INTRODUCTION TO LAKES AND LAKE PROCESSES

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Three Days Training Course on
HYDROLOGICAL INVESTIGATIONS FOR CONSERVATION AND MANAGEMENT OF LAKES
(1-3 March, 2011)

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INTRODUCTION

The earth land is dotted with hundreds and thousands of natural depressions filled with water, called natural lakes. Moreover, it has always been the attempt of the human beings to bring water into their vicinity ever since the beginning of the human civilization itself. This has lead to the creation of hundreds of thousands of manmade lakes. In India a reservoir called Suadarshana Lake was created during the Maurya period. Even in water scarce arid and semi arid regions of Rajasthan, hundreds of manmade lakes have been created during the medieval times by the then ruling kings.

Lakes are valuable natural resources. They are being used as natural centres of civilization and to cater the civilian needs. They serve variety of purposes like domestic purposes, drinking water, irrigation, commercial purposes, aqua-culture, recreation, transport etc. In many regions they are the only source of water. Many saline lakes like the Sambhar Lake in Rajasthan support the salt industry. Lakes are also otherwise source of many rare minerals. Many lakes support exclusive flora and fauna and thus play a vital ecological role. In India, many lakes are related with different socio-cultural activities. Many cities have been built on the piles of lakes. Thus, for their socio-economic values, lakes are quite often referred to as catalysts in the development of a region.

It is said that there are about three million lakes on the earth and that about 95% of the Earth's fresh liquid water is contained in lakes. Most of the world's fresh water lakes (about 75%) occur on the three continents- N. America, Africa and Asia and account for 25%, 30% and 20% respectively. Lake Baikal in the South Eastern Russia, with a depth of more than 1000 m, is the worlds' deepest and most voluminous body of fresh water and contains nearly as much water as in the five Great Lakes of North America together. The latter are large in surface but their average depth is very much less than that of Lake Baikal. The 19 major lakes of the earth account for nearly 38% of the total surface area of the lakes. Although fresh water lakes are much more numerous and important, some of the world's largest lakes are saline. Both the combined areal and volume of saline lakes are about 85% of the respective totals for fresh water lakes. Saline lakes are mostly located in Asia. Caspian sea which, area wise, is the largest lake of the world is a saline lake and contains about 76% of the total volume of all the world's saline lakes. The total volume of lake water and river water with respect to total fresh water of the earth are 0.3% and 0.003% respectively. In other words, in terms of the earth's total fresh water, lake water is 10 times more than the river water. The number of lakes in Nordic countries like Sweden and Finland is very high. Minnesota State of America has more than 15000 lakes of surface area greater than 0.04 sq. km. As far as India is concerned, no statistics are available regarding the total lake water resources of the country.

WHAT IS A LAKE?

Quite often the term "lake" is used as a synonym for natural lakes, reservoirs, tanks and ponds. That is, any form of inland surface water body is called a lake. However, a lake is different from a reservoir, pond and tank in some respects. Firstly, like ponds, lakes are natural water bodies unlike the reservoirs and tanks. A lake is formed because of some geological process, as water fills any natural depression and as such they have a natural shoreline along their periphery. Because of the continuous action of the waves, this shoreline is barren. Ponds are also natural in origin but because of their relative smaller size, the waves generated are not big enough, so that their shoreline is not barren and is occupied by vegetation. Moreover, pond water is also extensively occupied by vegetation. The reservoirs and tanks, on the other hand are artificially created, the reservoir; by damming a river valley and the tanks; by artificial excavation. There are other technical differences also. To quote a few, for example, output from the lakes is near the surface whereas outlet of a reservoir is at one of the several depths. Lower most depression in a lake can occur anywhere in its basin but the maximum depth of the reservoir is always near the dam. A reservoir bottom has a regular slope from head to tail while in lakes, the bottom slopes is not uniform. Reservoirs also have greater areal water loads and shorter residence times than lakes. Lakes are generally located in the centre of the drainage basin and hence the tributary input to it enters at several points. By contrast, reservoirs are usually constructed at the downstream end of the drainage basin. Because of these differences certain hydrological and ecological processes may vary between these water bodies. Bio-chemical analysis needs different sampling strategies to be followed for reservoirs and natural lakes. So, do the lakes mean only natural lakes or even manmade lakes? It appears that although there are some differences in certain hydrological and ecological processes, the differences are not very much significant except is some respects. As such, even two natural lakes would behave differently if their morphology or climatic settings are different. It should also be noted that a demarcation between natural lake and a natural pond on the basis of size is yet to be established. Thus, in my view, although lake should technically mean only natural lakes, for the purpose of research and management, all these water bodies should be classified and studied under lakes only, while still keeping in mind their technical differences.

HYDROLOGICAL DEFINITION OF LAKE

The matter of precise definition of a lake is yet to receive adequate attention and a unique definition of natural lake does not exist. Most of the text books on lake start without actually attempting to define the object they are going to deal with. As early as in 1952 Zumberge defined a lake as "an inland basin filled with water". But this definition was too general and as is obvious includes ponds also in its scope. Since tanks and reservoirs are easy to differentiate from lakes, being artificially created, the problem really is to differentiate a lake from a pond. This is because both of them are natural in origin and moreover, lakes in their natural course of extinction, due to processes of sedimentation and eutrophication, actually turn into ponds. So, Welch (1952), in the same year, suggested some size restriction while differentiating lakes from ponds. The former he suggested should have "an area of open, relatively deep water, sufficiently large to produce somewhere on its periphery, a barren swept shore". In contradiction are ponds which according to him are "very small, very shallow bodies of standing water in which quiet water and extensive occupancy by higher aquatic plants are common characteristics" . Since, exactly where the cutoff in size comes has not been defined by Welch, so, Zumberge and Ayers (1964) defined the lake as "an inland basin filled or partially filled by a water body whose surface dimensions are sufficiently large to sustain waves capable of producing a barren wave swept shore. However, as they have themselves suggested, "a really quantitative definition of a lake may well require some recognition of Welch's stipulation of a wave swept shore, possibly expressed in terms of some numerical index containing maximum wave size". Such an index is yet to be established even after four decades after its suggestion. An arbitrary size of 0.01 sq. km is suggested by some researchers to demarcate between a lake and a pond. All the existing definitions however, appear in agreement on inclusion of only inland water bodies in the category of lakes and hence, lakes having regular intrusion of sea water are not considered as lakes. Thus, despite its name Lake Chilika is not a lake.

