised flow chart for lake - watershed simulation

Baptiste lake, Alberta (Crowe and Schwastz, 1981b) and Wabamun lake in Central Alberta (Crowe and Schwartz, 1985). The model first extend the water balance approach through a lumped element type of simulation. Water is routed through the land based portion of the hydrologic cycle and the lake. Secondly, the model build up the ability to cycle mass into and through the lake. The chemistry of the lake fluctuates in response to hydrologic inputs, evaporation and freezing.

5.0 Conclusions

The assessment of the water balance in lakes is an important prerequisite to eutrophication and other water quality studies. This is specially true for regions where average rainfall and evaporation may be of similar magnitude. Water balance studies, as such, are basic to calculate nutrient budget vis-a-vis to assess the causes of lake deterioration and to suggest ameliorative measures. Water balance study helps to find the response of lakes to changes in catchment. Deforestation, conversion of grassland into cropland, intensification of agricultural production, land amelioration etc. are energy input into a catchment. This energy input affects microclimate and reduces evapotranspiration thus increasing runoff and siltation viz. nutrients input. Eutrophication in the lake is one of the reason for such nutrient enrichment. This is more so in tropical lakes. Besides, the lake processes, the water balance studies help to understand an inter dependence of lake and adjoining catchment. This knowledge is used to develop and conserve lake basin and adjoining catchment area which would increase the life span of this otherwise transitory feature of the earth and lake water could be gainfully harnessed to meet the various requirements of the community (Bhar & Khobragade, 1993).

The water balance studies enable us to plan the various uses of lakes which atleast partially in conflict. Some uses like recreation and navigation require constant water level and other uses like hydropower and water supply require it to be full. To maximize the flood control potential of a lake it should remain empty.

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 areal averaging technique, as well as the errors in gaging. A rain gage 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 gaged value to the lake of interest.

Accuracy of water budgets decrease as shorter time frames are considered. Therefore, errors associated with annual estimates of a hydrologic component should not be applied to shorter term values. The concept of "residence time" or equivalent should be used with caution particularly for stratified lake. A two-box model will be a better approach for water balance study of a stratified lake instead of residence time concept.

The term "large" and small lakes are relative and arbitrary. For the convenience of the investigators and suit a specific study, some threshold values of surface area of a lake (500sq.km) or volume of a lake (10 Cu. km) has been at times are designated to demarcate between a large and small lakes(Nace,1978). An serious attempt to distinguish between a large and small lake was made recently which is based on some working hypotheses in limnological terms(Tilzer and Serruya,1990). It is an accepted fact that large lakes possess specific system characteristics that distinguish them from small lakes. Some of them are worth understanding for further consideration, testing, validation, adaptation for specific geographical area.

1 Hydrography Characteristics:

a) Water Retention Time:

In general, both the area and the volume of the lake are greater not only in absolute terms but also in relation to the area of the watershed. In addition to being heavily influenced by the amount of annual precipitation, the ratio of watershed to lake surface area has a great bearing on the water retention time which tends to be longer in large than in small lakes.

b) Internal Water Movements:

The large surface area allows increased wind fetch and hence deeper mixing of near-surface water layers even during lake stratification. The large surface area, moreover, allows the build-up of horizontal gradients in air pressure above the lake. Temporal changes in wind and air pressure patterns lead to oscillations of the water masses, both external and internal. Such oscillations are a very common phenomenon in large lakes but are virtually absent or insignificant in small lakes.

c) Heat Budget:

Because large lakes tend to be deeper and have smaller surface-to-volume ratios than small lakes, they have greater heat storage capacities and lose smaller proportions of their total heat content during winter. As a consequence, large lakes have a much smaller tendency to freeze over than do small lakes that are located in comparable climatic regimes.

2. Biogeochemical Cycles:

a) Internal Cycling:

Internal cycling of matter-both nutrient salts and organic material-plays a much greater role, as computed to interactions with the surroundings, in large than in small lakes. As a consequence, processes in large lakes as a whole tend to be less susceptible to short-term perturbations than in small lakes.

b) Nutrient Retention:

In large lakes, once nutrients have entered the system, they remain within the system considerably longer than in small lakes, owing to prolonged water retention times and more efficient internal regeneration, both by purely chemical processes and biological processes. This causes long-term perturbations within the catchment area to have significantly longer lasting effects in large as compared to small lakes.

c) Nutrient Cycling by Settling Particles:

On the other hand, in large lakes, nutrients tend to be removed efficiently from the euphotic zone by settling particles, which may either contain nutrients themselves or may scavenge them from the surrounding water by adsorption. This is because sediment resuspension is of lesser significance in large and deep than in shallow and/or small lakes.

3. Food-web structure:

a) Trophic State:

Both external and internal nutrient loading should be smaller in large than in small lakes because of the relatively smaller watershed area and surface-to-volume ratio of the water body, respectively. Hence, large lakes in general should be more oligotrophic than small lakes.

b) Primary Productivity:

Massive blooms of algae are extremely rare in large lakes, not only because large lakes tend to be less eutrophic but also because their upper water layers are mixed more frequently than those of small lakes. The mixed layer in large lakes, moreover, causes shallow phytoplankton to be exposed to lower average irradiance levels than in small lakes. The phytoplankton respond by adapting their photosynthetic apparatus.

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