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CLASSIFICATION OF LAKES AND INVENTORY OF NATURAL LAKES IN INDIA

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PREFACE

Lakes are important hydrologic entity having definite boundaries and are easier to visualize unlike other types of storage in the hydrologic cycle. They contain over 95% of the earth's fresh liquid surface water. Lakes are transitory features of the earth surface and each has a birth, life and death. The life span of a lake may vary from a short spell of few floods to millions of years. It is reported that there are almost three million lakes and most of them are located in the Northern hemisphere.

Lake hydrology is a new area and some studies on evaporation, sedimentation and quality aspects on piecemeal basis have been done. In order to view and understand it in a totality in the hydrologic cycle to conserve water in terms of quantity, quality and regimen, understanding of hydrology of lake is essential and work has been initiated. The first report in this area entitled "classification of lakes and inventory of natural lakes in India" is a technical note and an attempt has been made to assimilate all the existing classification of lakes having relevance to hydrology. The report included an inventory of the important natural lakes in India. It is hoped that the report will be useful for further works in this regard.

The report is part of the work programme of newly created Lake Hydrology Division of the Institute. The study is carried out by Shri S.D. Khobragade, Scientist B and by Shri A.K. Bhar, Scientist E of the Lake Hydrology Division.

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Abstract

The earth land is dotted with about three million lakes, most of them being located in Northern Hemisphere. Many times lakes, ponds and reservoirs are wrongly considered as simile but there are certain basic differences between the three. According to Zumberge and Ayers (vide Chow, 1964) a lake is defined as an inland basin filled or partially filled by a water body whose surface dimensions are capable of producing a barren wave swept shore.

Lake hydrology is a relatively new science and not much research on lake hydrology has been carried out in the world. In India research studies have been undertaken mostly on chemical and biological aspects of lakes. A few studies have been done on water quality and sedimentation also but other aspects of lake hydrology remain almost untouched. The increasing popularity of lake due to its various usage leads to deterioration of lake water both in terms of quality and quantity. To solve the hydrologic problems effectively a classification system based on hydrological approach is needed. But no such system exists hitherto. Most of the classification systems in existence consider only the biological, thermal and chemical behaviour of lakes. There are other few studies of lakes related to specific problem. Classification given by Hutchinson in 1957 is based on the origin of lakes and is adopted by most scientists. The various ways of classifying lakes include classification based on region, origin, thermal behaviour, biological and chemical characteristics and morphology of lakes. These classifications, though adequate for other related areas of lake studies, are not adequate to meet the requirements of hydrological studies. So a classification system needs to be developed wherein lakes can be classified into various classes depending upon the hydrological parameters such as interaction of lake water with ground water, residence time of lake etc. These parameters can be clubbed with the other hydrological and hydrometeorological parameters which control the hydrology of lakes and hydrology and ecology of the surrounding catchment. Such a classification system will facilitate better and proper management of lakes.

The technical note deals with the various categories of existing lake classification with salient features of each class supplemented by a few examples in each category. A list of important lakes in India is also included at the end.

1.0 Introduction

1.1 General

Numerous and ancient are the attempts of man to bring water environment into his midst which may be called as the "Limnetic Drive" of human nature. Lakes are used extensively by many people as the natural centres of civilization. Venice and Mexico cities were built on the piles of the lakes whose waters were used for municipal supply and transportation (Clemens, 1959 vide Back, 1981). In India, during Maurya period (320 B.C.), a major reservoir called Sudarshana Lake was made at the foot of Mount Girnar in Western India (Wunderlich et al., 1987).

Lakes are an integral part of a drainage basin. A lake is a landlocked body of water with a horizontal surface water level. Lakes are short lived landscape features usually lasting only a few centuries or a millenia. The earth land is dotted with hundreds of thousands of lakes. Lakes contain over 95% of the Earth's fresh liquid water. (Scott, 1989).

The world distribution of lakes, like that of ground water and the ocean, but unlike that of rivers, is related more closely to the presence of basins suitable for water accumulation than it is to climate, (Scott, 1989). It has been estimated that there are about three million lakes on earth. They have total area of about $2.7 * 10^{6}$ sq. km and volume of water equaling $165.8 * 10^{3}$ cu. km. and it is not an easy task to evaluate the lake water resources. (Bowen, 1982). Most of the world's fresh water lakes occur on three continents - North America, Africa and Asia and account for 25 % , 30 % and 20 % i.e. more than 70 % of the world's fresh surface water. Large lakes in other continents - Europe, South America and Australia contain a comparatively small amount ; 300 cu. km or 20 % . The large lakes of North America contain approximately 32,000 cu. km of water of which over three - fourth is in the five Great lakes. Large lakes in East Africa contain some 36,000 cu. km of fresh water. Lake Baikal in the South Eastern Soviet Union in Central Asia is the World's deepest and most voluminous body of fresh water and contains nearly as much water as the five Great Lakes of North America. The latter are large in Surface area, but their average depth is very much less than that of Lake Baikal. It is stated that 95 % of the lakes in the Soviet Union and 85 % of their total area are located between 50 th and 75 th northern parallels (Tamrazyan vide Bowen, 1982).

Thousand of lakes occur in the North Central U.S.A. The state of Minnesota alone has more than 15,000 lake greater than 4 ha (0.04 sq. km) in area (Winter, 1977). The number of lakes in some countries like Sweden and Finland is very large. Although fresh water lakes are much more numerous and important, some of the world's largest lakes are saline. Saline lakes cover an estimated total area of 700,000 sq. km and contain 105,000 cu. km of water. Both the combined areal extent and volume of saline lakes are therefore about 85 % of the respective totals for fresh water lakes. Saline lakes are located mostly in Asia and are dominated by the Caspian Sea, which, despite its name, is considered the world's largest lake. By itself , the Caspian Sea contains about 80,000 cu. km or about 76 % of the total volume of all the world's saline lakes. (Nace, 1978).

Most of the lakes are minor in size and shape and very few are large. The lakes with areas more than 350 sq. miles (907 sq. km) or even 35 sq. miles (90.7 sq. km) are exceptional. Lake Baikal and the Lake Tanganyika in Africa are known to have maximum depth over 3280 ft (1000 m) and mean depth over 1640 ft

(500 m) (Walton, 1970). The large lakes i.e. lakes with more than 500 sq. km surface area, account for 93 % of the total surface area of the fresh water in the world and 88 % of the total fresh water volume of the world (Munawar, 1987). 87 % of these lakes are found in the northern hemisphere (Asia, Europe and North America), while large lakes of the southern hemisphere are located mostly in the African Rift Valleys (Munawar, 1987). The nineteen major lakes of the earth account for 38% of the total area of the lakes. (Bowen, 1982). The total volume of lake water and river water with respect to total fresh water of the earth are about 0.3 % and 0.003 % respectively (Black, 1991). In other words, in terms of the earth's total fresh water, lake water is 10 times more than the river water. Table 1.1 gives information on lake water volumes of the earth whereas Table 1.2 gives information about the largest lake in each of the continents of the globe. Some useful information about the nineteen major lakes of the world is furnished in table 1.3. Unfortunately no data are available on total lake water resources of India.

Table 1.1 Lake Water Volumes of the Earth

Category	Total lake water volume (* $10^3 km^3$)	(%)	Number of lakes on earth	Notes
Largest	158.6	95.54	19	Caspian, Baikal, Tanganyika, Nyasa, Michigan, Huron, Victoria,Maracaibo Great Slave,Issyk-Kul, Ontario, Great Bear, Aral, Ladoga, Titicaca, Kivu, Erie, Onega.
Large	2.0	1.20	15	Rudolf, Winnipeg, Van, Nicaragua, Venern, Athabasca, Edward, Dead Sea, Balkash, Albert, Chad, Tana,Geneva, Sevan, Zaysan.

(Source : Bowen, 1982 ; pp 186).

Table 1.2 Largest Lakes of the Continents

Continent	Total Area ($mile^2$)	Largest Lake	Area of The Lake ($mile^2$)
Asia	17,297,000	Caspian Sea	143,240
Africa	11,708,000	Victoria	26,827
North America	9,406,000	Superior	31,820
South America	6,883,000	Titicaca	3,205
Antarctica	5 40 ,000	-----	
Australia	3,287,000	Taupo	234
World	57,821,000	Caspian Sea	143,240

(Source :English et al., 1990 ; pp 34)

Table 1.3 Characteristics of Major Lakes

Lake	Area	Volume	Shoreline	Depth	
	(m^2)	(10^3 Acre ft)	(m)	Avg.	Max.
Caspian Sea	169300	71300	3730	675	3080
Superior	31180	9700	1860	475	1000
Victoria	26200	2180	2130		
Aral Sea[a]	26200	775			
Huron	23010	3720	1680		
Michigan	22400	4660			870
Baikal[a]	13300	18700		2300	5700
Tanganyika	12700	8100			4700
Great Bear[a]	11490		1300		
Great Slave[a]	11170		1365		
Nyasa	11000	6800		900	2310
Erie	9940	436			
Winnipeg[a]	9390		1180		
Ontario	7540	1300			
Ladoga	7000	745			
Chad[a]	6500				
Maracaibo[a]	4000				
Rudolf[a]	3475				
Athabasca	3085				
Titicaca	(World's highest lake at an elevation of 3800 m amsl in Peru Bolivia)				

a - Area fluctuates.
(Source :Bowen, 1982 ; pp 160).

1.2 Importance of Lakes

A lake is easy to visualize because it has definite boundaries. Such boundaries are not definite in other type of storage in the hydrologic cycle. As such, if it is full, it cannot accept more water without yielding some at its outlet. If it is empty, obviously its capacity is equal to its volume. If the lake is partially filled , its capacity to store water is somewhere between the two extremes, and the ability of the lake to buffer or attenuate a flood input is moderated over the empty condition.

The residence time of lake is 21 years and that of river is 2.1 years calculated over a global basis. As such it provides a natural storage without artificial barrier and is a viable means to accelerate or enhance recharge of known ground water supplies.

The relative lack of motion of lake water also makes the lake basin a sediment trap and sedimentation hastens the growth of aquatic plants.