LAKE AS A HYDROLOGIC UNIT

Lakes form an important component of the Hydrologic cycle. The precipitation falling over the earth ultimately reaches the oceans and is evaporated back to the atmosphere not before it visits lakes through the rivers and streams. In case of closed lakes, water is directly evaporated without meeting the oceans unless and until there is a considerable seepage to other open water body or stream. Calculated on the global basis, the residence time of lake is 21 years and that of river is 2.1 years. Thus, lakes provide a natural storage without artificial barrier for water, during their movement in the hydrologic cycle. The lake storage is easy to visualize because lakes have definite boundaries. Such boundaries are not definite in other types of storage in the hydrologic cycle. The lake storage provides a viable means to accelerate or enhance recharge of known ground water supplies.

Hydrologic characteristics of lakes vary considerably because of differences in the depth, length, width, surface area, shape, basin material, climate, nature of inflows and outflows, and other factors. Lakes may have some common features but often exhibit strikingly different performance characteristics. This individuality has environmental values and as such it presents the problem of having to understand both the general nature of the system and variations due to local conditions. This means that each lake requires it own hydrologic model but these models need to be characterized by different degree of variance from a generalized conceptual model.

Lakes, especially if they are large, can influence the surrounding climate. Large lakes owing to their volume have more capacity to accept heat. This heat storage in lakes act to stabilize the air temperature, minimizing and lagging variation in adjacent region, both in summer and winter.

The relative lack of motion of the lake water also makes the lake basin a sediment trap. Sediment bring nutrients with them which hastens the growth of aquatic plants causing eutrophication. These processes fill the lake slowly turning them first into ponds and swamps and then into marshy lands ultimately into a terrestrial land causing their extinction. As such, lakes are only transitory features of the earth surface. Each lake has a birth, life and death. The life expectancy of the lake may vary from a short spell between two floods to million of years.

LAKE AS AN ECOSYSTEM

A lake is an ecosystem in itself. A lake ecosystem, like any other ecosystem, has both living (biotic) and nonliving (a-biotic) components. (Fig. 1). The physico-chemical properties of the lake water and the various physical phenomena such as radiant energy, water motions etc form the abiotic environment while the lake flora and fauna form the biotic component of the lake ecosystem. The living components fix, circulate, transform and accumulate the energy and matter by photosynthesis, decomposition, herbivory predation, parasitism and other activities, forming complex food webs. The nonliving components flux and cycle the energy and matter through hydrological processes such as evaporation, precipitation, erosion and deposition and water movements. Solar energy is the only significant source of energy for the lake ecosystems.

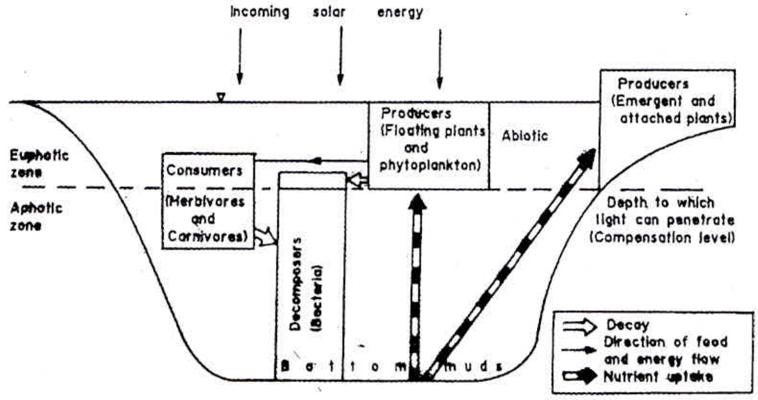

Fig.1. The lake ecosystem

Unlike most terrestrial ecosystems, the lake ecosystem has definite boundaries. The shoreline serves as the lateral boundary. The air-water interface as the upper boundary and, the maximum sediment depth as the lower boundary. Lake ecosystems are open ecosystems relative to various fluxes, and as such their metabolism and biochemistry strongly reflect the inputs and outputs of energy, water and chemicals from their surroundings. Input and output of energy and matter from lakes further connect the lake ecosystem with other ecosystems in the biosphere (lake-catchment interaction).

LAKE MORPHOMETRY

Lake morphometry deals with quantification and measurement of lake forms and form elements (shape and size). Morphometric data are of fundamental importance in many limnological and hydrological studies. As a matter of fact they are the starting points for many investigations. For example any water balance, heat balance of, nutrient study requires the knowledge of storage capacity and volumes of lakes. As such the estimation of the depth-area-capacity relationships is the fundamental requirement of these studies. A number of parameters and indices exist to indicate the size and shape of the lake basins. Some important ones are described below:

Lake Area (A): the area of the water surface
Total Lake Area (A_t) : the lake area plus the area of the islandislets and rocks within the limits of the lake shoreline.
Lake Volume (V): volume of the water in the lake
Maxium length (L_{max}): the line connecting two most remote points on the shoreline
Maxium effective length (L_e): the stright line connecting the two most distant points on the shoreline overwhich wind and waves may act without interuptions from land or islnads.
Effective length (L_s): The straight line from an arbitrary position on the lake to the most distant point on the shoreline without crossing land or islands, which may reduce the impact of wind-induced waves.
Effective fetch (L_f): The length of straight lines from an arbitrary position on the lake to the shoreline points averaged over directions, which deviate less than 45 degrees from the main wind direction.
Maximum width (B_{max}) : The straight line perpendicular to the maximum length, which connects the two most remote points on the shoreline without crossing land (islands may be crossed)
Maximum effective width (B_e): the straight line perpendicular to the maximum effective length, which connects the most distant points on the shoreline without crossing land or islands.
Maximum depth (D_{max}): greatest depth of the lake
Mean depth (D_{av}): lake volume (V) divided by lake area (A)
Hypsographic curve: depth-area curve for the lake
Shoreline length (l_0): length of the circumference of the lake
Total shoreline length(l_t): the shorline length plus the length of the cicumference of all islands and islets.
Shore development (S_d): it is a measure of degree of irregularity of shoreline. It is given by

