ISOTOPE TECHNIQUES FOR LAKE WATER BALANCE AND SEDIMENTATION

PREFACE

Lakes are one of the most important natural resources available to mankind. Water balance studies of lakes are important to obtain information about the availability of water in lakes at any time, keeping in view the fact that most lakes have a relatively short span of life. One of the most important factors which severely affects the life of the lakes is the sedimentation of coarse and fine particles in the lake, thereby reducing the water capacity of lakes.

The convetional methods of water balance and sedimentation studies of lakes are time-consuming and inaccurate. The advent of isotopic techniques has provided a fillip to these studies improving the accuracy and precision of results significantly. This report presents a review of isotopic techniques in general, detailed methodology for water balance and sedimentation studies for lakes, and some important case studies on these aspects from different parts of the world.

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ABSTRACT

Water balance and sedimentation are the two very important aspects of lake studies. Lakes are not the eternal features on earth and most lakes have a limited life in terms of quantity of water. Identification of recharge zones of lakes and precise estimation of different components of water balance equation such as precipitation, evaporation, surface and subsurface inflow and outflow are therefore the first step in hydrological studies of lakes. The conventional methods of estimating these parameters are indispensable but are not properly equipped to measure some of the parameters such as subsurface inflow and outflow. The isotopic methods have contributed significantly to measure these parameters with fair accuracy.

Sedimentation of coarse and fine particles in lakes reduces the water capacity of lakes and is the most serious problem threatening the life of almost each and every lake. The understanding of the causes of sedimentation, estimatation of sedimentation rates and study of sediment distribution patterns are the essntial tasks of hydrologists working on lakes. In situations where long-term record of sediment data on lakes do not exist, isotopic techniques are the only way of estimating sedimentation rates. These techniques are also helpful in finding out the sediment distribution patterns and in predicting the lake bed configuration. The continuous monitoring of suspended sediment concentration is also possible using nucleonic sediment gauge. The isotopic techniques are much less time-consuming and are very precise with the advent of very sophisticated isotopic instruments.

The isotopic techniques for the study of water balance and sedimentation of lakes including case studies have been discussed in detail. The instrumentation, status of lake studies in India and brief details of the conventional techniques have also been described in this report.

1. INTRODUCTION

Despite decades of research on lakes, a unique definition of lakes does not exist. Following the works of Zumberge and Ayers (1964) and Welch (1952), considering different aspects of lakes viz. geological, hydrological etc., the requirements of a water body to be called a lake can be summarized as follows : (a) It should fill completely or partially a basin or several connected basins; (b) It should have essentially the same water level in all parts with the exception of relatively short occasions caused by wind, thick ice cover, large inflows etc.; (c) It should have so small an inflow to volume ratio that a considerable portion of suspended sediment is captured; (d) It should have a size exceeding a specified area e.g. 0.01 km^2, at mean water level.

Lakes have been classified on the basis of a variety of parameters. Hutchinson (1957) identified 11 major genetic types of lakes viz. tectonic, volcanic, landslide, glacial, solution, fluvial, aeolian. shoreline, organic, anthropogenic and meteorite lakes. The morphometric classification of lakes (Hakanson, 1981) defines a very convex lake (type VCx), convex lake (type Cx), slightly convex lake (type SCx), linear lake (type L), and concave lake (type C). The thermal clasification of lakes (Forel, 1901; Hutchinson, 1957) divides the lakes on the basis of climatic zones and the different classes are Amictic lakes (ice climate), cold amictic (ice climate outside the tropics), Dimictic, warm monomictic (summer dry or with strong oceanic influence), Oligomictic (always humid), warm polymictic (tropical rain forest), cold polymictic (frost climate of tropical high mountains), meromictic (all regions). A lake classification based on the water balance (Szesztay, 1974) has different classes of lakes based on the relative dominance of infow factor (I), outflow factor (O), and the magnitude of the mean annual flux (F).

Lakes are one of the most important natural resources available to mankind. They contribute to fulfill the ever increasing demand for water for a variety of purposes such as domestic, industrial, recreation, fisheries and transportation. many a times, particularly in the mountainous regions, lakes are the only water storage available in the area. The understanding of physical aspects and hydrology of lakes is essential for their

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proper use and conservation. The quality and quantity of water is closely linked to the water and energy budgets, mixing, stratification and other physical aspects of the lake. On the geological time scale, lakes are transitory features on the earth's surface. Most lakes have a natural life cycle in which they proceed from oligotrophic to eutrophic states; sediments accumulate and eventually the water body develops into a marshy land area. Man's influence now-a-days greatly accelerate this process. The future of many lakes depend to a great extent on the measures which are taken in our decades.

There are various conventional techniques which can be used for the study of water balance and sedimentation in lakes but with limited accuracy and uncertainity in the prediction. The nuclear techniques have emerged as a strong tool for different kinds of hydrological investigations and different hydrological parameters can be estimated with desired accuracy. The water balance and sedimentation in lakes can also be studied with a desired accuracy using artificial and environmental stable isotopes. However, the combination of conventional and isotopic techniques can be used in a better way for the study of water balance and sedimentation in lakes and predictions can be made precisely with required accuracy.

In this report, the details of isotopic techniques for the study of water balance and sedimentation in lakes have been discussed alongwith brief description of conventional techniques, instrumentation, case studies and status of lake studies in India.

Before going into details of application of isotope techniques for lake water balance and sedimentation, it is better to describe in brief the basics of isotopes.

2. ISOTOPES

Isotopes are the atoms of an element having same atomic number and different atomic masses, e.g. Hydrogen possesses three isotopes having atomic number 1 and atomic masses, 1, 2 and 3.

The number of protons in the nucleus of an atom determines the characteristics of the element. This is called its atomic number

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and is represented by the symbol 'Z'. Mass number or atomic weight of an atom is the sum of the number of protons and neutrons in the nucleus of an atom. It is commonly designated by the symbol 'A'.

Thus, the atomic number in the case of protium (^1H) will be 1 and its mass number will also be 1 as there is only one proton in the nucleus while in the case of deuterium (^2H or D), the atomic number will be 1 and atomic mass 2 as nucleus has one proton and one neutron. Similarly, the third isotope of the hydrogen, tritium (^3H) has two neutrons and one proton in the nucleus and therefore, its mass number/atomic mass will be 3 while atomic number will be 2. Oxygen has three isotopes having atomic number 8 and atomic masses 16, 17 and 18 respectively (^{16}O, ^{17}O, ^{18}O) and carbon has three isotopes ^{12}C, ^{13}C and ^{14}C.