Being the valuable natural resource lakes have always been of great importance to mankind. From ancient times they have been providing water for domestic purpose. Since long lake water is being used for industrial and irrigation purposes. Lake is also one of the means of transport and has always attracted the attention of human beings from the recreational point of view. Besides, it can also play an important role in supplying energy for driving turbines. Some saline lakes are the useful sources of some important minerals as well. In short, a lake is a sort of catalyst in the development of city. But unfortunately the popularity of lakes often leads to its deterioration. The increased input of industrial and domestic waste and other sediments and the human activity not only hampers the capacity of the lake but also causes an increase in the productivity of the lake which causes the biological and chemical changes in the lake waters leading to hazards like death of fish, obnoxious odours and unsightly conditions.

1.3 Definition of Lake

The matter of a precise definition of a lake has received insufficient attention and a unique definition of lake does not exist. Lakes are natural reservoirs in which water is temporarily stored during its passage to sea. They receive water as precipitation on their surfaces, from surface influence, and from ground water entering as springs. Nace, (1968), called wide places in a river as lakes. But this could be true only for small lakes that are impounded by relatively minor and geologically temporary obstructions across river channels. Hydrologically there is a need to distinguish a lake from a wide river section.

As defined by Zumberge and Ayers (vide Chow, 1964) which is generally used, a lake is an inland body of water filled or partially filled by a water body whose surface dimensions are sufficiently large enough to sustain waves capable of producing a barren wave swept shore.

1.4 Difference between lake, pond and reservoir

Often lakes, ponds and reservoirs are wrongly considered as simile. So it is essential to understand the differences amongst them.

The lake is a natural body of water having an area of open, relatively deep water, sufficiently large to produce a barren wave swept shore on its periphery where as ponds are very small, shallow bodies of standing water which is extensively occupied by higher aquatic plants. On the other hand a reservoir may be natural valley that is dammed artificially or a concrete feveed artificial lake not associated with natural catchment. A lake is filled by stream flow or precipitation only whereas ponds and reservoirs are filled either by natural flow (impounding type) and / or by water pumped from neighouring catchments (pumped storage type). Water from the pond and reservoir is used for supply for any purpose such as hydropower generation or irrigation etc there is a rapid variation in the water levels unlike the natural lakes. This affects the habitat in the ponds and reservoirs on large scale (Henderson, 1984). The lakes, like the other naturally formed water bodies, exhibit the shore line formation characteristics. Artificially produced reservoirs and ponds do not have a well defined shore (Litton et al.1974). So, according to the hydrologic definition of lake envisioned by Zumberge and Ayers (vide Chow, 1964) reservoirs created by damming rivers, ponds, tanks etc. should not be categorized as lakes.

Inputs and outputs of the natural lakes are near the surface whereas outlets of a reservoir or a pond is at one of the several depths or from two or three levels simultaneously. The lower depression in a natural lake may occur anywhere in its basin but the maximum depth of the reservoir bottom is always near the dam, unless a natural lake is included in the impoundment area. A reservoir bottom has a regular slope from head to tail that was established by the river before damming. In case of natural lakes the basins are scooped out below river level and hence bottom slope is not uniform. Natural lakes normally begin as oligotrophic bodies of water having low productivity on the other hand reservoirs inundate rich bottom lands and fertile top soil on river slopes and so normally begin with high productivity potential. With passage of time natural lakes tend to become productive unlike reservoirs which tend to suffer productivity decrease with time (Walton, 1970).

A majority of lakes have a ratio of mean depth to maximum depth which exceed 0.33, the value that a conical depression would have with increasing age. Lakes in easily erodible rocks generally have ratios between 0.33 and 0.50. The ratio tend to increase as maximum depths are filled in .Old lakes are commonly bordered by a band of swamps which are shallow and weedy. But a reservoir do not maintain any such ratio and are not bordered with swamps in due course of time. (Walton, 1970).

Deep release from storage reservoirs provides the possibility of discharge of nutrient rich hypolimnion water. With lakes on the other hand the outflow mostly is on the surface and there is often a marked accumulation of dissolved nitrogen and phosphorus compounds in the hypolimnion (Uhlmann, 1979).

Reservoirs generally have larger drainage basins, surface areas and drainage basin to surface area ratios than natural lakes. The mean and maximum depths are usually greater in reservoirs than in lakes. Reservoirs also have greater areal water load and shorter residence times. Because of the large drainage basin to surface area ratio and greater water load, nutrients load to reservoirs is larger than those to lakes. However, because of the shorter residence times of water and greater mean depths, the average phosphorus and chlorophyll concentrations in reservoirs are usually lower than those in lakes.

Reservoirs are generally constructed either to store or control the flow of rivers and streams, primarily in regions where there is excess or scarcity of water. As a result, reservoirs are geologically younger than natural lakes. The world wide distribution pattern for lakes shows a bimodel pattern. The largest percentage lies between approximately 35^{o}- 55^{o} latitude in both the southern and northern hemisphere and between approximately 15^{o}N to 20^{o}S latitude around the equator. In contrast, the reservoirs do not exhibit this bimodel distribution (Ryding et al., 1989).

Natural lakes are located in the centre of relatively symmetrical and contiguous drainage inputs entering the lake at several points around the lake whereas reservoirs are usually constructed at the downstream boundary of a drainage basin. Thus, the reservoir drainage basins are often narrow and elongated with only a small portion of the basin being contiguous with reservoir (Ryding et al., 1989).

1.5 Origin of Lakes

In coming to the question of origin of lakes, it is apparent that depressions are first of all formed on the earth's surface under favourable conditions, some of these hollows contain water and are therefore, described as lakes. The topographic depressions which accommodate lakes are known as lake-basins. Lakes can be created by different number of various natural events. Natural agencies like wind, water etc. individually and collectively tend to reduce the surface of the earth to a continuous and gradual slope. In their endeavour to do so, the agencies at times produce, at least temporarily, some depressions on the land surface which when filled with water make lakes. They commonly occur above the mean sea level and the basins always have their bottoms below the water table. (Mukherjee,1964)

Most lakes however have been produced by glacial, volcanic or tectonic processes. Tectonic basins are depressions caused by the deep movements that resulted in faulting or upwarping of earth's crust. Volcanic activity has created many crater lakes. Glacial activity during the most recent period of major ice advance and retreat resulted in a abundance of lakes in N. America and Europe. Great Lakes, which collectively form the largest continuous volume of fresh water in the world, were formed by ice scour, water erosion and subsidence under massive ice sheets (Hammer, 1977).

Natural impoundments of most recent origin include solution lakes and depression formed by river and wind activity. Besides these, there are many other natural processes by which lakes can be formed. Eleven such major natural processes have been recognized by Hutchinson in 1957 (Ven Te Chow, 1964). These will be discussed separately under classification of lakes.

1.6 Hydrology of Lakes

Lakes, though constitute only small portion of the total water resources system of the earth, are important assets. Besides the importance and utility of lakes for mankind discussed earlier lakes play an important role in the field of hydrology.

Of significance is the fact that the hydrologic characteristics of lakes vary considerably because of differences in the depth, length, width, surface area, basin material, surrounding ground cover, reservoir, prevailing winds, climate, surface inflows and outflows, and other factors. Lakes may have some common features but often exhibit strikingly different performance characteristics. This individuality has environmental value and as such it presents the problem of having to understand both the general nature of the system and variations due to local conditions.(Zumberge and Ayers vide Chow, 1964). This means that each lake requires its own hydrologic model but these models need to be characterized by different degree of variance from a generalized conceptual model.(Viessman et al., 1977).

Heat storage in lakes act to stabilize the air temperature, minimizing and lagging variation in adjacent region, both in winter and summer (Linsley et al., 1983). Lakes also exhibit interesting thermal stratification like reservoirs. But number of problems in lakes are sharply increasing. In order to evaluate the lake problems for their better management heat budget, nutrient budget and water budget of lakes are needed. To understand these problems a thorough understanding of lake hydrology, along with chemistry, biology and physics of lakes and their interrelationship is needed. Owing to all these facts research studies have been going on in many countries of the world, especially in America and Europe. In America a great deal of research work has already been carried out on the Great Lakes. But most of the research has been on the chemistry, biology or the nutrient balance of the lakes. The hydrological aspects covered in the studies are mostly evaporation, sedimentation and water balance. Less attention has been paid to the other hydrological aspects such as interaction of lakes with ground water (Winter, 1980). Most studies have concentrated on individual or small groups of lakes resulting in a great deal of information on these lakes but the transfer value of the information is often limited (Winter, 1977).

In India, though attention is being paid on lake studies since long, research studies on hydrology of lakes still remain an unexploited field. Barring studies on chemistry, biology and few on sedimentation and water quality, research in lake hydrology is almost negligible. But a need is felt now wherein different aspects of lake studies like general hydrologic description including water balance, lake meteorology and interaction of lakes with the environment, evaporation studies of lakes, influence of lakes on the surrounding region, interaction of lakes with the stream flow, lake water interaction with the ground water, seepage and sedimentation studies on lakes etc. should be given due weightage. This is particularly important to understand the natural lakes, its behaviour with environment and its role in the environmental ecology and hydrologic cycle. This will help in better and proper management of the lake water resources and to tackle problems the lakes are facing, consequently providing a way for more realistic approach for their proper management.

Keeping in view the above facts a new Lake Hydrology

Division has already been started at the National Institute of Hydrology, Roorkee (U.P.) ; India.

2.0 Classification of Lakes

2.1 General

There is no unique and uniform method of classification of lakes. Different scientists have classified lakes into various ways, on the basis of their origin, thermal behaviour , biological and chemical characteristics etc.. Classification given by Hutchinson in 1957 is based on origin of lakes and is accepted by most scientists although classification based on thermal behaviour and biology is also followed by many. The other methods of lake classification are of relatively less importance.

In this report different ways of lake classification are presented with some salient features of each class with examples. These are :

1) Classification based on region,
2) Classification based on origin,
3) Classification based on thermal behaviour of lakes,
4) Classification based on biological properties of lakes,
5) Classification based on chemical characteristics of lakes,
6) Classification based on presence or absence of outlets,
7) Classification based on geometrical shapes of lakes,
8) Classification based on water balance of lakes and
9) Other minor classifications of lakes

2.2 Classification Based on Region

On the basis of their locations in the different climatic zones of the world, lakes are broadly classified as follows (Das, 1991) :

2.2.1 Tropical Lakes

Lakes of tropical zone (longitude $23^{o}30'$N to $23^{o}30'$S) are called tropical lakes. These lakes have the summer temperature range of 25^{o}C to 30^{o}C and winter temperature range of 16^{o}C to 20^{o}C.