$$S_d = \frac{l_o}{2\sqrt{\pi A_t}}$$

Lake bottom roughness (R) : a measure of the degree of irregularity of the lake bottom. It is given by

$$R = \frac{0.165(l_c + 2)\sum_{i=0}^{n} l_i}{D_{50}\sqrt{A}}$$

where,

l_I = length of the i^{th} depth contour
l_c = contour line interval

Volume development (V_d): it's a measure used to illustrate the form of the lake basin. It is defined as the quotient between the lake volume and the volume of a cone whose base area is equal to the lake area (A) and whose height is equal to the maximum depth (D_{max})

$$V_d = \frac{3D_{av}}{D_{max}}$$

It should be noted that most of the morphometric parameters have at least a slight dependence on the fluctuations of water level. For those parametrs which are strongly affected the water level should be specified. Sedimentation in the lake also changes the values of many parameters. In small lakes and reservoirs even the the annual changes may be considerable.

PHYSIO-DYNAMIC PROCESSES IN LAKES

Water Balance of Lakes

Lake waters are used for variety of purposes including the developmental activities. For the success of these programmes a regular, timely and required supply of water is essential. This is possible only with accurate estimation of the available water at any specific time to meet these demands. Thus, water balance studies enable to plan the various uses of the lake water. Water balance studies are also prerequisite to the nutrient budgeting and hence, for quantitative assessment of the eutrophication problem.

The water balance of a lake is illustrated in Fig. 2. It is basically same as the water balance of any drainage basin. It is the statement of law of conservation of mass (continuity equation). A simple water balance equation for a lake can be written as:

$$\Delta S = I_s + I_u + P_l - Q_s - Q_u - E_l$$

where,

ΔS = change of water storage
I_s = surface inflow
I_u = underground inflow
P_l = lake precipitation
Q_s = surface outflow
Q_u = underground outflow
E_l = lake evaporation

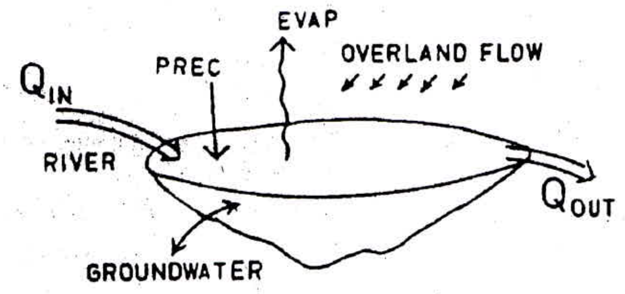

Fig. 2: Water balance of a lake

Precipitation on the lake is generally not different from precipitation over the surrounding land except in case of very large lakes which affect the local climate and there by, also the precipitation on land. Thus, precipitation into a lake is usually measured by the rain-gauges located near or around the lake. 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. However, this portion is usually very small and neglected. Continuos observations of discharge should be carried out for as many inflowing rivers as possible. Surface outflow should also be measured directly. Stage discharge relationships can also be created for surface inflow and outflow. Evaporation is the most difficult component to estimate accurately. A number of methods are available to estimate lake evaporation. Energy balance method is considered to be the most accurate of all the available methods. However, estimation of energy balance terms requires intensive instrumentation, which is often not economically feasible. The most popular of the other methods are the methods based on the pan evaporation and the Penman method. The popularity of pan method is because of the fact that it is simple to use and also the data availability is generally met. However, the pan method requires locally available monthly pan coefficients. Change in lake storage can be estimated from water levels using the hypsographic curve. In the absence of hypsographic curve this term is generally estimated as residual. Groundwater components are generally neglected in lake water balance studies owing to the difficulties in their estimation. However, ground water components can be very significant in some lakes and hence, should be considered. The groundwater components can be determined by measuring ground water tables and some mapping of the lake/aquifer contact zone.

Although the water balance equation looks simple, its practical application poses many difficulties causing errors in estimation of different components. The errors in lake water balance components can be broadly classified into two groups: (i) errors of measurement and (ii) errors of regionalization. Selection of units is also important in water budgeting. If the area of the lake varies considerably as a function of water level, a volumetric unit is preferable. For lakes with a practically constant surface area, it is more convenient to express water components as the depth of a layer.

Lake Evaporation

Estimates of evaporation rates are very important and are needed for various purposes such as water resources planning and management, water availability studies, heat balance studies, temperature modelling etc. When the radiant energy is supplied to the lake water, kinetic energy of the water molecules is increased. When the water molecules attain enough kinetic energy, they escape from the water body overcoming the intermolecular forces and eject themselves into the atmosphere. The amount of energy expended by a unit mass of water while passing from liquid to vapour state at constant temperature is called the heat of evaporation or the latent heat of vapourization. If external energy is not made available, energy is removed from the water body while evaporation is taking place resulting in lowering of water temperature. Thus, evaporation is indirectly a cooling process. Continuous supply of heat energy causes accumulation of more and more vapour molecules increasing the partial vapour pressure. This continues till the level of saturation vapour pressure is reached and water molecules are rejected in the form of condensation. If the vapour pressure of air above the free water surface is already equal to saturation vapur pressure, neither evaporation nor condensation takes place and it is said to be in equilibrium state. However, in practice an equilibrium stage never exists under normal conditions. This is because the atmosphere into which evaporation takes place, is infinite and various transport processes will also operate to transport the vapour in the atmosphere both parallel as well perpendicular to the lake water surface and prevent equilibrium from occurring.

From the above description it is clear that, under given conditions, evaporation is proportional to the vapour pressure deficit. It was first recognized by Dalton in 1802 (Daltons Law). Thus,

$$E = c(e_s - e_a)$$

where,
E = lake evaporation, e_s = saturation vapour pressure, e_a = actual vapour pressure, c = a coefficient to account for the other factors which affect evaporation.

Evaporation is a very complex process. A variety of meteorological and physical factors affect the rate of evaporation from a lake. These include radiation, temperature, humidity, wind and atmospheric pressure, water quality, size and shape etc. However, it is very difficult to quantitatively assess the relative importance of each of these factors.