Isotopes can be classified as stable isotopes and unstable isotopes. The 'stable isotopes' are the atoms of an element which do not change their constitution with time and considered to be happy with their number and/or arrangement of protons, electrons and neutrons. The stable isotopes can also be classified as environmental isotopes (^2H, ^{18}O, ^{34}S) and those which are found on the earth. The 'unstable isotopes', also called 'radio-isotopes', are those which have an 'unhappy' electronic configuration. Therefore, they attempt to become stable atoms by either spontaneously re-arranging the particles or by emitting particles from their nucleus with an accompanying loss of energy. The radioisotopes can be further classified as natural and artificial (^3H, ^{90}Sr, ^{137}Cs, ^{210}Pb). Natural radioisotopes can be divided into two categories i.e. environmental (cosmic rays produced- ^3H, ^{14}C, ^{32}Si, ^{210}Pb) and primordial radioisotopes (^{238}U, ^{232}Th, ^{40}Kr).

2.1. Radioactivity

The phenomenon of conversion of unstable atoms to the stable form is called radio-activity. The unit of activity is denoted by Ci (Curie), equal to $3.7*10e10$ disintegrations per second. In case of very low activity, it is also denoted by Becqueral (Bq) and one Becqueral is equal to one disintegration per second (1 dps). The specific activity is denoted by Curies per gram. The energy of

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disintegration or radiation is denoted by KeV or MeV

The types of emissions occuring during a radioactive decay are as follows:

(i)   Emission of an alpha particle, known as doubly ionised helium atom, (2 proton + 2 neutron);

(ii)   Emission of a Beta particle (Electron having some kinetic energy);

(iii)   Emission of a gamma ray (Photon).

2.2. Half life

Half life of a radioisotope is the time span required for the activity to decay to one half(1/2) of its initial strength/activity. A radioisotope decays exponentially and a definite time is required to fall to any given fraction of its initial strength. The different radioactive isotopes will have different half life as the decay is characterized by the properties of the atoms. The disintegration of an atom can be expressed by the equation,

$$\frac{Disintegration}{Time} = \frac{dn}{dt} = - n\lambda \ldots\ldots\ldots\ldots(1)$$

Where n is the number of atoms and λ is the decay constant of those particular atoms.

Half life (T1/2) of a radioisotope is given by the following relation,

$$\text{Half life } (T_{1/2}) = 0.693/\lambda \ldots\ldots\ldots\ldots(2)$$

2.3. Environmental isotopes

Environmental isotopes are those isotopes which occur in the environment in varying concentrations and over which the investigator has no direct control. The stable environmental isotopes most commonly used in hydrology are Deuterium, Oxygen-18, Carbon-13, Sulphur-34. The radioactive environmental isotopes, Tritium and Carbon-14 are also used in hydrological studies. Of

these isotopes, Deuterium, Oxygen-18 and Tritium, being constituent of the water molecule, are conservative and hence ideal water tracers. Other isotopes such as Carbon-13, Carbon-14 etc. which occur as dissolved compounds are non-conservative i.e. their physico-chemical behaviour is not identical to water. Other less commonly used isotopes are Silicon-32, Argon-39, Krypton-81, Krypton-85 and Chlorine-36. Generally, environmental isotopes are not used as an independent tool, but to supplement the hydrological and geochemical information, and to help in a better understanding of the processes taking place in a given hydrological system.

2.3.1. Stable Isotopes - Deuterium and Oxygen-18

Deuterium and Oxygen-18 occur in oceans in concentrations of about 310 ppm and 1990 ppm for HDO and $H_2^{18}O$ respectively. The varying concentrations of these isotopes in natural waters can be measured in an isotope ratio mass spectrometer and are expressed as delta values where,

$$\delta = \frac{Rs - Rstd}{Rstd} \times 10^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where Rs = Isotopic ratio (D/H or $^{18}O/^{16}O$) of sample

$Rstd$ = Isotopic ratio of standard

Values are expressed as per mil deviation with respect to a standard. The standard universally used is SMOW - Standard Mean Ocean Water. When water changes state through co.densation or vaporisation, an isotopic fractionation occurs due to the difference in the vapour pressures and diffusion velocities in air of different isotopic species of water (water vapour is in equilibrium with liquid water). The isotopic fractionation is inversely related to temperature. Hence, the stable isotopic composition of precipitation gets depleted at higher latitude (latitude effect), at higher altitude (altitude effect), and away from the coast (continental effect). A seasonal effect is also observed i.e. precipitation in rainy season is more depleted in stable isotopes compared to winter precipitation.

In contrast to the condensation process, the evaporation does not take place under equilibrium conditions. During evaporation,

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lower isotopic species preferentially leave the surface so that the remaining liquid gets more and more enriched with time. The degree of enrichment depends on the relative humidity of atmosphere, temperature etc. The δD and $\delta^{18}O$ of natural water arecorrelated as follows :

$$D = 8 \; \delta^{18}O + 10 \ldots\ldots\ldots\ldots(4)$$

For waters subjected to evaporation, the slope of the above line is < 8 (generally between 1 and 6). Hot waters from geothermal areas will show a $\delta^{18}O$ shift on $\delta D - \delta^{18}O$ plot due to exchange with the rock.

2.3.2. Radioisotopes — Tritium and Carbon-14

Tritium, the radioactive isotope of hydrogen, has a half life of 12.23 years and emits low energy beta radiation ($\simeq 18$ Kev). Environmental concentration of tritium in natural water is expressed in tritium units (TU) or Tritium ratio (TR) (1 TU = 1 atom of ^3H in 10^{18} atoms of ^1H). Environmental tritium in precipitation has two probable sources; firstly interaction of cosmic rays in nature in the upper atmosphere with Nitrogen atoms, i. e.,

$$^{14}N + n \; ---> \; ^3H + \; ^{12}C. \ldots\ldots\ldots\ldots\ldots(5)$$

Secondly, environmental tritium is man-induced and has been derived since 1952 due to the detonation of thermonuclear devices (bomb tests) which has injected periodic pulses of tritium into the atmosphere. The concentration of tritium in precipitation increased by three orders of magnitude in 1963 above the cosmic rays source. The global distribution of tritium in precipitation was obtained through IAEA - WHO network of stations collecting monthly samples, and the data are regularly published by IAEA.

^{14}C is a radioactive isotope of Carbon that has a half life of 5730 years and emits beta radiation (Emax = 156 kev). Environmental ^{14}C is expressed as percent modern carbon-14 (pmc). The ^{14}C concentration of atmosphere before thermonuclear tests was 100 pmc. After the nuclear tests, the concentration in the northern hemisphere was nearly doubled in 1963 and then decreased subsequently. Carbon-14 is not an isotopic tracer of water

molecule and it occurs in water as various species of dissolved inorganic carbon. The non-conservative nature of carbon-14 demands full use of complete water chemistry as well as ^{13}C of the dissolved carbon for the proper interpretation of ^{14}C data. The use of ^{14}C as a dating tool is based on the following radioactive equations,

$$N = No\ e^{-\lambda t} \quad \dots\dots\dots\dots\dots\dots\dots\dots(6)$$

$$(Age)\ t\ =\ \frac{t1/2}{\ln 2}\ x\ \ln(\Lambda o\ /\ \Lambda t)\ \ \dots\dots\dots(7)$$

Where Λo and Λt are the initial and final ^{14}C activity respectively.