2.2.2 Temperate Lakes

Lakes of temperate zones (longitude $23^{o}30'$ to $66^{o}30'$ N and $23^{o}30'$ to $66^{o}30'$S) are called temperate lakes. Their waters have the summer temperature range of 16^{o}C to 20^{o}C whereas the range for winter temperatures is 4^{o}C to 8^{o}C.

2.2.3 Polar Lakes

These are the lakes of the polar zones. In these lakes the summer water temperature ranges from 0^{o}C to 4^{o}C.

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 and polar lakes are referred to as sub-polar lakes. Sub-polar lakes may have a midsummer temperature exceeding 4^{o}C. For sub-tropical lakes the temperature of the water never falls below 4^{o}C at any depth (Reid and Wood , 1976).

2.3 Classification of Lakes Based on Their Origin

2.3.1 General

Lakes had been classified on the basis of the origin of their basins as early as in the late nineteen century. Zumberge and Ayers (vide Chow, 1964) report that Davis in 1882 grouped the basin forming processes into three categories viz. constructive, destructive and obstructive, with a view that the geologic origin are concentrated in certain geographical regions of the earth. Zumberge and Ayers (vide Chow, 1964) further report that in 1895, Russell published a lake classification system based on the natural agencies which produce lakes. He defined ten major natural agencies. Based on the work of Russell, Hutchinson in 1957 presented a more systematic classification of lakes classifying the lakes into 76 different types under eleven major lake forming processes. This classification is considered as most recent and complete (Zumberge and Ayers vide Chow, 1964). This system classifies the lakes into following types.

2.3.2 Tectonic Lake Basins

Tectonic mechanism in late Miocene times have been responsible for large scale movement which caused formation of large inland seas in south east Europe and south Asia, remnants of which include the Aral, Caspian and Black Seas. These lake basins are produced by the tectonic forces like earthquake, folding, faulting etc. which cause profound changes at the earth surface such as upliftment of submarine structural basin or depressions which are formed by differential marine sedimentation above the mean sea level, upwarping of earth's crust and impounding the water of whole drainage system etc. (Zumberge and Ayers vide Chow, 1964).

Tectonic basins usually have elongated shape, steep side slopes and great depths since they lie in depression caused by downward movement of a section of the earth's crust or upliftment of the area surrounding the basin (Bowen, 1982). Most tectonic lake basins are oligotrophic but some like Nainital Lake in India have become eutrophic (Das, 1991). Lake Tanganyika in East Africa and Lake Baikal in Siberia ; two major lakes of the world - are of tectonic origin. Dead sea - the lowest lying lake in the world at 396 m below mean sea level - is also of this origin.

Following are the different types into which tectonic lakes can be classified (Walton, 1971) :

2.3.2.1 Relict Lakes

These lakes are formed by the uplift of the sea bottom. The basin has the original structural identity retained from its marine period.

Example : Caspian sea.

2.3.2.2 New Land Lakes

These are formed by the upliftment of the marine surface on which there were irregularities due to uneven sedimentation. Example : Lake Okeechobee, Florida.

2.3.2.3 Lakes formed by upwarping all around a basin

Example : Lake Victoria in Central Africa

2.3.2.4 Lakes in areas of local subsidence due to earthquakes.

Example : Reelfoot Lake, Tennessee.

2.3.2.5 Lakes in basins formed by folding and by upwarping of the earth's crust across its lower end.

Example: Fahlensee Lake in Switzerland.

2.3.2.6 Lakes on old peneplain surfaces in intermontane basins.

Example: Lake Poso.

2.3.2.7 Basins in grabens between faults.

Examples : Lake Baikal, Lake Tanganyika and Pyramid Lake, Nevada.

2.3.2.8 Basin on tilted fault blocks.

Example : Albert Lake, Oregon.

2.3.2.9 Lakes formed by movement reversing drainage pattern

Example : Lake Kioga in Central Africa.

2.3.3 Basins of Volcanic Origin

These are the basins which are formed due to volcanic disturbances. These disturbances are many. The depressions, formed due to collapse of the volcano, when get filled with water form lakes. The depression may be crater or calderas. Craters are the inverted conical depressions at the crest of volcanic cone and calderas are much larger depressions resulting from collapse of the central part of the volcano after the quantities of lava are discharged from the underlying magma (Zumberge and Ayers vide Chow, 1964). Lake basins are sometimes formed when the growth of the volcanic cone obstructs a preexisting drainage system. When the solidified crust of a new lava flow collapses after the fluid lava beneath has drained away, lake basins are formed (Zumberge and Ayers vide Chow, 1964) . Lava may issue from fissures rather than from the volcanoes in the form of flow rather than eruption. The sheet lava thus formed may contain depression. When it hardens it can fill with water to become lake (Reid, 1976). Lakes of volcanic origin are often deep and usually smaller than those of tectonic origin.

Some of the examples of volcanic lake basins are : Crater Lake (9.5 km wide of 600 m deep) in Oregon (due to crater explosion and collapse). Lake Toyaka in Japan, Laga do Bolsena in Italy, Medicine Lake of California, Lake Toba in Sumatra etc. (Walton, 1970). Lake Kivu in East Africa and sea of Galille (formed by Lava damming).

2.3.4 Lake Basins of Glacial Origin

Glaciers have produced more lake basins than any other single agency (Zumberge & Ayers vide Chow, 1964). Glacially produced basins range in size from the smallest lakes to the Great Lakes of U.S. There are many such lakes in Russia, Finland and Canada. Lakes of glacial origin include the following types :

2.3.4.1 Lakes on or in ice

These lakes lie entirely on or in glaciers. They are formed by differential melting (Zumberge and Ayers vide Chow, 1964). They are rare but have occurred on alpine glaciers ; on the surface and within glaciers and on ice sheets (Walton, 1970).

2.3.4.2 Lakes dammed by ice

These lakes are formed when the glacier tongues dam the valleys. Example : Lake Marjelensee, Switzerland (Walton, 1970). Lake Malaspina, Alaska (Sly, 1978).

2.3.4.3 Lakes formed by damming action of moraine

Such basins may persist even after the glacier which formed the moraine has disappeared (Zumberge and Ayers vide Chow, 1964).

Exa : Lake of Maltmark in Switzerland (Walton, 1970).

2.3.4.4 Cirque Lakes or Ice Scour Lakes

At the heads of the glaciated valleys the movement of ice and captured debris often erodes out an amphitheater shaped basins called cirques which later on gets filled with water to form a cirque lake. These lakes are surrounded on all sides except the outlet by steep walls. (Reid and Wood, 1976). Exa. : Iceberg Lake at Glacier National Park, English Lake District (Walton, 1970) and lakes in Canadian and Scandinavian Shield areas.

2.3.4.5 Paternoster Lakes

Often the axis of the valley draining the cirque is marked by a chain of lakes occupying a descending series of basins; the linked series of smaller lakes which may be linked to the beads of a rosary are referred to as the Paternoster Lakes (Reid and Wood, 1976).

2.3.4.6 Fjored Lakes

Valley glaciers and continental sheets may scour or quarry deep rock valleys. These are called fjored lakes (Zumberge and Ayers vide Chow, 1964). These lakes are long, narrow and deep and are present in many high latitude regions of both northern and southern hemispheres. Exam. Nord Fjored lakes in Western Norway and larger lakes of English Lake District (Walton, 1970). Coastal valleys can be transformed into fjored lakes after being scoured by glaciers by a relatively small drop in sea level. A typical fjored is partially bounded at its mouth by a transverse ridge of bedrock, a sill, rising toward sea level from the floor of the embayment. A number of such lakes have been described in British Columbia, Norway, New Zealand and British Isles (Reid & Wood, 1976).

2.3.4.7 Thaw Lakes

These are produced by continental glaciation mainly occurring on coastal plains and in river valleys in the permafrost and Tundra area. These lakes are formed when the layer of permanently frozen soil thaws partially during summer causing the formation of a lens shaped slightly dammed mass of silt which loosens and is easily moved with repeated freezing and thawing. Eventually the surface sags to form a small lake basin (Reid and Wood, 1976). Exa. : Shallow lakes (less than 3 m deep) in coastal plains of New Jersey ranging in area from few hundred square meters to over one and half sq. km.

2.3.4.8 Kettles Lake

These lakes are formed by the melting of massive isolated chunks of buried ice left behind as the glaciers retreated northward. Kettle basins are common in Minnesota, Wisconsin and Central Canada (Reid and Wood , 1976).

2.3.4.9 Lakes dammed by terminal or recessional moraines

In many regions where the bedrock is relatively soft glaciers scour out long, narrow basins. The retreating glacier often leaves behind a terminal moraine which is massive enough to dam the newly formed valley. Finger lakes of Central New York were formed in this way. Other examples are Lucrene, Como and Constance lakes of the Swiss Alps (Reid and Wood, 1976).

2.3.4.10 Thermokarst Lakes

These are produced by collapse of the ground resulting from the melting of ice or frozen grounds in regions underlain by permafrost (Zumberge and Ayers vide Chow, 1964). Exa. : Many lakes in Northern Alaska around point barrow (Walton, 1970).

According to Das (1991) , Sheshnag Lake, Bhutop lake and Lake Devkund in Garhwal, India are glacial lakes.

2.3.4.11 Lakes due to repeated glaciation

In North America, all the larger lakes bordering Canadian shield like Great Bear, Great Slave, Winnipeg and the Laurentian Great Lakes owe much of their origins to the effects of repeated glaciation.