Ground Water-Lake Interaction

Interaction of lakes and ground water is one of the least understood components of the lake system. It is often neglected in most water balance studies. However, it is very important with respect to water balance. Moreover as a carrier of the non-point source of pollution, it can be significant contributor to the lake water quality. To understand ground water-lake interaction, it is necessary to define the boundaries of the groundwater system interacting with the lake, for example the thickness and extent of the geologic units comprising the system. It is also necessary to define the internal characteristics of those units, such as hydraulic conductivity, storage coefficient, porosity and secondary porosity such as fracture patterns. In addition to these physical characteristics, it is necessary to define and monitor the distribution of hydraulic head within the ground water system relative to lake level. To determine the distribution of head, the configuration of the water table (the upper surface of the saturated zone) in the drainage basin of the lake needs to be defined using the a network of water-table wells. Such wells are constructed so that they penetrate only the upper surface of the ground water system. In addition, group of piezometers are needed to define the vertical gradient of hydraulic head within the ground water system at selected locations in the basin.

Surface Heat Budget and Internal Heat Transfer

The energy balance of lake and the internal heat transfer processes are illustrated in Fig. 3. The surface heat balance equation for a lake can be expressed as follows:

$$\Delta H = H_s - H_{sr} + H_l - H_{lr} - H_b + H_e + H_c + H_p$$

where,

ΔH = net energy flux
H_s = incident short-wave radiation
H_{sr} = reflected short-wave radiation
H_l = incident long-wave radiation
H_{lr} = reflected long-wave radiation
H_b = back radiation
H_e = latent heat flux
H_c = sensible heat flux

H_p = heat flux from precipitation

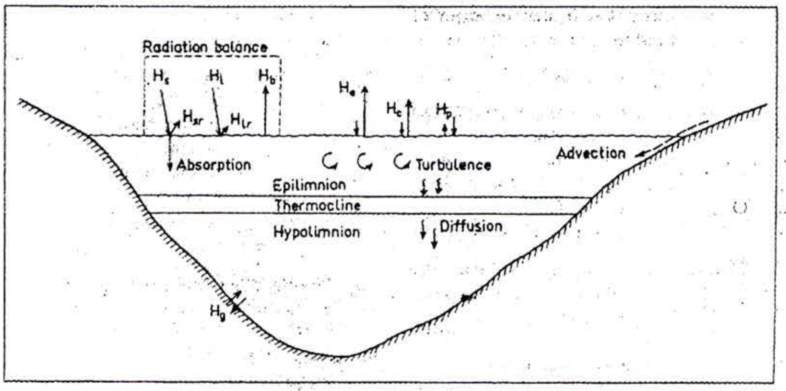

Fig. 3: Energy balance of a lake and internal heat transfer processes

The above equation is based on the law of conservation of energy. As such the change in heat stored in the lake has to be balanced by the heat inputs from radiation to the lake and the loss of heat energy from the water body. Most of the terms of the radiation balance are self explanatory. Net radiation can be either measured directly or estimated from various empirical equations which are available in standard text books. Solar radiation (incoming short-wave radiation) passes through the atmosphere with relatively little absorption although considerable scattering occurs. At the lake water surface some of this insolation is reflected. The reflectance of water (albedo) is very low (0.03-0.1). The lake water also emits long-wave radiation because of its temperature. It is called back radiation. This long-wave radiation is re-radiated (reflected) by the clouds and atmosphere as reflected long-wave radiation. Latent heat flux denotes the transfer of heat from the lake to the atmosphere associated with evaporation. Transfer of sensible heat between a lake and the atmosphere takes place by a combination of conduction and convection. Heat is transferred across the water surface by conduction to or from the air at the air/water boundary. This conduction occurs only in very thin layer of air at the boundary itself and depends on the temperature gradient across that boundary. Beyond this region sensible heat is transferred by turbulence or connective processes both in the air and the water. The relative importance of the components of the heat balance shows distinct climatic, seasonal and diurnal variations.

There are a 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 distribution in the lake and affect essentially the chemical and biological characteristics. The different processes of internal heat transfer are:

(a) Absorption of short-wave radiation : while all the long-wave radiation is absorbed very near the surface, solar radiation can be transmitted to a depth of several tens of meters.
(b) Wind induced mixing: This is by far the most important process of internal heat transfer in many lakes. If the lake is unstratified, the influence of wind reaches to the whole water mass. If a thermocline is developed, a certain fraction of kinetic energy of the wind is converted into potential energy which deepens the thermocline. Wind also causes horizontal

mixing.

(c) **Advective mixing**: The flow patterns due to inflows and outflows redistribute heat in the water mass. Advective currents are mainly horizontal.

(d) **Convective mixing:** An unstable density stratification results in turbulence and mixing. This causes redistribution of the heat.

(e) **Diffusion**: Molecular diffusion transports heat whenever a temperature gradient exists. Turbulent diffusion occurs as a consequence of fluid motion. Thus, former type depends on the properties of the lake water while the latter on the water motions.

The relative importance of the various processes varies. In some cases one or several of the processes are negligible; for example advection in a very large lake or wind induced circulation in ice covered lakes. In some lakes none of these processes of internal heat transfer are effective enough to cause considerable warming in the deeper parts of the lake. If the amount of heat energy received by the water surface is large, this leads to a strong stratification.

Thermal Regime

Relationship between the water and temperature is one of the most striking phenomenon of lakes. This relationship is observed in seasonal variations. In many lakes these variations take the form of pronounced changes in the overall thermal structure and dynamics. Climatic characteristics of a region and morphometric parameters of a lake determine the thermal behaviour of its water mass to a large extent. Various other processes involved are the absorption of heat, heat dynamics, density phenomenon and wind action. Thus, a detailed description of the thermal processes in a lake requires the study of extremely complex interaction of many physical phenomena. The thermal regime of the lake can be best appreciated by considering the annual thermal cycle.