In routine ^{14}C dating, initial ^{14}C concentration is known by analyzing dendro-chronologically dated tree °rings. However, in hydrology , the situation is much more complicated and many models have been suggested to predict the initial ^{14}C content.

2.4. Artificial Radioisotopes

The ideal radiotracer for hydrological application is tritium as HTO. However, tritium can not be detected in-situ in the field as it has a long half life (12.26 years). Hence, it is not suitable for short term studies. A number of radioisotopes in suitable forms, are available for field applications, a few of which are presented in table 1. Most of them (γ ray emitter) could be detected in-situ in the field using Gamma ray spectrometer or Rate meter/Scaler.

Table 1

Isotope	Radiation of interest	Half-life	Energy (MeV)	Minimum detection limit
^{3}H	Beta	12.26Yr.	0.018	0.1
^{51}Cr	Gamma	27.8 d	0.324(9%)	0.8
^{58}Co	Gamma	71 d	0.81(100%)	0.06

^{60}Co	Gamma	5.27yr.	0.17(100%) 1.33(100%)	0.03
^{82}Br	Gamma	35.76hr.	0.55(69%)0.82(26%) 0.61(13%)1.03(31%) 0.69(29%) 1.3(31%) 0.76(86%)1.16(16%)	0.02
^{131}I	Gamma	8.05d	0.08(2.2%)0.28(5.3%) 0.36(82%)0.64(9%) 0.72(3%)	0.08
^{46}Sc	Gamma	64d	0.89(100%) 1.12(100%)	0.03

Another advantage of radiotracer is its high sensitivity of detection. They can be detected even at a dilution of 10^{-12} Curie. Conventional chemical tracers are usually 1000 times less sensitive to detection.

3. WATER BALANCE IN LAKES

The water balance of lakes provides very useful information about the availability of water in lakes at any time. Also, if the water balance is monitored regularly after a specified period (say yearly or after every 2-5 years depending upon the situation), the information of change in the value of different components of water balance (discussed below) will require important precaution/measure in order to control the required availability of water in the lakes. The general principles of water balance and computational techniques have been diccussed in the following sections.

3.1. General Principles

The basic parameters of the water balance of the lake may be classified as recharge and discharge. These can be further divided as inflow from precipitation, surface runoff and groundwater, and outflow from river and evaporation. These factors can be studied by various conceptual techniques and also by some specific

techniques developed in recent years. It has also been observed that not only hydrogeological and hydrometerological factors, but also hydrodynamic conditions in the lake basin, influence the water balance of lakes.

The water balance equation of a lake can be expressed as follows :

$$\Delta S = I_s + I_u + P_l - Q_s - Q_u - E_l , \quad\dots\dots\dots\dots\dots(8)$$

where

ΔS = change in water storage

I_s = Surface inflow

I_u = Undergraound inflow

P_l = Lake precipitation

Q_s = Surface outflow

Q_u = Underground outflow

E_l = Lake evaporation

The water balance of lakes is determined by the conditions of humidification in the area where the lakes and their drainage basins are located. In humid areas, precipitation is more than evaporation from water surface, and in arid areas, evaporation from water surface is more than precipitation. An intermediate zone may also be distinguished where humid and arid conditions alternate. Each zone is characterised by its own type of structure and dynamics of water balance. In humid areas, there are lakes with outflow whereas in arid areas lakes without outflow prevail. In the intermediate zone, lakes usually have weak outflow. Quantitatively, the water balance of lakes can be computed by using conventional techniques. However, there are few components like inflow and outflow which can not be measured with the desired accuracy using conventional techniques. Therefore, isotopic techniques are employed to compute these parameters with a desired accuracy. The details of these techniques are discussed in the next sections.

3.2. Conventional methods of computing water balance of lakes

The conventional methodologies for computing different components of the water balance equation are described as under :

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3.2.1. Lake precipitation (Pl)

Precipitation into a lake is usually estimated from the raingauges located near and around the lake. This method gives rise to unavoidable wind errors. A more accurate estimate of lake precipitation can be achieved by installing raingauges on the islands, if any, in the central part of the lake. Raingauges on the rafts have also been used. Care should be taken in regionalizing point values from the surroundings of the lake because lake precipitation is generally lower than precipitation over surrounding land areas. The ideal requirement is to average the values from raingauges installed all around the lake, upstream as well as downstream portions. The total number of raingauges to be installed should depend upon the size of the lake and the variability of rainfall over different parts of the lake.

3.2.2. Surface inflow (Is)

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. Continuous observation of discharge is carried out in as many inflowing river as possible. In case of the perennial rivers, rating curves can be computed for manipulating the discharge values for any time period. The main source of error is due to regionalization of point discharge data from the gauged basin over the ungauged catchments. Therefore, the portion of gauged catchments should be as large as possible. For the seasonal inflows into the lake through streams, nalas etc., the direct measurement of discharge is difficult, particularly if the number of such inflows is large. Instead, a relationship should be developed between precipitation and discharge through such inflows from which discharge can be computed. In this case, however, the precipitation should be measured very accurately.

To measure the surface inflow from nalas and small streams, V-notches or weirs can be permanently installed at suitable places. Alternatively, pigmy type current meters can be used to measure the discharge of the streams or nalas. In case of continuously flowing nalas, automatic water level recorders can also be installed at 'V' notches or weirs in order to have a

continuous record of discharge.

3.2.3. Lake evaporation (El)

Methods of measurement and estimation of evaporation are still inadequate. Three groups of methods currently in use are :

(i) Balance method : This involves application of energy and/or water balance. Use of this method requires the measurement of all other components of the respective balance equation except the component related to evaporation. In terms of energy balance, this implies 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.

(ii) Comparative methods : This involves the use of evaporation pans or tanks followed by the use of pan or tank coefficients. In this method, the relationship between lake evaporation and pan evaporation is complex because of a marked difference between the thermal regimes of pans and lakes. Seasonal changes in sub surface heat storage are not reflected in pan observations. The most commonly used coefficient to estimate annual or seasonal lake evaporation from Class A pan data is 0.7.

(iii) Aerodynamic methods : The aerodynamic methods are based on the concept that evaporation is proportional to the vapour pressure gradient between the evaporating surface and the air, with a coefficient which is strongly dependant on wind velocity,
$$E = f(v) (\rho_s - \rho_a), \quad \dots\dots\dots\dots\dots\dots\dots(9)$$
where,
$f(v)$ = proportionality coefficient often called wind function.
ρ_s = saturation vapour pressure.
ρ_a = vapour pressure of air.

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3.2.4. Surface outflow(Qs)

In general, surface outflow is the most accurate component in the lake water budget. The volume of water being used for different purposes are generally known precisely which can be used in the water balance of lakes directly. For both regulated and unregulated lakes, the error in this component can usually be of the order of 15%.