2.3.5 Solution Lakes

Solution lakes are quite common in regions which are characterized by carbonate or evaporative rocks like the Balkan peninsula. The dissolution of bed rocks by flowing ground water and / or sub surface drainage channels and / or percolating surface water causes the formation of solution basins. In the percolation process surface water may start to dissolve the limestone at points of fracture or other weaknesses. The inflowing water moves easily through the stone and with continued flow the doline develops. The limestone may also be dissolved from below when water moving in a sub surface aquifer weakens the roof of an underground chamber causing the roof of the chamber to collapse leaving a fairly regular cone like doline (Reid & Wood, 1976). The rock basins so formed are called sinks which are generally funnel shaped in cross section (Zumberge and Ayers vide Chow, 1964). The water levels in solution lakes generally fluctuate rapidly in response to changes in groundwater storage (Walton, 1970). If the bottom level of the doline does not reach down to the local water table the sink will be essentially dry. If the bottom of the sink extends down to the range of fluctuations of the water table a temporary lake appears in the rainy season which dries up when the water table drops (Reid & Wood, 1976). A deeper sink will be basin of a permanent lake. Occasionally a newly formed sink may suddenly alter the shape of a lake bottom - or a clogged sink may suddenly be opened - with dramatic effects on a preexisting lake (Reid & Wood, 1976).

The newly formed solution lakes typically contain little CO_2 in any form. The low quantity of carbonates in the substrata results in little of the bound or half bound forms of CO_2. The paucity of soluble minerals as nutrients in biological processes inhibits the development of large biotic population that would contribute CO_2 through respiration reducing the decomposition (Reid & Wood, 1976). Solution lakes are usually slightly acidic with pH ranging near 6. lakes of higher acidity (pH 4 to 6) are common in regions of lowlands and bogs (Reid & Wood, 1976).

In the later stages solution lakes may become sealed off from the surrounding ground water by sediments much of which is unsoluble residue originally present in the bedrock. (Zumberge and Ayers vide Chow, 1964).

Examples of solution lakes include Orange Lake in Florida, U. S. A. (Reid & Wood, 1976). Deep Lake, Florida and Lake Murrensee, Glarus in Switzerland (Walton, 1970).

2.3.6 Basins formed by stream action

Flowing water is a common geologic agent which can produce closed basins. Flowing waters may release their load of material held in suspension such as soil and organic debris and they may cut away at their beds forming lake basins through erosion. Streams with steep gradients and relatively high velocities lose their carrying power and drop their loads of sediment when they join larger streams.

The different types of lakes formed by the fluvitile action are as follows :

2.3.6.1 Plunge pool lakes in basins excavated below water falls

The force of the stream over a cliff as a waterfall will erode a pool at the foot of the fall. This plunge pool may become enlarged and the original stream may eventually become extinct, leaving a basin which later on gets filled to become a lake (Reid & Wood, 1976).

Examples : Falls Lake and Castle Lake in the Grand Coulee, Washington (Walton, 1970).

2.3.6.2 Fluviatile dams holding lakes

These lakes are formed by stream deposition at the confluence of a tributary and the main channel. In some cases the main channel is dammed by excess sediments brought in by the tributary (Zumberge and Ayers vide Chow, 1964).

Lake Pepin on the Minnesota - Wisconsin state line was formed by the deposition of alluvium carried by the Chippewa river. The Chippewa deposited its load across the main channel at its junction with the Mississippi, thereby creating a fluviatile dam in Mississippi. Lake Pepin was thus formed upstream (Reid & Wood, 1976). Similarly Tulare lake, California had its origin in an alluvial fan built by the Kings River across the valley of San Joaquin (Reid & Wood, 1976).

2.3.6.3 Lateral Lakes

The reverse process may occur when a large stream builds its banks with the sediments so quickly that the junction with the tributary is closed off. Consequently a lake is formed by the action of the main river. Such lateral lakes are found along the Sacramento river of California and the Red river of Texas and Louisiana (Reid & Wood, 1976). Other examples include lake Tung-ting and other lakes on the Yang-tze kiang (Walton, 1970).

2.3.6.4 Ox-bow Lakes

These lakes are created when the S - shaped meandering streams erode the outside shores of its broad bends and in times the loops are cut off by sediments deposited by parent stream leaving basins (Reid & Wood, 1976). These are generally shallow and crescent shaped (Reid & Wood, 1976). The ox-bow lakes may be entirely land locked and lentic or there may be little flow (Das, 1991). Many ox-bow lakes are seen at the mature flood plains of Mississippi and some of its tributaries in Louisiana and neighbouring states (Reid & Wood, 1976).

The Indian examples of ox-bow lakes include Lake Wular, Nagin Lake and Anchor Lake in Kashmir (Das,1991).

2.3.6.5 Lake behind the hard rock bar

If a stream bedded on soft rock runs on to the hard rock, outcrop differential erosion will form a basin rapidly and water will accumulate here behind the hard rock bar. Such a lake will of course be shorter lived because the erosional action will proceed and ultimately wear away the hard rock bar completely (Bowen, 1992).

2.3.6.6 Fluviatile deposits of deltas dividing an original lake into two lakes

Examples : Lakes Brienzersee and Theenersee in Switzerland and Lakes Derwent Water and Bassenth Waite in English Lake Dist. (Walton, 1970).

2.3.7 Basins formed by wind action

Due to the erosive process of wind; fine, light materials such as clay and sand are removed producing closed depression. Deposition of wind borne sediments is also responsible for formation of lake basin. These basins later on get filled with water to form lakes. Lake basins formed by wind action are generally shallow and contain water only during certain seasons (Walton, 1970). Lake basins of this sort were formed during arid phases of geologic time era and hence undergone several alternating wet and dry climates. (Zumberge and Ayers vide Chow, 1964).

Lake basins formed by the action of wind include,

2.3.7.1 Basins dammed by wind blown sand

Drifting sand during migration of sand dunes sometimes obstruct the natural drainage and forms lakes (Zumberge and Ayers vide Chow,1964).

Examples : Moses Lake in Washington (Zumberge and Ayers vide Chow, 1964).

2.3.7.2 Lakes between well oriented sand dunes

These lakes are formed due to the depression created because of the shifting of sand dunes and hollowing of troughs between dunes (Reid, 1976).

Examples : Cherry country, Nebraska (Reid, 1976).

2.3.7.3 Deflation basins

Removal of loose materials from an area may form eroded deflation basins. Under the favourable conditions of adequate rainfall and suitable rock and soil conditions, deflation basins can become permanent (Reid & Wood, 1976). Such conditions are not always found in deflation regions and many of the basins do not contain water. On the other hand lakes do not occur in some arid regions. It is suggested in such cases that the basins were formed earlier under arid conditions becoming filled later after repeated changes in climate (Reid & Wood, 1976).

Numerous deflation basins are found in northern Texas and New Mexico, South Africa and parts of Australia (Walton,1970).

2.3.8 Basins developed by shoreline processes

Action of waves and currents along the sea coasts and shores of inland lakes produce many isolated lake basins by forming the bars across the openings of embayment with the transport and redistribution of clastic sediments (Zumberge and Ayers vide Chow, 1964).

Lakes formed by shoreline processes include,

2.3.8.1 Maritime coastal Lakes

These lakes are formed by the deposition of the sediments across the mouth of an embayment, lagoon or estuary.

Examples : Lakes of the Landes area on the west coast of France (Walton, 1970).

2.3.8.2 Lakes cut off from larger lakes by a bar built across the bay

Some times smaller lakes are cut off from the larger parent lake by the formation of a spit. (Reid & Wood, 1976). In Minnesota, Buck Lake was thus cut off from the parent Cars Lake which eventually closed off the smaller lake (Reid & Wood, 1976). Lake Nabugabo on north east coast of Lake Victoria in Central Africa was also formed in the same manner (Walton, 1970).

2.3.8.3. Lakes divided by the meeting of two spits

Inland lake basins may undergo bisection into separate basins when spits or points of accretionary origin join through lakeward growth from opposite shores (Zumberge and Ayers vide Chow, 1964).

Examples : Marion Lake , Offer Tail County , Minnesota (Walton, 1970).

2.3.8.4 Lakes enclosed by two tombols or spits joining an inland to the mainland

A special case of coastal lake formed by building of coastal deposits occurs when an off-shore island is joined to the mainland by two bars called tombolos. (Zumberge and Ayers vide Chow, 1964).

Example : Lake Stagno di Orbetello on the West Coast of Italy.

2.3.9 Lake basins produced by landsliding

Landslides caused by various agents such as wave action, earthquake, heavy rains, artificial excavations etc. can produce variety of lakes. These include (Zumberge and Ayers vide Chow, 1964),

2.3.9.1 Lake held by landslide dam

Large mass of rock, soil, mud or other unconsolidated material may fall away from an adjacent slope and block a stream valley or river, producing lakes (Reid & Wood, 1976).

Landslide on the Gros Ventre Range in Wyoming dammed Gross Ventre River forming a 5 km long lake in 1925 (Reid & Wood, 1976). When the water overflowed the top of the dam after two years, it caused a disastrous flood.

When the landslide occurs it results in the sudden translocation of earth materials from a higher to lower elevation. If the final resting place of landslide debris is across a stream valley, the impounded waters form an elongate lake (Zumberge and Ayers vide Chow, 1964). The lake may drain suddenly when the water spills over the slide dam producing disastrous floods downstream. Landslide lake will tend to fill rapidly with sediment because the inflowing stream has its sediment carrying capacity lowered as it enters the newly formed lake (Zumberge and Ayers vide Chow, 1964).

If the slide material is not tightly consolidated eventual erosion and destruction of dam may occur. However, if the slide material is compacted and the impounded stream is small and fills the basin slowly, long lived lakes may result (Reid & Wood, 1976).

Examples of lakes under this category include lake Sarez in the Pamir mountains, Lae des Chaillexon, on the Franco - Swiss boundary, Lake San cristobal in Colorado, Lake Fork of Gunnision River, Ireland, (Walton, 1970). Gohna Lake in Garhwal was produced in a like manner along one of the tributaries of the Ganges (Mukherjee, 1964).

2.3.9.2 Lakes on irregular surface of landslides

If the landslide debris are large enough and have irregular surfaces on them then the surfaces after getting filled with water create smaller lakes (Zumberge and Ayers vide Chow, 1964).

Example : Lake Lac de st. Andre in Mount Granier (Walton, 1970).

2.3.10 Lake basins formed by organic accumulation

Lakes are also formed entirely or partly by the action of dead or leaving plants or animals. These lakes are few in numbers, but involve distinct basin forming processes.

These lakes include,

2.3.10.1 Phytogenic dams

These are formed by living or dead plant material when they block the normal flow of water. Dense growth of aquatic and marsh plants may impound waters effectively especially in the regions where there is a long period of vigorous plant growth (Reid & Wood, 1976).