The density of water being primarily a function of its temperature, changes with change in temperature. If less dense water becomes overlain by more dense water, convection or water overturn takes place. The behaviour of water when heated from 0^0C to 4^0C is unusual. Unlike most other liquids, where density decreases on heating, density of water actually increases from 0^0C to 4^0C. The maximum density is attained at 4^0C and further heating decreases the density. Because of this unique temperature density behaviour of water, it undergoes thermal stratification forming layers or zones of different densities. The uppermost layer is called the epilimnion and the bottom, relatively deep layer is called hypolimnion. Between these two layers is a zone of rapid temperature drop called thermocline or mesocline which is generally 2 to 3 meter thick. A thermal cycle of a temperate lake is illustrated in Fig 4 and Fig.5.

Knowledge of the water temperature and thermal regime of the lake is essential to understand various processes. Thermal structure is the frame for all the biogical life. Temperature at different depths essentially affects the kinetics of biochemical reactions and solubility of different gases in the water. Vertical transport of different chemical species is mainly due to diffusion. The transport rate diffusion is strongly related to temperature gradients. Temperature gradient also has a significant role in the process of mixing. Vertical temperature distribution has a dramatic effect on the spread of pollution.

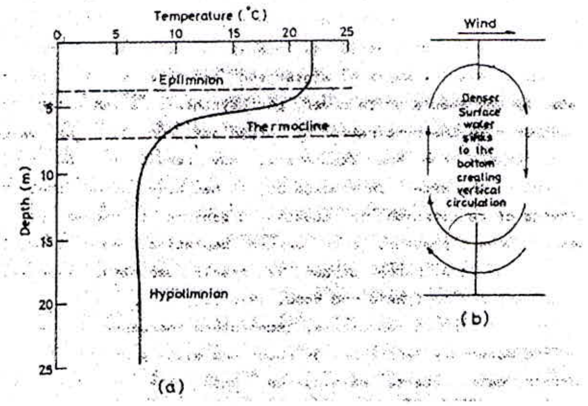

Fig. 4: Temperature profile of a typical temperate freshwater lake in summer

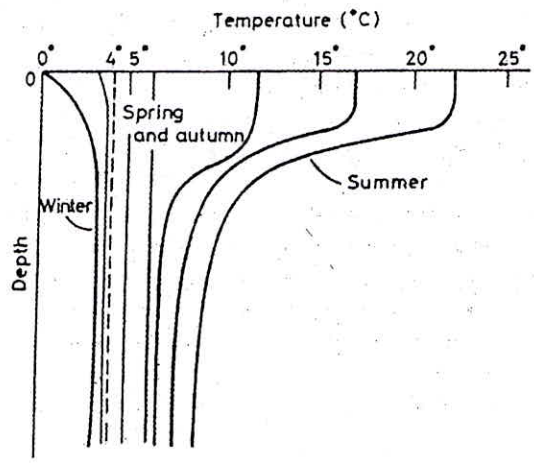

Fig. 5: Schematic evolution of temperature versus depth profiles over the year for a typical dimictic lake of temperate climate

Eutrophication

At birth, lakes are deficient in nutrients and hence, are unable to support aquatic life. At this stage they are referred to as oligotrophic water bodies. With passage of time nutrients brought by sediments from the catchment get accumulated in them and their productivity increases. Through bacterial and other decompositions of the sediments, the water bodies become rich in nutrients on which phytoplankton thrive. With increase in phytoplankton and food supply, the zooplankton and other forms of animals also increase. Thus, with increase in species diversity and biological productivity, these water bodies pass from oligotrophic phase through the mesotrophic phase into the eutrophic phase (Fig. 6). Eutrophication, thus, denotes the addition of nutrients and consequent increased productivity level of a water body. It describes the biological effects of an increase in concentration of plant nutrients, usually nitrogen and phosphorous, but sometimes others such as silicon, potassium, calcium, iron or manganese, on the aquatic ecosystem. It represents the natural aging process of the lake. This process usually takes many hundreds of thousands of years to occur. Lakes undergoing such a natural eutrophication generally have a good water quality and exhibit diverse biological community throughout much of their existence. However, human interference in the catchment changes the natural eutrophication dramatically through increased rates of nutrient input. This artificial eutrophication is called cultural eutrophication and, is the main cause of concern for most lakes.

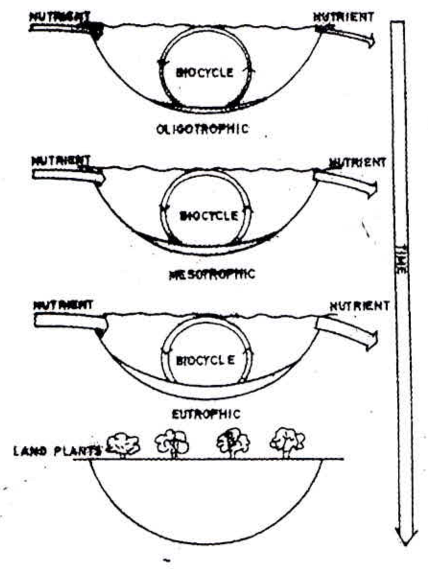

Fig. 6: Different stages leading to eutrophication in lakes

Nutrients are added to the lake water primarily through the lake catchment and the atmosphere. The nutrient sources may be point or non-point. The principle sources of nutrients (Fig. 7) are municipal wastes, industrial wastes, agricultural runoff, forest runoff, Urban and sub-urban runoff and atmospheric fall outs.

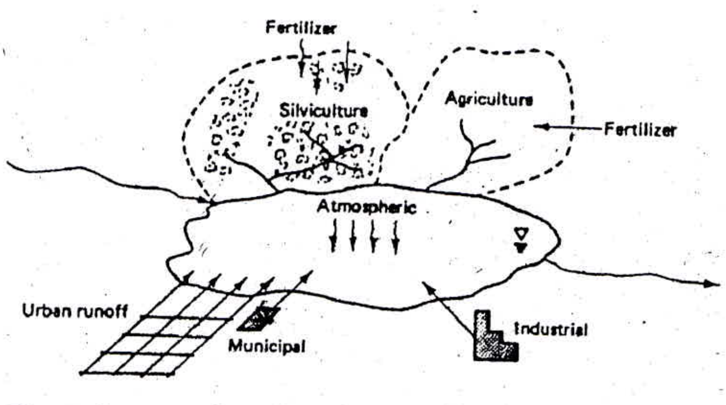

Fig. 7: Sources of nutrients in eutrophication problems

Fig. 8 describes the basic process of phytoplankton-nutrient interaction. The inorganic nutrients brought to the lakes are used by the aquatic plants and converted into organic plant material through the process of photosynthesis. The energy for photosynthesis is supplied by the solar radiation. As the water temperature increases, the nutrients in dissolved form are utilized by the plankton causing an increase in the phytoplankton biomass. This process continues until nutrients reach levels that will no longer support the growth and increase in phytoplankton biomass ceases. Decline in phytoplankton biomass is then observed, mainly due to predation by zooplankton. Nutrient recycling again causes the bloom. Thus, eutrophication of a lake/water body depends upon the geographical location of the water body, degree of penetration of the solar radiation to different depths, magnitude and type of nutrient inputs, and the particulars of water movement through flow transport and dispersion.