3.2.5. Subsurface inflow (Iu)

The subsurface input to the lake include inflow from groundwater and seepage through the dam, if the lake is regulated. Variations in bank storage can be considered as a special case of underground flow. The proportion of underground flow in the total balance of lakes varies widely. There is no direct method for computing the subsurface inflow to the lake. However, in dry period, if all other parameters of the water balance equation are known, the change in storage can be ascribed to the underground inflow. This estimate may be erroneous if there is a subsurface outflow component also. In that case, this will give the cumulative effect of subsurface inflow and outflow.

3.2.6. Subsurface outflow (Qu)

Subsurface outflow is a rarer phenomenon than inflow. Subsurface outflow may occur from small mountain lakes where lake bed is lined with permeable soils or from lakes where there is often no drainage network developed. For estimating the subsurface outflow from the lake, an extensive survey of the surrounding area is required to map all the springs, seepage, or leakage which may be connected to the lake.

3.2.7. Storage changes

The change in storage of lakes is directly estimated from the data on the dimension of lake, depth of water column, and water level fluctuations. The sources of error in the estimation of storage change involve inaccuracies in the measurement of water level fluctuations. Some other factors have minor influences;

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these include changes of water density, sedimentation, copious aquatic vagetation and ice phenomenon.

3.3. Water balance of lakes by isotopic techniques

To asses the factors involved in the evolution of the isotopic composition of a lake, it is better to consider first some simple systems to gain the experience and to know the effect of different processes involve individually with high accuracy, i.e. one should take up the lake studies in the following order if at all it is possible; i) water bodies drying up without inflow ii) Lake without outflow - so called terminal lake iii) Lakes at constant volume(water level controlled by overflow over a dam).

Isotopes have found their most useful application in lake water balance studies in the determination of subsurface inflow and outflow which are difficult to evaluate otherwise. Under favourable circumustances, the evaporation term can also be estimated, however, accuracy is generally poor. The other parameters are normally directly measured using the conventional methods. Both environmental as well as artificial isotopes are used for water balance studies of lakes.

3.3.1. Using Environmental Isotopes

The estimation of water balance of lakes using environmental isotopes is possible only in isotopically well-mixed lakes in which evaporation has significantly raised the heavy isotope content with respect to inflow. However, in particular cases, isotopes might provide an independent tool to check water balance computations made by other methods.

Lake water samples are collected from different depths and at different times and concentration of ^{18}O or ∂D is measured in each sample. From the variation in the isotopic composition at the surface of the lake, indirect estimates of evaporation can be done. There have been some empirical relations developed for this purpose. The variation of isotopic composition at depth indicates the variation in subsurface inflow and/or outflow. Given the total volume of the lake and the change in storage, the percent change

in ^{18}O and D values can be directly converted into total subsurface inflow to the lake. When the lake water enriched in heavy isotopes (through evaporation) outflows to a ground water system, an increase of the $\partial^{18}O$ and ∂D values in the groundwater results. In most cases, however, it has been shown that lake contribution to ground water is neglisible or very minor, often contrary to the hydrogeologists expectations. However, in the proximity of lakes, the lake water may significantly contribute to ground water recharge, but further away, it is rapidly diluted by other sources of recharge.

The mass balance and the isotopic balance of a generic, well-mixed lake, are given by,

$$\Delta V = (I - Q - E)\Delta t \qquad \dots\dots\dots\dots\dots\dots (10)$$

$$\partial_L \Delta V + V\Delta\partial_L = (I\partial_I - Q\partial_L + \frac{E}{1-h+\Delta\epsilon} (h\delta_A - \frac{\delta_L - \epsilon}{\alpha} + \Delta\epsilon))\, \Delta t$$
$$\dots\dots\dots\dots\dots\dots (11)$$

where,

    V = volume of the lake

    I = inflow rate to lake (runoff + ppt. + groundwater)

    Q = outflow rate from lake (surface runoff + groundwater)

    h = relative atmospheric humidity normalized to lake surface temperature

    E = net evaporation rate

    α = isotopic equilibrium fractionation fctor between liquid water and vapour

    $\epsilon = \alpha - 1 + \Delta\epsilon$ = total isotopic enrichment factor resulting from the sum of the equilibrium ($\alpha-1$) and the kinetic enrichment factor ($\Delta\epsilon$).

    ∂_L, ∂_I, ∂_A = isotopic composition of lake inflow and atmospheric moisture.

The terms involving h and ∂_A appearing in eq. (11) take into account the molecular exchange with atmospheric moisture which is also an important process affecting the isotopic composition of lake water.

The equilibrium enrichment factor ($\alpha-1$) can be calculated by using the following equations given by Majoube (1971) :

(D) $1000 \ln \alpha = 24.844 * 10^6 T^{-2} - 76.248 * 10^3 t^{-1} + 52.612$

$$\ldots\ldots\ldots\ldots(12)$$

(^{18}O) $1000 \ln \alpha = 1.237 * 10^6 T^{-2} - 0.4156 * 10^3 t^{-1} - 2.0667$

$$\ldots\ldots\ldots\ldots(13)$$

where T is the absolute temperature in Kelvin.

The equations described above can be modified according to different situations observed in the lakes. However, some of these parameters are difficult to estimate and constitute the major source of errors in the use of above equation; they are especially h, $\partial\Lambda$ and ϵ. The relative humidity is difficult to evaluate even if continuous measurements are available in stations on the lake because h increases across the lake in the wind direction in a manner which depends on the metereological conditions and is difficult to predict. The same applies to $\partial\Lambda$, the isotopic composition of the atmospheric moisture varies across the lake as the contribution of lake vapour increases.

To overcome some the difficulties inherent to the method, Dincer (1968) proposed, whenever possible, the use of an index of a terminal lake located in the region and therefore presumably submitted to identical evaporation conditions as other lakes. In a somewhat similar manner, evaporation pans have been used at different times and sites of the lake in order to find out the reliable mean values.

In case of salt lakes, the salts which do not partake to a large degree in the water to atmosphere transition, are very useful traces for establishing additional balance equations specially, cl^-, magnesium and lithium content, were found reasonably conservative under a variety of situations. However, this method fails when the leakage/seepage of the salt water takes place and contribute the unknown quantity of salt.

3.3.2. Using Artificial Isotopes

Tritium can be used for water balance studies of lakes. If tritiated water is injected to raise the tritium concentration of the whole lake about 100 times above the natural level, then

theoretically, lake's tritium content should decrease with time (Gilath and Gonfiantini, 1983). If the tritium concentration of inflow water and atmospheric moisture are much smaller than that of the spiked lake, the water budget equation reduces to,

$$C_L \simeq C_L^0 \exp - \frac{t}{V} \left(I - E + \frac{E}{\alpha (1 - h)} \right) - \lambda t, \quad \ldots\ldots\ldots(14)$$

where,

V = volume of the lake

I = inflow rate to lake (tributaries + ppt + gw)

E = net eveporation rate

h = mean relative humidity

α = tritium fractionation factor at evaporation

λ = tritium decay constant ($0.0558 \ a^{-1}$)

C_L, C_L^0 = tritium concentration of lake at time t & 0.