Examples : Silver Lake , Halifax county , Novascotia (Walton, 1970). Lake Okeechobee, Florida is partially impounded by vegetation (Reid & Wood , 1976).

2.3.10.2 Lakes in closed coral atolls

These lakes are formed by the accumulation of coral fragments in tropical and subtropical oceanic regions (Zumberge and Ayers vide Chow, 1964). Some lagoons have coral rims which completely isolate them from the surrounding ocean and form a separate lake (Zumberge and Ayers vide Chow, 1964).

Examples : Lake on Washington Island in the central Pacific (Walton, 1970). Some of these coral lakes retain underground connection with sea and therefore rise and fall with the tide. But others are sealed off completely by fine-grained sediments of organic origin (Zumberge and Ayers vide Chow, 1964).

2.3.11 Lake basins formed by the activity of higher organisms

Man creates lakes artificially by constructing dams across the river valleys. These are big artificial lakes. Smaller lakes are also produced by different activities of man such as stone gauging; lime stone, coal and metal ore rock removal etc. Artificially dammed lakes are dendritic in shape and are invariably deeper at the dam end than the farther upstream. These lakes generally fill with the sediments brought in by erosion and its deposition which reduce the capacity and life of the lake (Zumberge and Ayers vide Chow, 1964).

Prominent examples of man made lakes are Lake Mead in Arizona and Nevada which is produced by damming the Colorado river with the Hoover dam and Lake Nasser in Egypt (Bowen, 1982). Tungabhadra and Bhakra Nangal are the major Indian examples. Because these artificial bodies of water are created for many purposes and are managed in countless different ways, their ecological features are sharply different from those of natural impoundments.

The activities of beavers; Caster canadensis, have created many small lakes in America and Canada. Beaver cuts logs and sticks and arranges them into a lattice work dam impounding upstream waters to form ponds and lakes. Some of the beaver dams are not only structurally sound but also have high capacity (Reid & Wood, 1976). One such Beaver dam in Montana is about 600 m long. Most others however are small, usually 25 m long and seldom more than 2 m high (Reid & Wood, 1976). One more example of such dam is the Beaver dam in Maryland, U S A (Das, 1991).

2.3.12 Lake basins formed by the impact of meteorites

The meteorite may strike the surface of the earth with an impact great enough to blast out a large depression. On explosion, a crater is created which later, on getting filled with water, becomes a lake. These lakes are generally circular in plan view (Zumberge and Ayers vide Chow, 1964).

Examples : Chubb crater in Ungava, Quebec is the largest known meteorite lake with diameter of two miles and depth of 800 ft. (Zumberge and Ayers vide Chow, 1964). Bay lakes of south eastern North America is another example (Walton, 1970). Lonar Lake in the Deccan Plateau of Maharashtra is an Indian example of this type of lakes.

2.3.13 Lakes of unknown origin

Generally lakes are formed by one or more processes discussed above. But there are few lakes whose origin are not yet known. For example the cluster of small, shallow lakes in eastern north Carolina and number of lakes of Atlantic coastal plain. These lakes occupy elliptical basins with the long axis oriented roughly north east- south east. The water is relatively sandy.

They are unusual in the sense that they are increasing in size unlike the most fresh water lakes which become smaller due to sedimentation and encroaching shorelines. Many theories have been put forward by different scientists to explain their origin but so far no theory has proven acceptable to all (Reid & Wood , 1976).

2.4 Classification of Lakes Based on Their Thermal Behaviour

2.4.1 General

In order to understand the classification of lakes on the basis of their thermal behaviour it is necessary to understand the thermal and seasonal cycle of lakes.

The density of water is primarily a function of its temperature. As the temperature changes density also changes. If less dense water becomes overlain by more dense water, convection or lake water overturn takes place (Reid & Wood, 1976). The behaviour of water when heated from $0^{o}C$ to $4^{o}C$ is unusual. Unlike most other liquids, where the density decreases on heating , density of water actually increases. The maximum density is attained at $4^{o}C$ and further heating decreases the density. This unusual temperature - density behaviour of water is the basis for classifying lakes. (Berner et al., 1987).

Because of this unique temperature density behaviour of water, it undergoes thermal stratification forming layers or zones of different densities. This is aided by the stirring action of the wind also. The uppermost shallow, wind stirred region of the lake is called the epilimnion where as the bottom, relatively deep, portion of the lake is termed as the hypolimnion. Between the two zones there is a zone of rapid temperature drop. This zone is known as thermocline or mesocline (Berner et al., 1987). The thermocline is generally 2 to 3 m thick. The thermocline including a gradient on either side of it is designated as the metalimnion

(Reid & Wood 1976). For the better understanding of the effects of temperature on lake circulation and classification, the effect of seasonal temperature changes on profiles of temperature versus depth for a typicaal medium sized lake of temperate zone is discussed below. It is shown in figure 1.a, 1.b and 2.

In summer the air temperature is maximum and so is the surface water temperature. The depth of heating of water depends on the wind stirring and extends down to where the wind effects die out. As the lake water temperature in summer is above 4^{o}C, the coldest water which is most dense is located at the bottom. There is very little vertical circulation of water. The hypolimnion is isolated from the atmosphere. A stable density stratification is existing. This is called the summer stratification (Berner et al., 1987). (Figure 2). With the advance of autumn, the air temperature drops and air cools. The epilimnetic water also cools, until the temperature matches with that of the hypolimnion. The thermocline does not exist and temperature is constant from top to bottom. As the surface water cools further the density distribution becomes unstable. Heavier water is at the top and a vertical convection occurs. The lake mixes or overturns from top to bottom. This overturn is called autumn overturn (Fig. 1.b, 2). It is aided by winds which are generally strong in autumn. With the continuation of temperature fall the constant top to bottom temperature drops with time until 4^{o}C is reached at which point a new behaviour takes place (Berner et al., 1987) (Figure 2).

As the surface water further cools below 4^{o}C it becomes less dense than the deeper water and stable density stratification develops ceasing the top to bottom overturn. Eventually surface water reaches 0^{o}C and freezes.

During winter the cold water surface and the ice cap, if

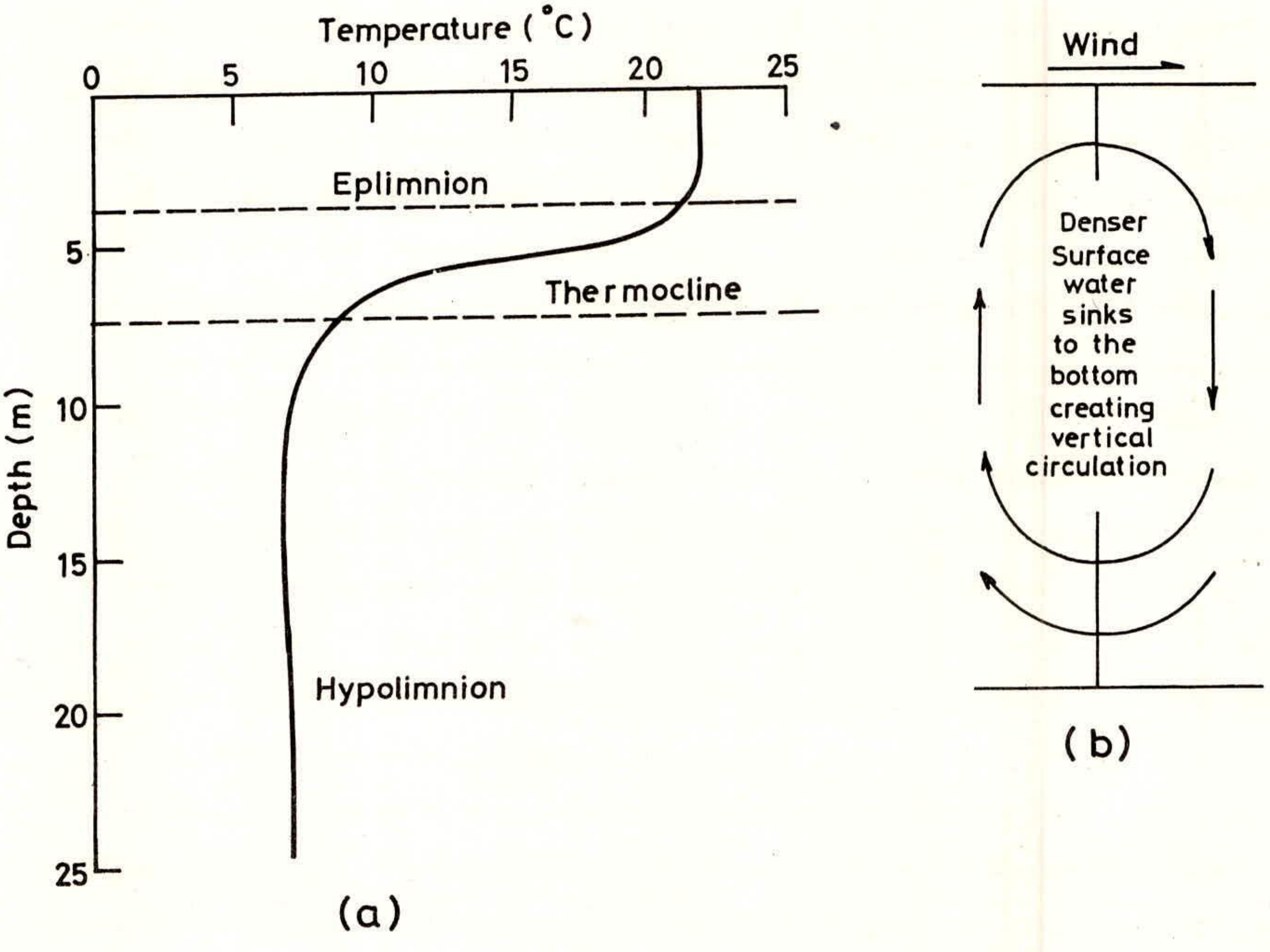

FIG. 1 a)-TEMPERATURE PROFILE OF A TYPICAL TEMPERATE FRESHWATER LAKE IN SUMMER (AFTER BERNER ET AL., 1987)
b) SPRING AND AUTUMN OVERTURNS (AFTER HAMMER, 1977)