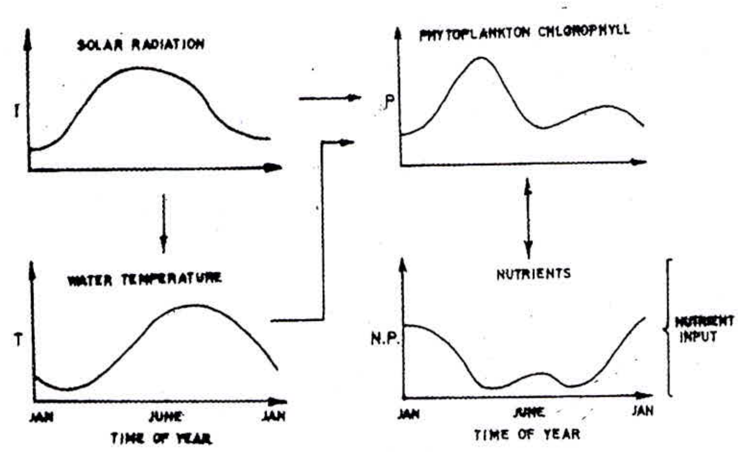

Fig. 8: Basic process of phytoplankton-nutrient interaction

Eutrophication has very serious consequences for the lake water use. Eutrophication produces an excess of algae and macrophytes in water bodies that can cause certain water use problems in water supplies, corrosion of hydroelectric equipment and upsets of different water treatment processes due to the reduction of the dissolved oxygen content, Clogging of water treatment plants, accumulation of ammonia in the water columns and resuspension of certain metals (Fe, Mn) from the sediments under anaerobic conditions. In eutrophied reservoirs, the high level of organic substances combined with the application of chlorine for drinking water supplies can generate substances potentially harmful to health. Toxins produced by cynobacteria can also be a health concern. The increased production of aquatic plants, particularly macrophytes cause such as aesthetic and recreational interferences. There are also problems related to odour and taste. Eutrophication can also cause death of fish due to reduced dissolved oxygen.

Sedimentation

Sedimentation is one of the serious problems of many lakes causing reduction in lake capacity and useful life of the lake. As such the knowledge of lake sedimentation process is very essential for control and management of the lake sedimentation. It is also essential for understanding the ecological behaviour of lakes. Although high concentrations of suspended matter may result in low primary production because of restricted light penetration, supply of excess nutrients to lake through sediments however, increases its productivity. The availability of dissolved oxygen in lakes may be limited due to high sediment oxygen demand. Benthos and fish are affected not only by the suspended sediments but also by the modification of habitat caused by depositional sediments. The chemical and biological activities of sediments produce heat, contributing to the heat budget of the lake. Sedimentary processes may also cause changes in the lake basin forms. The sediment character controls the chemical composition of the lake water. So, the interaction of sediments with the lake water, both within the water column and at the bed of the lakes, controls the quality of the surface water. Sediment also contains biological life. It is a substrate for bacterial activity.

Nature of sediments depends upon the rock type in the drainage basin. Siltation rates are mainly dependent upon conditions in the drainage area. Other factors include morphological and hydrodynamic factors. Effects of drainage basin are mainly due to morphology, climate and land use. There are three main sources of sediments for lakes. Water and wind are the main natural agents which bring sediments into the lake. Organic matter produced in the lake is an internal source. Besides, there is also a problem of re-suspended bottom material.

The bed load brought by the river is initially deposited preferably on shallow water near the shores. Fine particles have low settling velocities and are kept in suspension by the water motion. The movement of sediment inside the lake is decided by the water motions. In most lakes wind is the most important flow generating mechanism. Wind exerts a shear stress on the lake water surface and the resulting momentum transfer causes the surface water to move in the direction of wind. Part of the stress maintains the wave pattern and part of it produces mean water motion. If the duration of the wind is sufficiently long, the wind stress leads to inclination of the water surface. When the wind velocity becomes small or its direction changes, the readjustment of the water surface takes place as an oscillatory motion. This standing wave is called seiche.

Fine material from the lake bottom is eroded and brought into suspension by influence of waves and currents. The shallow bottoms from which fine loose material is stirred up at every storm and where there are no extended periods of deposition are called erosion bottoms. Transportation bottoms prevail where fine material is deposited but where erosion takes place during severe storm. Areas where fine material is deposited and erosion never occurs are called accumulation bottom. In shallow lakes there are no accumulation bottoms where material can deposit. The bottom sediments close to the shores as well as in the central parts of such lakes are a mixture of fine and coarse material.

Re-suspension of the settled sediments is basically governed by the balance between hydrodynamic forces seeking to move the particle and the stabilizing forces due to gravity. Wave action is the dominating force for resuspension in lakes. Once the sediments have been re-suspended, they will be redistributed in the lake according to the current pattern and diffusive character of the flow. When the energy level is reduced due to decrease in the wind speed, then the sediments will settle to the bottom. The result is that basically the near shore areas will be void of fine sediments. They will gather in the deeper areas. The shape and depth of the lake basins affect the circulation of water and thus the distribution and deposition of fine sediment particles.