Therefore, by knowing the concentration of tritium injected at different times, the unknown parameter of the water balance equation can be evaluated. The methodology of this technique is as follows.

Tritiated water is injected in the lake and is allowed to mix so that the tritium concentration is homogenised in the entire lake. Lake water samples are collected at regular intervals and tritium concentration is measured in each sample through a liquid scintillation counter. Using these values, the required parameters like subsurface inflow and outflow can be computed at any particular time.

As is obvious, this method can be used only for small lakes. In large lakes, a huge quantity of tritium will be required to raise the tritium concentration of the lake to a desired level. Further, this method requires an accurate evaluation of the evaporation and relative humidity if being used for estimating groundwater inflow/ouflow into/from the lake. The tracer in fact interacts with atmospheric moisture and necessary corrections should be made to compensate this effect.

Another way to use the radioisotopes for the measurement of inflow into the lake through visible gullies, nalas, and springs is to mix either a gamma ray radioisotope like Br-82 or tritium at a suitable point in the inflowing channel. The dilution of the

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radioisotopes is measured at a certain distance from the mixing point (known as mixing length) by using a rate meter/scaler if gamma ray tracer was injected, or by collecting tritiated water samples and analysing the diluted activity wih the help of liquid scintillation counter, if tritium was injected.

In order to compute the subsurface inflow/outflow a special tracer probe is used which comprises of a tracer injection and mixing device, inflatable rubber packers to isolate a portion of the bore-hole and a built-in scintillation detector assembly. The probe is lowered to the desired depth in a borehole, the packers are inflated to isolate a portion of the borehole (to define the dilution volume and avoid vertical currents). The radiotracer is injected and well mixed in the dilution volume. If Co is the initial concentration of tracer and C is the concentration after time t, then filtration velocity (Darcy velocity) is given by the equation:

$$V_f = \frac{\pi d}{4 \phi} \times \frac{\ln(Co/C)}{t} \qquad \dots\dots\dots\dots\dots\dots\dots (15)$$

Where d is the diameter of borehole, Co is the initial concentration and t is the time interval after which tracer concentration C was observed.

The details of this technique has been mentioned in NIH publication no. TR-150 under the section on 'Bore-hole dilution technique'. However, this technique can be used only if the surroundings of the lake are porous.

3.3.3. Case studies

A great number of lake studies have been carried out in the past few decades. Fontes and Gonfiantini (1967) evaluated the water lost by evaporation for two small ephemeral lakes in the western Sahara, Algeria using isotopic method. Evaporation under extremely arid conditions resulted in a remarkable heavy isotope enrichment. The ∂-values fitted a curve fom which the average relative humidity was evaluated.

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Water balance study using Tritium was conducted by Payne (1970) for Lake Chala on the border between Kenya and Tanzania. Tritiated water (1900 Ci) was injected in February, 1964 in a number of sites in the lake. Samples collected in December of the same year at 10 different sites showed that the tritium distribution was practically homogeneous all over the lake. This good homogeneity was also observed in six successive sampling programmes until Oct.1968 during which the tritium concentration decreased steadily, from 1400 to 800 TU. A least square fit between 'ln (C_L)' and 't' produced which, knowing the amount of tritium injected, lake volume was evaluated. In addition, from the slope of the linear correlation between 'ln (C_L)' and 't', net discharge into groundwater was computed from the eq.,

$$S = \frac{1}{V}(I - E + \frac{E}{\alpha (1-h)}) - \lambda \quad \dots\dots\dots\dots\dots(16)$$

Lewis (1979) evaluated the evaporation rate by using a two-box model (corresponding to epilimnium and hypolimnium) and a periodic function to describe evaporation. Zimmerman (1979) studied two small artificial lakes in FRG, and deduced the various terms of the water balance from the change in isotopic composition with time. Dincer et al (1979) applied isotopic methods to evaluate the fraction of water lost by plant transpiration in the Okawango swamps (Botswana) with respect to the total evapotranspiration losses.

Allison et al (1979) used environmental tritium to estimate groundwater inflow to two small lakes located within an extensive sedimentary basin, the Gambier Embayment of the Otway Basin. The ratio of groundwater inflow to the total flow was found to be 30% and 14% for the two cases which would have been difficult to estimate using other geochemical or hydraulic techniques. In addition, tritium also had an advantage over oxygen-18 and deuterium as it showed greater relative differences in concentration between groundwater and lake water.

Zuber (1983) applied isotope balance method to a small artificial lake assumed to be under steady state condition. It was shown that the long-term averages and non-normalized temperature can be used in the balance equations. The applicability of this approach was tested by interpretation/reinterpretation of several

known case studies. The water balance equation for each of the lakes considered was solved with the aid of the isotopic balance of ^{18}O. Applying the calculated components of water balance, the isotope balance equation of deuterium was solved for finding the values of kinetic enrichment for deuterium.

Turner et al (1984) studied the Blue Lake, southeastern Australia with an objective to estimate the total groundwater inflow and outflow rates. Environmental isotopes ^3H, ^{18}O, ^2H, and ^{14}C in the lake water and recharging groundwater was used to establish the lake water balance. The water balance calculations indicated a total groundwater inflow to Blue lake between $5.0 * 10^6$ and $6.5 * 10^6$ m^3/yr, corresponding to a residence time of water in the lake of ~ 6 yr. The relative proportions of inflow to the lake from two possible source aquifers could not be derived because their concentration did not show a sufficiently large control to distinguish the two water sources.

4. SEDIMENTATION IN LAKES

Lakes are important in the conservation of a very basic national resource-waters. The threat on the life of the lakes due to high rates of sedimentation has caused serious problems particularly in the developing countries. The loss of storage capacity of the lakes due to unwanted sedimentation can have a profound effect on the functioning and objectives of the water system. Recent examples of some of these effects can be found in Burma, India, Indonesia, Kenya, Nigeria, Pakistan and Sudan.

In broad terms, solution of the problems requires a comprehensive study of the catchment with regard to the following aspects:

i)   Measurement of erosion effects in the catchment and identify the sediment sources, including those related to particular land usage,
ii) Identification of areas of sediment storage;
iii) Measurement of temporal changes in sediment storage;
iv) Measurement of transport of eroded materials or sediment by overland (including aeolian processes), and b) fluvial processes

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v)   Determination of sedimentation rates;

vi) Measurement of changes in sediment distributions;

vii) Acquisition of data in order to generate soil loss prediction equations.