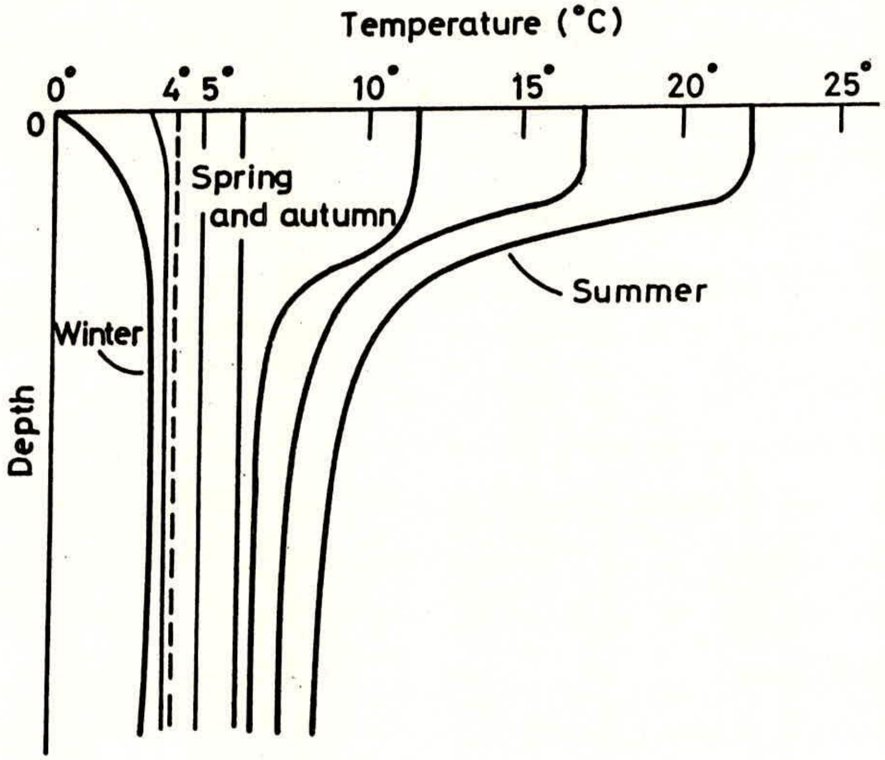

FIG. 2- SCHEMATIC EVOLUTION OF TEMPERATURE Vs DEPTH PROFILES OVER THE YEAR FOR A TYPICAL DIMICTIC LAKE OF TEMPERATE CLIMATE. DASHED LINE REPRESENTS THE MAXIMUM DENSITY AT 4°C (AFTER BERNER ET AL.,1987)

any, prevents any wind stirring of the deeper water and situation called winter stratification is attained which is opposite to the summer stratification. In winter stratification the deeper water is isolated from the atmosphere (Berner et al., 1987) (Fig. 2).

As spring approaches, temperature increases and surface water starts warming up. When the surface water temperature reaches that of the deep water, stratification unstability occurs and consequently a spring overturn takes place (Figure 1.b, 2). The water then warms up from top to bottom during further warming until stable density stratification is established inhibiting the vertical mixing. Further heating in summer increases this stratification until the original situation of summer is reattained and thus the seasonal cycle is completed (Berner et al., 1987) (Figure 2).

This thermal behaviour of lakes varies from region to region where the temperature variation differs and the thermal seasonal cycle is seen only in those lakes where the basins are sufficiently deep enough to allow the stratification mixing and formation of hypolimnion.

The thermal classification of lakes takes into account the altitude , geographical location with respect to latitude and the depth of the basin (Reid & Wood, 1976).

Depending upon the lake water stratification and number of overturns per year the lakes are classified as follows :

2.4.2 Amictic Lakes

In these lakes there is no mixing of surface and bottom water due to permanent ice cover on the top of the lake. These lakes are completely insulated from outside influences of water and other factors.

Examples : Antarctic and high altitude lakes (Das,1991).

2.4.3 Holomictic Lakes

These lakes are wholly mixing that is circulation is complete and extends upto the bottom. In these lakes the temperature the hypolimnion decreases uniformity to the bottom (Reid & Wood, 1976).

Depending upon the overturns the holomictic lakes are further divided into various subclasses as follows :

2.4.3.1 Dimictic Lakes

These lakes undergo two overturns per year. These lakes are typical of the temperature zone and in high altitude subtropical zone where the temperature variation from summer to winter is not drastic. These are also called temperate lakes (Reid & Wood, 1976). The two overturns take place in spring and autumn. Thermal stratification is direct in summer and it is inverse in winter.

For a dimictic lake, when it overturns in the spring and fall, nutrients are carried to the surface where they stimulate phytoplankton growth. When the lake water is stratified in summer the dead plankton and organic debris accumulate and decompose on the bottom consuming oxygen from hypolimnion in the process and releasing nutrients. Gradually a layer of organic rich sediments builds up. If the lake was originally deep, the hypolimnion has a large volume and can supply adequate oxygen for organic decomposition. If however the lake was originally shallow, as it fills up, the volume of the hypolimnion becomes too small to supply oxygen to counteract organic matter decomposition and as a result the bottom becomes depleted in oxygen in summer (Berner et al., 1987).

Three orders of dimictic lakes are recognized (Reid & Wood, 1976). These are, 2.4.3.1.1 First Order Lakes

These lakes have bottom water temperature of about 4^oC in summer with little or no circulation.

2.4.3.1.2 Second Order Lakes

These lakes are stratified and have bottom temperature well above 4^oC in summer.

2.4.3.1.3 Third Order Lakes

These lakes are unstratified and their circulation is continuous.

2.4.3.2 Monomictic Lakes

In these lakes there is only one mixing of surface to bottom water per year. The mixing may be either in summer or in winter. They are further divided into cold monomictic lakes and warm monomictic.

2.4.3.2.1 Cold Monomictic Lakes

In these lakes there is only one overturn which occurs in summer. This is typical of polar or high altitude cold climates where the water temperature never exceeds 4^oC at any depth and as a result there is a continuous mixing during summer. In winter the lake is covered by ice and is thermally stratified. The thermal stratification here is inverse with top water temperature of 0^oC and bottom water temperature of 4^oC (Das,1991).

Examples : Some polar lakes and most sub - polar lakes (Das, 1991).

2.4.3.2.2 Warm Monomictic Lakes

In these lakes the only overturn occurs in winter. This is typical of the subtropical regions where the temperature of water never falls below 4^oC at any depth. Hence these are also called as subtropical lakes(Reid & Wood, 1976). These lakes are directly stratified in summer which is maintained till the onset of winter when the temperature drops. Top waters have $1^{o}C$ - $2^{o}C$ temperature and bottom water temperatures are $8^{o}C$ - $4^{o}C$ (Das,1991).

Examples : Most subtropical lakes such as Lake Nainital and Lake Bhimtal in India (Das, 1991). and lakes of the Italian Lake District (Berner et al., 1987).

2.4.3.3 Oligomictic Lakes

These lakes are typical of the low elevation tropical zones where the air temperature changes very little over the year. As a result well defined cyclic temperature versus depth region in lakes is not present. These are also called tropical lakes.

The water temperature is always considerably higher than $4^{o}C$ (Das, 1991). These lakes mix rarely at irregular intervals. Hence the well defined overturns are missing. Because of rare circulation of water these lakes are characterized by a condition of hypolimnetic oxygen depletion (Reid & Wood, 1976). The overturn depends upon the variety of unpredictable factors and stratification is variable from place to place (Berner et al., 1987).

Examples : Bhopal Lakes, India (Das, 1991).

2.4.3.4 Polymictic Lakes

In these lakes mixing is continuous but occurs at low temperature usually just over $4^{o}C$ (Das, 1991). These lakes are characteristic of the high mountains in the equatorial regions (Reid & Wood, 1976). Polymictic lakes, by virtue of the continuous circulation exhibit a generally high, uniformly distributed oxygen content throughout the year (Reid & Wood,1976).

Stratification does not develop due to heat loss to a relatively uniform environmental temperature (Reid & Wood, 1991).

Examples : Lake Victoria, Africa (Das, 1991).

2.4.4 Meromictic Lakes

These lakes are permanently stratified and therefore do not circulate completely throughout the year (Bowen, 1982). These lakes undergo only partial mixing (Reid & Wood, 1976) (Figure 3). The bottom portion of these lakes usually contain large quantities of dissolved salts and these increase the density (Reid & Wood,1976). The bottom layer is warmer than the top layer though the bottom water is not less dense than the upper water. Stratification occurs because of the vertical, chemically produced density gradient (Bowen, 1982). The non circulating (non mixing) bottom of the lake is called monolimnion or metalimnion. The density gradient is referred to as chemocline. The water above the chemocline in which thermal stratification occurs is called as mixolimnion (Bowen, 1982). The mixolimnion is partially mixed by winds. Monolimnion contains a heavy concentration of salts derived from the sediments by bio-chemical process. Heat in the bottom layer is apparently gained from the bacterial activity and from insolation. Since there is no circulation by currents heat is mainly lost through conduction.

Water of the monolimnion are usually anaerobic (Reid & Wood, 1976). Depending upon the circulation pattern above the chemocline, the oxygen content may take the form of a clinograde curve (Reid & Wood, 1976).

Example : Lake North Gate in Michigan, U.S.A..(Thurman, 1985), Soap Lake in Washington (Reid & Wood, 1976).

A slightly different classification is suggested by Berner et al., (1987). They have added two special categories of lakes that is the very shallow lakes and the very deep lakes. Their classification is given in table 2.1.