The amount of sediment carried by the incoming river can be measured or estimated from models. However, the amount of locally produced material and re-suspended sediments can not easily be determined. Long term sedimentation in a lake is best determined by comparing bathymetric maps from different years. The sediment rate over the shorter periods can be determined using sediment traps. These can be bottom placed or floating. To get representative values for the lake they should be placed on accumulation bottom and for the floating ones, 1-2 m above the bottom. Isotopes techniques are recently becoming popular for estimation of sedimentation rates in lakes.

CLASSIFICATION OF LAKES

Lakes are very complex hydrologic systems. A number of physical, chemical, biological and hydrological factors interact with each other in complex interrelationships, to define the ecological behaviour of a lake. The varying geometry of each lake and the varying geography and geology of their catchments further add to the complexities. Classification is an attempt to bring together lakes with similar behaviors in one group so that results of research findings on a lake, can be applied with confidence, to other similar lakes of that particular group.

Various schemes of lake classification are in existence for variety of purposes. Some of the important classification schemes are described below:

(A) Classification Based on Region

Based on the region (latitudes and related temperature variations) lakes are classified as tropical lakes, temperate lakes and polar lakes. Lakes having temperature ranges intermediate to those of tropical zones and temperate zones are called sub tropical lakes. Lakes having temperature ranges intermediate to those of temperate zones and polar zones are called sub sub-polar lakes. However, since within a region the climate would vary depending upon the altitude also, so a dimension of altitude is sometimes added to the above classification and lakes are classified as low altitudes lakes and high altitude lakes. Thus, we also have classes likes low altitude tropical lakes, high altitude tropical lakes etc. However, the boundary to demarcate between the various altitudes is not defined.

(B) Classification Based on Origin

An exhaustive classification of lakes based on their origin is presented by Hutchinson (1957) who divided the lake into 11 major categories and 76 sub categories. It is beyond the scope of this lecture notes to discuss all those classes. Some of the important classes are Tectonic lakes, Volcanic lakes, Glacial lakes, Solution lakes, Lakes formed by stream action, Lakes formed by wind action, Lakes formed by shoreline processes, Lakes produced by landslides, Lakes formed by organic accumulation, Lakes formed by activity of higher organisms and Lakes formed by impact of meteorites. Lakes whose origin is not known or can not be covered under any of these categories are clubbed as Lakes of unknown origin.

(C) Classification Based on Thermal Regime

Thermal classification involves classifying the lakes on the basis of stratification, mixing and number of overturns per year. The lakes are mainly classified as:

(i) **Amictic lakes** : These lakes are completely insulated from outside influences of water and other factors because of the permanent ice cover. There is no mixing of water.

(ii) **Holomictic lakes**: These lakes are wholly mixing that is circulation in complete and extends up to bottom.

(iii) **Meromictic lakes:** These lakes are permanently stratified and therefore do not circulate completely throughout the year. The stratified bottom never circulates.

(iv) **Polymictic lakes**: in these lakes mixing is continuous.

Holomictic lakes are further classified as Dimictic lakes and Monomictic lakes. Dimictic lakes undergo two overturns per year. In Monomictic lakes there is only one overturn per year. Monomictic lakes may be either Cold Monomictic (overturn in summer) or Warm Monomictic (overturn in winter).

(D) Classification Based on Trophic Status

Trophic status describes the productivity status of lakes based on nutrient concentrations, alagal population etc. Based on the trophic status, three major categories of lakes are identified.

(i) **Oligotrophic lakes :** lakes with lowest trophic level, low level of nutrients and clean water

(ii) **Eutrophic lakes**: Lakes with highest trophic level and high concentration of nutrients and plankton. Water is murky.

(iii) **Mesotrophic lakes**: Lakes with intermediate properties between those of oligotrophic to eutrophic lakes.
It needs to be mentioned that trophic status is not an absolute term but a relative term. Different workers have given different schemes from trophic status boundaries based on different parameters.

(E) Classification Based on Chemical Properties

Based on the chemical nature of the lake water, and calcium contenet lakes have been variously classified. Thus, based on the chemical nature of the lake water lakes can be acid lakes, saline lakes or fresh water lakes. Based on the calcium carbonate contents they are classified as soft water lakes, very hard water lakes, hard water lakes and medium water lakes.

(F) Classification Based on Presence of Outlets

Based on the presence of outlets, lakes are classified as open lakes and closed lakes. Open lakes (also called exorheric) are those lakes that have some form of outlet, while closed lakes (also called endorheric lakes) do not have any outlets. They lose water only by evaporation and do not have any significant seepage loss. A third category called ephemeral lakes is also added sometimes. These are intermittent to open and closed lakes. In these lakes there is an outflow but only during high water stages. Seepage lakes are a type of closed lakes, where a considerable water is lost through seepage, besides evaporation.

(G) Classification Based on Nature of Inflow:

Based on the nature of inflow, a lake can be classified as seepage Lake or a drainage lake. A seepage lake is a one which do not have any stream draining into it. They are recharged by ground water only. On the other hand drainage lakes have surface water as the main input.

(H) Classification Based on Morphometry

Lakes are also classified based on the morphometric parameters such as shape, size, depth, area, volume etc. Based on the shape lakes are broadly classified as irregular shaped lakes and geometrically shaped lakes. The geometrically shaped lakes are further divided as circular lakes, sub-circular lakes, elliptical lake, sub-rectangular lake, dendritic lakes, triangular lakes and lunate lakes.

Based on surface area or volume, lakes are generally classified as small lakes, large lakes and very large lakes. Similarly based on the average depth, very shallow, shallow, deep and very deep lakes. However, exact boundary conditions in the case of area, volume and depth do not exist.