These studies can be carried out only after a full understanding of the physical processes of sedimentation in lakes and the source and nature of sediment supply into the lakes. A detailed discussion of these aspects is available in the status report on 'Sedimentation in lakes' being prepared by A.K.Bhar and S.D. Khobragade at the National Institute of Hydrology. Here, only a brief outline is attempted.

4.1. Sedimentary processes in lakes

Sedimentation in lakes record the effects of climatological or man-made changes in and around the catchment of the lakes/reservoirs. The composition of the sediments and sedimentation rates provide important clues about the paleohydrologic conditions of the region.

The important factors influencing the sedimentation processes in lakes are as follows :

1. Nature and size of watersheds surrounding the lake basins; high relief areas contribute coarser particles whereas the low-gradient areas contribute finer material.

2. Size and shape of the lake which control the wave action within the system and hence affect the sedimentation behaviour.

3. Orientation of lake relative to dominant wind direction.

4. Thermal stratification and density of lake water, particularly important with respect to movement of fine particles.

5. Climatic factors such as precipitation, evaporation etc.

The sedimentary processes in lakes is controlled by the imposed shear stress resulting from wave and current action which itself is influenced by particle size, cohesive strength and bed form. The sediment response to these factors are manifested in terms of erosion, transport and deposition.

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Lake erosion is, in almost every way, similar to sea erosion, except that the effects produced in lakes are usually less conspicuous because they are smaller and the waves and undertow currents, which do nearly all the erosive work, are less powerful. In large lakes, however, the resulting features of lake erosion such as wave-cut terraces, cliffs, caves, stacks, and arches are practically identical with similar features produced by sea erosion.

Deposition in lakes is also similar to deposition in the sea in many respects Beaches, barriers, bars, deltas, and wave-built terraces are essentially the same whether formed in sea or lakes. Mostly, land derived sediments carried into the lakes by streams or other agencies settle on their floor, and therefore, lakes act as perfect settling basins. Delta growth in lakes is particularly strong because of both absence of very appreciable tides and the usual lack (except in some very large lakes) of very powerful wave and undertow action. A deposit rather characteristic of some fresh lakes is marl which is a light grey mixture of carbonate of lime (often in the form of shells) and clay. Decaying vegetable matter accumulates in many lakes and swamps in humid climatic regions. Such material often forms rather extensive bodies of peat. In certain fresh lakes fed by streams rich in dissolved carbonate of iron, the soluble material may, on entering the lakes, become oxidised to the insoluble limonite and be deposited on the lake floor.

1.2. Source and Nature of Sediment Supply

Rivers and streams are the major sourcs of sediment supply to lakes and reservoirs. The nature of sediment transported ranges from pebbles and coarse sands (bed load) to finer sands, silts and clays (suspended/wash load) depending upon a number of variables such as water discharges, bed' slope, velocity, turbulence etc. Because of the low current velocities available to transport the sediment through a lake, the bedload and larger suspended sediments are quickly deposited as the water enters a lake to form a delta. The finer particles remain in suspension longer and are deposited further downstream. As the water-sediment mixture progresses into the lake, the flow velocity approaches zero and

movement, if any, results from complex circulation patterns. Whereas the coarse particles move only while currents or bed shear exceed local threshold values, the very fine sediment moves whenever the water is in motion. The fine particles has low settling velocities and are kept in suspension by the turbulent motion.

There has been conflicting views regarding contribution of sediments to world oceans from different climatic zones (see Holeman, 1968; Fournier, 1960; Fleming, 1969). However, these studies have established that the lakes in arid or semi-arid areas are most likely to suffer from severe sedimentation problems and those in temperate zones are less likely to experience such difficulties.

Although in most lakes sedimentation is principally from inorganic material, in many shallow lakes, in areas of low relief and where rivers carry small loads, the indigenous phytoplankton populations may contribute significant quantities of particulate matter to the lake bed. In some lakes and shallow reservoirs the productivity defined in terms of organic carbon generated is considerable. Biogenic silica from the skeletons of diatoms is also an important component of the system.

1.3. Conventional methods in lake sedimentation studies

The most common conventional technique and surest way of obtaining an accurate determination of the amount of sediment being carried to a lake by streams is to measure the flow rate and sediment concentration of the inflowing waters just upstream of the lake. Measurements of fine sediment concentrations usually invlove collecting a sample of the water-sediment mixture, separating the sediment, and weighing. Measurement of bedload discharge is difficult; usually the measurements have been made with samplers or sediment traps.

The other conventional methods for estimating sedimentation rate in a lake involve periodic bathymetric surveys of the lake. The range-line method (Eakin, 1939; Vanoni, 1977; Guy, 1978) is the most widely used for medium to large size lakes requiring an

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underwater survey utilizing hydrographic surveying methods. The basic measurements required for these surveys are positon of the boat, and depth of water or bed elevation. The amount of sediment accumulated is essentially computed from the differences in bed elevations occurring between surveys. The usual methods to directly measure the amount of accumulation include polling, spudding , and coring.

Although the remote sensing techniques do not come under conventional technique, but it is important to mention here that low level remote sensing has found useful applications in estimation of suspended sediments in reservoirs and the same can be extended to lakes. Aerial photographs can be used to prepare contour maps to. determine sediment volumes and to trace turbidity plumes which may help to define the distribution of sedimentation. Digital image processing of high resolution satellite data (SPOT) can also be used for lake sedimentation studies. The information about suspended sediments obtained at different times using this technique can be utilized to predict the deposition or settling rate of sediments in the lake.

The bulk density of a sediment deposit is the dry weight of sediment per unit volume. The bulk density therefore provides a simple and direct conversion from the dry weight of sediment added to the reservoir to the volume of water displaced. Traditionally, these measurements have been made by use of core samples. A variety of samplers have been used to obtain undisturbed samples of reservoir deposits for determining the bulk density and/or grain size distribution.

Grain size information of the lake sediments is also important in predicting erosion, transport, deposition and compaction of sediments. The size distribution of incoming sediment is very important in determining the pattern of deposition in a reservoir. This is one of the most important aspects in the evaluation of the amount of space a given weight or quantity of transported sediment will occupy in a lake. Out of the wide range of sizes of sediment particles being supplied to the lake, the large and intermediate sizes (gravel and sand) can be analysed using standard techniques. The small sizes (clays, silts, and fine sand) are conventionally

measured by pipet method based on the settling characteristics of sediments in water. The modern instruments for these analyses include Coulter Counter (Coulter, 1956; Berg, 1957) based on elecetrical conductivity profile, Laser particle size analyser (Wertheimer et al, 1978; Haverland and Cooper, 1981) based on the internsity and scattering angle of laser light by partticles in suspension, SediGraph (Jones et al, 1988) based on the gravitational settling of particles in a small cell etc.

1.4. Isotopic techniques in lake sedimentation studies

The follo in sections describe the principles, methodology and case studies of a variety of aspects related to lake sedimentation using isotopes.