According to them, very shallow lakes are always stirred

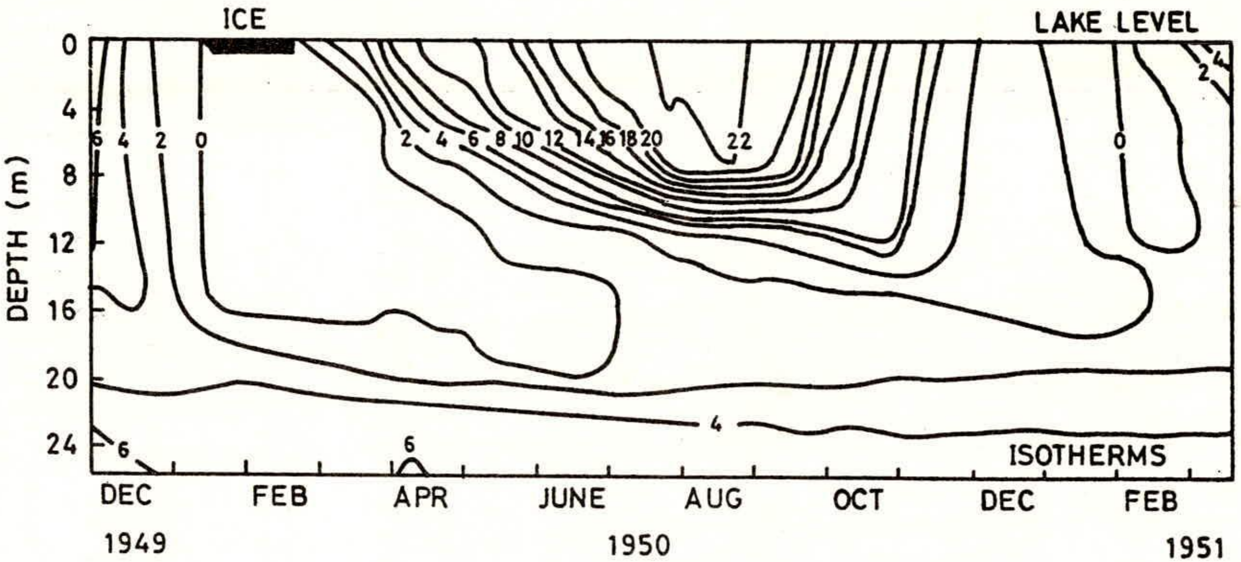

FIG. 3 - SEASONAL TEMPERATURE VARIATIONS IN A MEROMICTIC LAKE
(AFTER REID AND WOOD, 1976)

by winds and hence never develop stratification or a hypolimnion, on the contrary in the very deep lakes like those of the East African Rift system, the large volume of the deep water allows only little or no heating or cooling of the hypolimnetic water during spring and autumn. In other words deep water acts as a sort of thermal buffer. Below a given deptoh there is a large reservoir of maximum density deep water at 4^{o}C that is not affected by wind stirring. Hence this water does not overturn and remains permanently isolated from the atmosphere (Berner et al., 1987).

Table 2.1 Classification of fresh water lakes by Berner et al.,(1987).

I. Holomictic Lakes (mixing between epilimnion & hypolimnion)
  A. Dimictic lakes (mixing twice a year).
  B. Monomictic Lakes (mixing once a year).
    1. Warm monomictic.
    2. Cold monomictic.
  C. Oligomictic lakes (mixing irregularly).
  D. Shallow Lakes (continuous mixing).
  E. Very Deep Lakes (mixing in upper portion of hypolimnion).

II. Meromictic Lakes (no mixing between epilimnion and hypolimnion).

2.5 Classification of Lakes Based on Their Biological Properties

Based either on the concentration of the plant nutrients or on the productivity of the organic matter or algal population, lakes are classified according to their trophic states. This classification was begun by Naumann (Thurman, 1985). It is as follows :

I. Oligotrophic Lakes   II. Eutrophic Lakes

III. Dystrophic Lakes   IV. Mesotrophic Lakes

2.5.1 Oligotrophic Lakes

Oligotrophic lakes are at their lowest trophic level and are usually deep with large volumes of relatively clear water. They have a low concentration of nutrient elements such as nitrogen and phosphorus. Phosphorus is generally less than 10 μg / litre (Berner et al., 1987). Rock weathering, soil transport and atmospheric precipitation are the major sources of phosphorus for an oligotrophic lake. (Berner et al., 1987). The D. O. C. (dissolved organic carbon) content of oligotrophic lakes is very less generally in the range of 1 to 3 mg / litre. Its total dissolved amino acid concentration is 30 to 300 μg / litre and concentration of humic substance is 0.5 to 1.00 mgc / litre (Thurman, 1985). The lack of nutrients results in few plants and hence a low rate of organic matter production by photosynthesis.

The depth of water is usually above 15 to 25 m (Berner et al., 1987). They have a large hypolimnion and narrow epilimnion with a thermocline and broad metalimnion (Das, 1991). Oligotrophic lakes usually have an orthograde (vertical) oxygen curve indicating an even distribution of oxygen throughout the water column due to low productivity and subsequent absence of oxygen depleting organic matter. In addition, oligotrophic lake water have deeper oxygen generating zones than eutrophic lakes because of penetration of light to a relatively greater depth thereby reducing the depth at which photosynthesis can occur (Pinto, 1981). Figure 4.a shows an orthograde curve for Skaneateles Lake, New York. An orthograde curve showing decrease in dissolved oxygen near lake bottom in a New Jercy quarry is shown in figure 4.b.

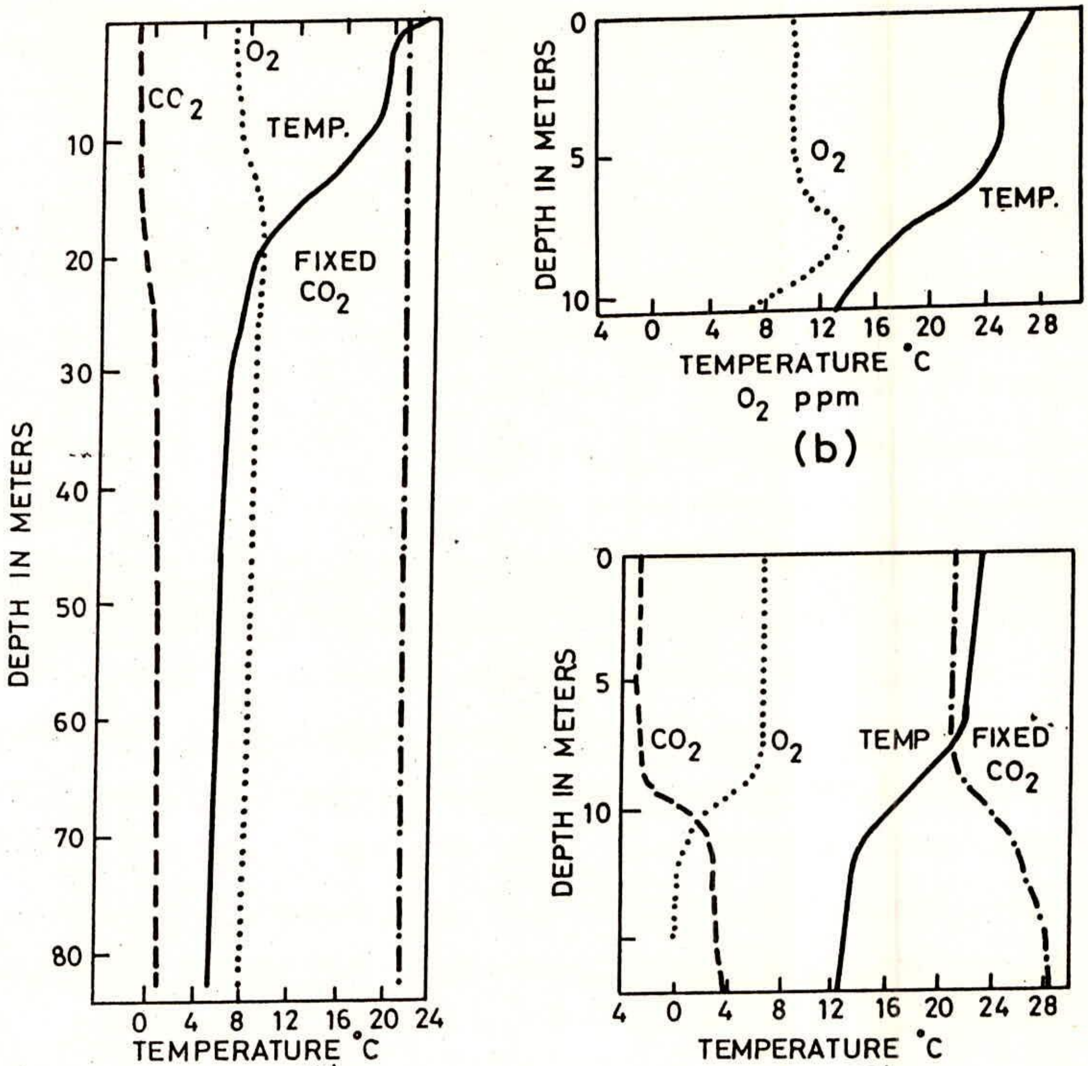

FIG. 4 - VARIOUS TYPICAL OXYGEN CURVES IN LAKES

(a) ORTHOGRADE CURVE FOR SKANEATELES LAKE, NEW YORK, AUGUST, 1910 ;

(b) ORTHOGRADE CURVE SHOWING DECREASE IN DISSOLVED OXYGEN NEAR LAKE BOTTOM IN A NEW JERSEY QUARRY ;

(c) CLINOGRADE CURVE OF VERTICAL OXYGEN DISTRIBUTION IN CONESUS LAKE, NEW YORK, AUGUST 1910 (AFTER REID AND WOOD, 1976)

The oxygen content of hypolimnion is less than 50 % (Berner et al.,1987). The iron is normally contained as the nonsoluble ferric complex (Reid & Wood, 1976). These lakes have a diversified bottom fauna and deep water fishes. Bottom sediments are generally sandy inorganic with low nitrogen (Berner et al., 1987). Fish production is low (Hammer, 1977).

Most mountain lakes are oligotrophic. Examples of oligotrophic lakes include Lake Geneva in Switzerland, Great Slave Lake in N.W.Canada (Berner et al., 1987), Lake Superior, Lake Huron in U.S., Lake Bhimtal, Lake Nakuchiami, Lake Sattal in Kumaun Himalaya ; India, Lake Tulyan, Lake Kishensar, Lake Kounsang, Lake Sheshnag, Lake Vishensar , Lake Shyok ; all in Kashmir, India (Das, 1991). Lake Tahoe ; Nevada, U.S. and Lake New Hampshire, U.S. (Thurman, 1985).