TEMPERATE LAKES VERSUS TROPICAL/SUB-TROPICAL LAKES

Of interest to the lake hydrologists in India should be the differences in the hydrology of the tropical/subtropical and temperate lakes. Temperate lakes and tropical/subtropical lakes have different climatic setting. This affects their ecological and hydrological behaviour. Compared to the temperate zone, tropical lakes and reservoirs are characterized by highly seasonal (predominantly summer) rainfall and a more limited annual temperature cycle. The mean annual temperature (approximately 25°C) is higher than in an temperate zone which is approximately 10-15°C. In temperate climates lake water temperature in winter always drops down below 4°C. Because of the unique behaviour of water below 4°C, lakes undergo thermal stratification and seasonal overturns. This peculiarity is not observed in low altitude lakes in tropical climates. Thus, lakes in temperate climates are stratified twice a year (once in summer and winter each). Lakes of the tropical climates do not generally develop stable stratification because the seasonal temperature variations are not pronounced. However, weak stratification is sometimes observed in summer in some lakes of this region. But they are easily destroyed by the action of wind. Lakes in the subtropical climates and the high altitude lakes in the tropical climates, if they have sufficient depth, however, develop stable stratification and remain stratified once during the summer with overturn taking place in the winter. Thus, in most of the shallow lakes at lower elevations in India, thermal stratification is not observed. In few lakes, however, a weak and unstable stratification of temporary nature is observed. In deep lakes at higher altitudes like the Kumaun lakes and the Kashmir lakes, however, stable stratification is observed during the summer.

WHAT IS LAKE HYDROLOGY?

Lake hydrology literally means hydrology of lakes. However, as far as the technical definition is concerned, the term lake hydrology has not been defined as yet in the literature. In my view, it can be comprehensively described as ***"that branch of hydrology which studies the various***

***physical and dynamic processes occurring within the lakes and their catchments, including the inter-relationships between the two, for their proper conservation, restoration and management, for the welfare of the human beings and other biological species*"(definition given by me).**

The term limnology is also related to lake studies. What is limnology? How does lake hydrology differ from limnology? Limnology is defined as the study of all types of fresh waters including lakes. However it does not study saline lakes. Since hydrology deals with all aspects of water, lake hydrology as one of its specialized sub discipline also studies all types of lakes including the saline lakes. More over, since the word "lake" is being used as a synonym for reservoirs, tanks and ponds also, the studies related to these water bodies also form part of the lake hydrology studies. However, the important question is what is the difference in the subject matter studied by the two disciplines when both study lakes? A scrutiny of the subject matter of both the disciplines bring out that the difference lies in the nature of the subject matter. While, limnology emphasizes the biological and ecological aspects of lakes, lake hydrology emphasizes the physical and dynamic processes in lakes and their catchments.

WHY STUDY LAKE HYDROLOGY?

Lakes serve variety of purposes. However, because of their socio-economic significance they have been quite often over exploited leading to qualitative and quantitative deterioration. Growing human interference in the catchment further aggravates the situation increasing the number of problems of the lakes. This has posed a serious threat to their survival and many lakes have been reported to have undergone quantitative and qualitative deterioration and even untimely extinction.

Problems of the individual lakes vary. Each lake will have its own set of problems depending upon its morphology, climate of the catchment, land use in the catchment, degree of human interference in the catchment and use of the lake water along with other environmental factors. Thus, some lakes particularly in arid and semi-arid regions, may face the problem of heavy evaporation and reduced inflows and may even dry out completely in summer as in case of some lakes in Rajasthan. Lakes, which support exclusive flora and fauna, may face threats to their ecological balance if the lake water management is not proper or if there is eutrophication problem. Many lakes, which are used by the industries for cooling purpose, suffer from thermal pollution. Most of the problems are lake specific. However, there are certain problems which are more or less common to many of the lakes in India. These include problems like pollution and water quality deterioration, sedimentation, eutrophication etc. Addition of organic and inorganic material from the industrial effluents, residential and agricultural areas and domestic sewage leads to the problem of pollution and subsequent water quality deterioration. Excessive deforestation in the catchment cause erosion of the soil in the catchment and leading to problem of siltation. Due to siltation the capacity and life of the lake decreases till it is completely filled up. Sediments also carry nutrients with them causing eutrophication. Eutrophication puts constraints on various uses of water and also ultimately turns a lake into a marshy area. Although it is true that all natural lakes have a definite life span and as such, are bound to have a natural death also, but their extinction is hastened by the processes of eutrophication and sedimentation. As such the lake water resources are getting depleted with time.

With decreasing quantity of available fresh water and increasing demand due to exponential growth in the population, proper conservation and management of all the fresh water resources including lakes has gained great significance in recent years. Moreover, the management has to be efficient, economic and environmentally friendly. This is not possible without a proper understanding of the hydrological and ecological behaviour of lakes. This behaviour depends on the complex interaction of the many physical and dynamic processes occurring within the lakes, their response to various forms of energy inputs, their interaction with the biotic life and also with the catchments. This is also because lake is an ecosystem in itself and most of the hydrological and ecological processes are interrelated directly or indirectly. For example, quantitative assessment of the problem of eutrophication is not possible unless a complete knowledge of the water balance, nutrient balance and nutrient dynamics of the lake is had. Thus, lake hydrology research endeavors to understand the various lake processes and their interrelationships and to develop models to describe them. The ultimate objective is to develop efficient techniques and methodologies for the restoration, conservation and management of the lake water for the society. It is for these reasons that one needs to study lake hydrology in totality and the various components of the lake hydrology, individually.

LAKE HYDROLOGY IN INDIA

Lakes have a history of research probably as old as the civilization itself in the sense that many lakes were artificially created during even the ancient times. However, a true scientific beginning of lake studies is probably not more than one and a quarter century old. India, too, has a history of lake research of well over a century. Studies on Kumaun lakes were reported as early as in the late nineteenth century. Original studies on Kumaun lakes were mostly on the geological origin of the lakes. The spectrum of lake studies slowly expanded. Initially it included the studies on the fauna and flora of the lakes. In the second half of the present century the analysis of the physico-chemical characteristics of the lake and their interaction with the biotic components gained momentum and even today remains one of the most significant aspects of lake studies in India. As such lake studies in India have always had a definite bio-limnological bias. This is because most of the studies are credited to the biologists. As such, mostly the bio-chemical, eutrophication and pollution aspects of the lakes are reported to be studied. The hydrological aspects of lakes are only occasionally addressed to. Few scattered studies are only reported on these aspects but compared to the total lake studies their number is very less. Most of the studies are related to the Himalayan lakes and only a handful of them are on the tropical lakes of arid and semi arid regions. However, with a growing concern for conservation and proper management of lakes, the significance of lake hydrology research is now being felt, especially since the last decade or so. More and more hydrological studies are now being reported. But the research is still in its budding phase and a lot more still needs to be done.

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