1.1.1. Computation of sedimentation rates

Environmental isotopes like Cs-137 and Pb- 210 can be used for the study of sedimentation rate in lakes. Cesium-137 is produced in the atmosphere due to the test of nuclear weapons. Since 1954, it has been globally detectable. It emits gamma radiations with the energy peak of 0.662 MeV and has a half life of 30.1 years. Cs-137 is strongly adsorbed on fine particles like clay minerals, silts and humic materials. In fact, the variation in the intensity of Cs-137 content of surface soils per unit area is linked with the intensity of fallout, percentage of clay and silt and cation exchange capacity. It follows that all surface soils with an adsorptive capacity will have a Cs-137 content and therefore be able to act as a self tracer. In a catchment, accumulation of a sediment layer in a lake is a measure of its trap efficiency. A comparison of Cs-137 content of catchment soils with that of the associated lake sediments shows a pronounced build-up of the latter. The sedimentation rates can be calculated from the depths of the two principal time horizons i.e. 1955 and 1964, in the Cs-137 concentration profile.

Since the nuclear weapons were mainly tested in the northern hemisphere, the fallout of Cs-137 is approximately 4 times greater at comparable northern versus southern latitudes. The amount of Cs-137 deposited on the earth has been measured at precipitation

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stations and many locations installed by IAEA and WMO. The data may be used to determine the cumulative input of Cs-137. Examples of such input have been shown in the reports of measurement from global network of US and UK monitoring stations.

For isotopic measurements, the undisturbed sediment samples are collected from the bed of the lake using a core cutter up to the depth of 20 to 100 cm. Some practical difficulties associated with the collection of undisturbed bed sediment samples are as follows :

i) The soft sediments in upper 20 cm.(may be more) depths may be disturbed during collection (penetration) and it may vary with different degree of compaction with increasing depth.

ii) The sediment sample may be disturbed during removal with the help of core cutter(tube) due to suction effect.

The core tube ranges up to 1 metre in length and 5 cm in diameter can be used for the collection of sediment samples from the bed using a hand corer, or a piston or box corer. However, gravity core sampling is convenient. Mackereth corer - a remotely operated pneumatic covers can be used for this purpose.

The sediment samples (cores) are cut into 1 cm sections and placed in a polythene bag. The Cs-137 core sections are analyzed by gamma ray spectrometry using Ge(Li) or intrinsic Germanium detectors (HPGe type).

1.1.2. Determination of concentration and density of sediments

As discussed above, the incoming coarse sediments settle quickly at the bed while the finer sediments remain in suspension for a longer period before finally settling down to the lake bed. Therefore it is necessary to measure the suspended sediment concentration in order to predict the future sedimentation rate. There are many conventional techniques for the measurement of suspended sediment concentration as discussed in section 3.3 of this report. The nucleonic sediment concentration gauges can also be used conveniently. The principle is that the concentration of

suspended sediment is related to the attenuation of gamma rays from ^{241}Am or ^{137}Cs radioactive source. The method is feasible for sediment concentration greater than 1-2 g/l. However, they are best suited for high turbidity measurements during floods

The density of the deposited sediment in a reservoir depends on several factors such as the type of sedimentary material, grain size, distribution and compaction of the sediment in the reservoir. Conventionally, the sediment density is determined by taking core samples from the bottom sediments and measuring the weight and volume of the deposit.

The conventional methods of measuring bulk density by a core sampler is labourious and time-consuming. The modern techniques based on nuclear density probes for measuring density and moisture in boreholes or in core samples has therefore gained wide acceptance. The density of sediment deposited in reservoirs can be easily determined by means of gamma scattering probes.

The most commonly used probe is equipped with a ^{137}Cs source and a gamma scintillation detector. The count rate of the linear rate meter is recorded visually or by a suitable recorder. By reference to a caliberation curve using several bentonote/sand or sodium silicate pastes, the bulk density equivalent of the count rate can be derived. A series of such readings through the material allows the construction of a density profile. Measurements on core samples by means of gamma transmission gauges are preferable for measurements of the deposited material in new area. Such nuclear methods are non-destructive and rapid and often give more accurate results than those obtained by other methods.

1.4.3. Determination of sediment types

Sediments of various compositions emit natural radioactivity of different intensities. A technique to trace the sediment transport and to identify sediment types is based on the measurements of gamma radiation of natural uranium, thorium and potassium, which are generally richer in clay than in coarse sediment sizes.

The values of natural sediment radioactivity strongly depend on the position of the gamma Scintillation detector with respect to the bottom. The difference between radiation emitted from sand and from clay are due to the mineral composition, whereas between clay and mud the difference may be due to the changes in water content which result in a deeper penetration of the probe into the sediments for soft mud.

Measurement of the radioactivity is made by lowering a gamma probe to the sediment or sliding it over the surface of compact sediment and detecting the gamma radiation by means of a scintillation counter. Signals from the probe are analysed by means of a multi-channel analyser and recorded by a printer or tape. This instrument is very useful for making detailed observations of the composition of sediments at each station, or dragging it along the bottom to observe difference between the natural littoral sand and dredge spoils material. The dredge material often has a different composition from the bed sand and consequently different radiation patterns will be observed. These differences can be utilised to elucidate the extent of the coverage of bottom sediments by the dredge spoils and will show the direction and extent of transport of the spoils by the bottom currents.

1.1.1. Sediment Redistribution Measurements in Lakes

The transport and spatial distribution of sediments entering an impoundment are functions of the balance between the flow velocities, gravitational forces and the secondary forces of flow turbulence. For reservoirs, draw-down procedures can be a very powerful initiator of sediment flows and redistribution while in lakes where the drawdown is neglisible, only the inflow velocity and other forces as stated above will control the spatial distribution of incoming sediments. Three generalized zones of sediment distribution and sedimentary processes in lakes have been recognised in the literature (Sly, 1978) :

i)   The upper zone in which complex deltas form as a result of flows entering the lake retaining their identity for some distance into the lake pool. The deltas grow outward by the formation of foreset (longitudinal flow) beds and upward through topset beds.

ii) The intermediate zone in which the residual river velocity, waves and wave-induced currents transport and deposit most of the river's wash load, and some of the fine sediments eroded from the bank of the lake, to form bottom set beds of fine clays, silts and colloids.

iii) The lower zone containing sediments eroded from the reservoir bank of the lake and transported by waves and wave-induced currents.

The Au-198 gamma ray radioisotope is mixed with inflowing water body like drains, open springs or channels in order to level the sediments. The Au-198 is adsorbed on the sediment surface and therefore the movement of the suspended sediments as well as the settled bed sediments can be studied by using a gamma ray detecting unit following a method same as for determining the type of sediment. The only difference is that natural gamma ray activity is measured while determining sediment types, whereas in case of sediment redistribution measurements, artificial gamma ray activity is measured.

1.1.5. Case studies

Stiller and Assaf (1973) carried out an study on sedimentation and transport of particles in Laka Kinneret using Cs-137. The location of the sediment layer containing maximum Cs-137 concentration permitted estimation of sedimentation rate in the range of 5 to 8mm/yr. It was shown that an equal amount of direct fallout (the insoluble Cs-137 fraction) and variable amount of Cs-137 (the excess Cs-137), originating from the catchment area are deposited. The amount of excess Cs-137 depended upon the distance from the Jordan influx into the lake. As an extension of his study on Lake Kinneret, Stiller (1979) applied ^{137}Cs, ^{210}Pb, ^{14}C for investigating the rates and patterns of sedimentation in Lake Kinneret. By studying stable isotopes of carbon and Oxygen, he established that the carbonates and organic carbon are derived from allochthonous and autochthonous sources and the suspended matter is from the Jordon river.

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Simpson et al. (1976) in their study of the Hudson River estuary, New York were able to classify three main types of distribution of ^{137}Cs in estuary sediment cores:

(a) Relatively low activities (19 mBq g^{-1}) generally confined to the upper 5-10 cm of sediment and associated with subtidal banks.

(b) Higher activities than in (a) of about 90 mBq g^{-1} in the top 10 cm, decreasing rapidly to about 7 mBq g^{-1} at about 15 cm and to about 1 mBq g^{-1} down to 40 cm. This type of profile was interpreted as being indicative of a high sedimentation rate in a shallow protected environment.

(c) Profiles with variable but high activities of about 70 mBq g^{-1} down to 40 cm and, in one case, down to 250 cm. Cesium-137 activity below 40 cm was stated by Simpson et al. (1976) to be a clear indicator of rapid sediment accumulation. It is speculated that temporal changes in ^{137}Cs profiles along a transact at each of the three zones could be interpreted as changes due to redistribution or accretion in exactly the same way that McHenry and Bubenzer (1982) interpreted changes in field distribution of ^{137}Cs .

Gasse and Fontes (1989) reconstructed the Holocene water level, sedimentary conditions and paleohydrology of Lake Asal, Djibout (central Afar). Field observations supported by ^{14}C dates and stable isotope analysis indicate that after an arid terminal Pliestocene phase, marked by coarse deposits due to exceptional flood, the Holecene cycle begins with complex, strontium-rich underground marine supply, and waters concentrated through evaporation.

Barnes et al (1978) carried out a detailed study of six lakes in western Washington State using ^{210}Pb measurements and historical records. Fine structure in the sediment profiles of ^{210}Pb were found to correlate with changing watershed landuse. Contemporary sedimentation rates varied from 0.37-2.9 mm/yr and were generally higher in pre-cultural areas; the highest sedimentation rates of 5.6-8.3 mm/yr were simultaneous with urbanisation. The present-day

sediment of all lakes were enriched in lead compared with older background material. The stable isotope profiles from all lakes except one were consistent with the local histiry of lead pollution based on ^{210}Pb geochronologies. Water column residence times for ^{210}Pb and stable lead were almost identical and were consistent with algal settling rates and sinking rates of fine silts and clays.

5. INSTRUMENTATION

Instrumentation is an important part of the hydrological studies of lakes for water balance and sedimentation. The instrumentation required for the measurement of various hydrological/hydrometerological parameters can be identified as follows :

5.1. Instrumentation for Water balance studies :

5.1.1. Hydrometerological set-up
(i) Raingauges - recording and non-recording type
(ii) Water level recorders
(iii) Pan evaporimeter - recording/manual type
(iv) Air temperature meter
(v) Humidity sensor/meter
(vi) Wind direction sensor
(vii) Wind speed sensor
(viii) Sunshine duration sensor
(ix) Solar radiation sensor
(xi) Global and balance radiation sensor

In order to measure the hydrometerological parameters, now-a-days dedicated type data logger (microprocessor based equipment) with sensors are available. These may be of telemetric type in which the sensors with field unit (data logger and other accessories) are installed at the lake site or in catchment and the base unit with MODEM accessoriesare installed at the laboratory or at a desired place. The connection among the sensors and the base unit is established with the help of MODEMS using antenna. However, in an alternative type, the sensors are connected with a long cable and therefore they can be installed at the site and the main unit

(data logger) can be placed at a suitable place (may be 50 meters away or more) connected with underground cable.

5.1.2. Surface/subsurface inflow and outflow (Hydrological set-up)

(i) V-notch or weir
(ii) Current meter (pigmy type)
(iii) Current meter with flow direction
(iv) Rate meter/scaler (nuclear equipment)
(v) Point dilution probe (nuclear equipment)
(vi) Soil moisture probe (nuclear equipment)
(vii) Liquid scintillation counter (nuclear equipment)

5.2. Instrumentation for Sedimentation studies :

(i) Water samplers (may be of different types)
(ii) Sediment samplers (may be of different types)
(iii) Bed sediment corer (may be of Macreth type or other different types)
(iv) Ultrasonic depth indicator
(v) Gamma ray spectrometer with HPGe detector (nuclear equipment)

6. STATUS OF STUDIES IN INDIA

Although lakes are an important part of the hydrologic system, there have been very limited studies on lakes. In many mountainous regions, they contribute significantly to the water demands of the region, even then attempts for management and preservation of lakes have been extremely poor. The Nainital lake is perhaps the best studied lake in the country, however, most of the studies have concentrated on biological and chemical parameters of lakes such as fish culturing, eutrophication, water chemistry etc. There is not a single study reported on the hydrological aspects like water balance and sedimentation aspects of any of the lakes in India.

A significant step in this direction has been taken by the National Institute of Hydrology, Roorkee where a hydrological study of the Naini lake has been started recently, funded by the Directorate of Environment, Government of U.P. through the

Nainital lake Development Authority. The main objectives of the study, apart from other related aspects, are to identify the recharge zones for the lake, to assess the total quantity of water available for the lake and to study the causes of rapid sedimentation in lakes. Apart from applying the conventional methods of water balance, the main emphasis is to use the isotopic techniques for computing the different parameters of water balance equation and for computing sedimentation rates, sediment distribution etc. A similar project has been initiated on the Rajasthan lakes by the Irrigation Department of Rajasthan, funded by INCOH (Indian national Committee of Hydrology) and assisted by the scientists of the National Institute of Hydrology, Roorkee.

7. CONCLUSIONS

As is clear from the status of hydrological studies of lakes in India that not even a single integrated study has been carried out so far. It is therefore concluded that there is an urgency to take up studies on water balance and sedimentation in lakes in the country at least for the lakes which are of utmost importance from water utilization point of view and are suffering from severe problems of sedimentation, deteriotion in water quality and reduction in water capacity and quantity. Further, as is mentioned in the report, all lakes have a natural life cycle and they all eventually develop into marshy land area after intense eutrophication and sediment accumulation. Therefore, we must start our attempts towards control and preservation of natural lakes before it is too late.

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