2.5.2 Eutrophic Lakes

Eutrophic lakes are at the highest trophic level and are nutrient rich with high concentration of plankton due to high productivity. Phosphorus is above 20 µg / litre (Berner et al., 1987). Organic matter is either autochthonous (produced in lakes) or allochthonous (transported from environment) (Reid & Wood, 1976).

The water of these lakes is murky with suspended plankton and often depleted in oxygen at depth (Berner et al., 1987). They have a narrow hypolimnion and large epilimnion. Hypolimnion is poor in oxygen due to high biological demand to decompose organic matter (Berner et al., 1987). Eutrophic lakes typically exhibit an oxygen distribution in the water column that is clinograde with high dissolved oxygen in the epilimnion which drops sharply at the metalimnion and remains low in the hypolimnion. Clinograde curve of verrtical oxygen distribution for

Conesus Lake is shown in figure 4.c. High level of epilimnetic oxygen results from oxidation of dead algae and other organic matter at the depths. The more severely eutrophic a lake is the greater will be hypolimnetic oxygen depletion because there will be more oxygen material undergoing oxidation.

Microscopic algae and aquatic weeds are the major phytoplankton (Hammer, 1977). Bottom fauna are tolerant of low oxygen conditions. Deep water fishes are absent. Sediments are mostly organic - rich in nitrogen (Berner et al. , 1987). The D.O.C. content of eutrophic lake is 3 to 34 mg / litre whereas the concentration of dissolved amino acid and humic substances are 1.5 to 5.0 mgc / litre (Thurman, 1985). Figure 5 shows the character of a small eutrophic lake.

A lake once becomes eutrophic it remains so at any rate for a very long time even if nutrients from point sources are reduced. However the rate of eutrophication of a lake can be retarded by reducing nutrient input (Hammer, 1977).

Examples : Dal Lake, Nagin Lake, Wular Lake, Anchor Lake, in Kashmir and Lake Nainital in U.P.; India. Lake Tanganyika, Lake Chad, Nasser Lake ; Africa. Lake Mendota and Lake Michigan in U.S. (Das, 1991). Lake Mosso in Denmark, Lake Suma in Japan. (Thurman, 1985).

Figure 6 shows the comparison between an oligotrophic and eutrophic lake.

2.5.3 Mesotrophic Lake

This is a transient state of lake from oligotrophic to eutrophic state. These lakes have intermediate properties between those of oligotrophic and eutrophic lakes (Berner et al., 1987). Their major properties are moderate fertility, low aquatic plant population, greenish water and moderate production of fish

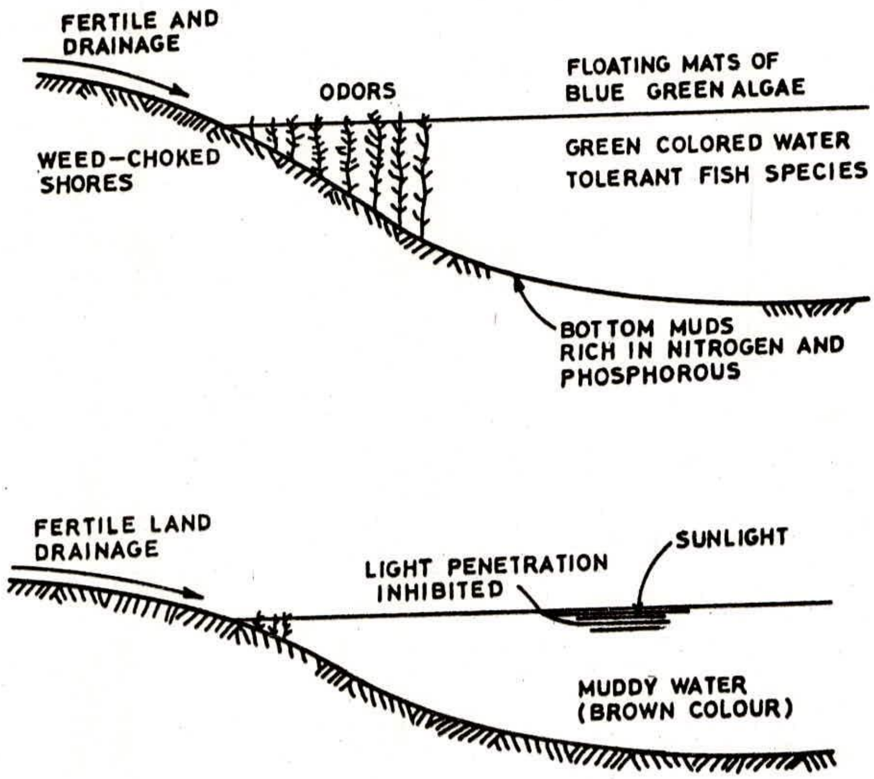

FIG. 5-THE CHARACTER OF SMALL EUTROPHIC LAKE

(a) FERTILE, CLEAR WATER LAKE WITH LOW SOIL TURBIDITY EXHIBIT HIGH PRODUCTIVITY

(b) TURBID, LIGHT INHIBITING WATER PREVENT EXCESSIVE PLANT GROWTH BY LIMITING PHOTOSYNTHESIS (AFTER HAMMER, 1977)

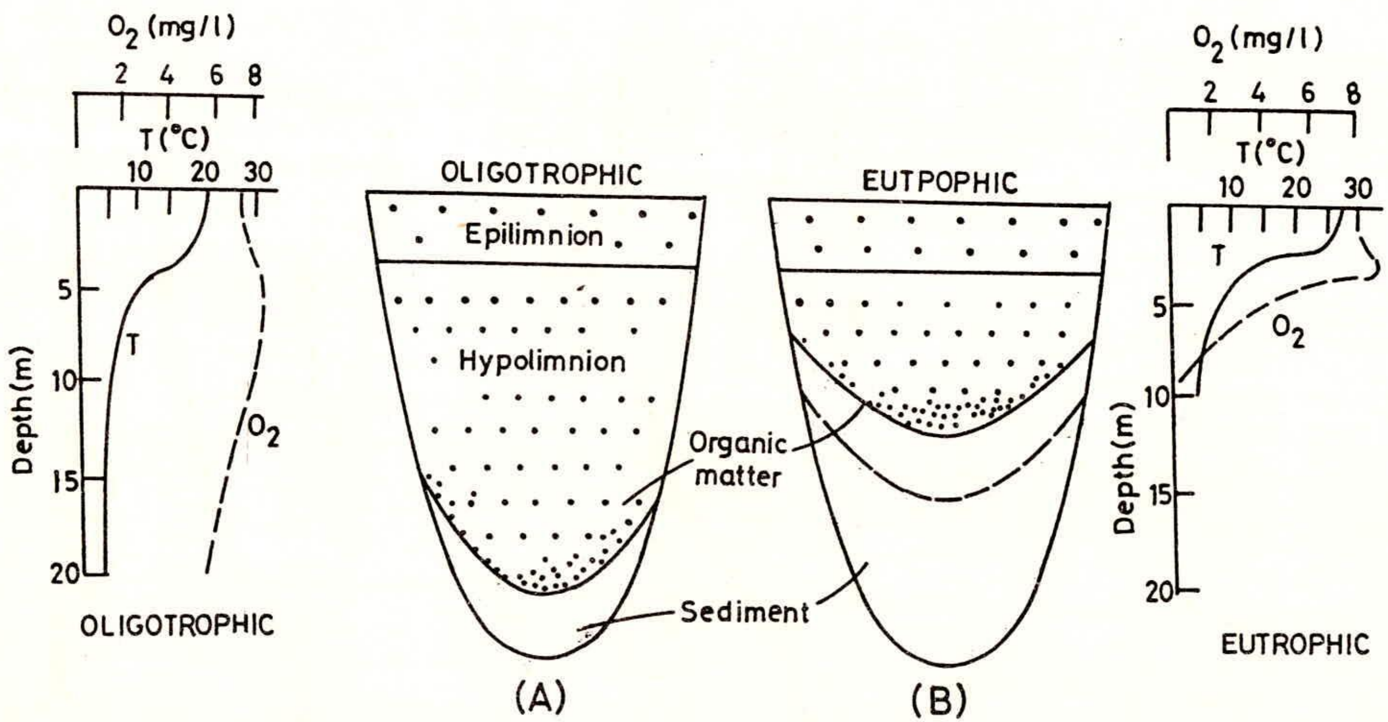

FIG. 6 – COMPARISION BETWEEN AN OLIGOTROPHIC LAKE (A) AND A NATURALLY EUTROPHIC LAKE (B) (AFTER BERNER ET AL.,1987)

(Hammer, 1977). The D.O.C. content is 2 to 4 mg / litre and concentration of humic substance is 1.00 to 1.50 mgc/litre (Thurman, 1985).

2.5.4 Dystrophic Lakes

These are shallow brown water lakes. Brown colour is due to the organic compounds. They have either very few or no organisms except a few aquatic insects occasionally (Das, 1991). They contain H_2S and ammonia. Their N/P ratio is very high. They have a low pH. Metallic pollution is present. D.O.C. content is 20 to 50 mg / litre and total humic substance concentration is 10 to 30.00 mgc / litre (Thurman, 1985). Fishes are absent. Diptera and Coleoptera are the major biological indicators of these lakes (Das, 1991).

Lake Laga-da-Orte in Italy and Lower Bhopal lake, M.P. ; India are the examples of dystrophic lakes (Das, 1991).

Berner et al. (1987) report that Chapra and Dobson have classified lakes into oligotrophic, eutrophic and mesotrophic on the basis of their primary production of organic matter using specific boundary values. Their classification is given in table 2.2.

Harper (1992) reports that Vollenweider in 1968 gave a trophic state classification of lakes on the basis of their phosphorus and nitrogen concentrations. He classified lakes in five classes. His classification is presented in table 2.3.

Table 2.2 Classification of lakes by Chapra and Dobson

parameter	oligotrophic	eutrophic	mesotrophic
i)Primary production of organic matter through photosynthesis by phytoplankton (gm organic $c/m^2/yr$)	< 150	> 250	150 to 250
ii)Phytoplankton biomass (measured as total concentration of chlorophyll A) (μg / litre)	< 3	> 6	3 to 6
iii)Phosphorus concentration (μg p / litre)	< 10	> 20	10 to 20
iv)Water transparency or clarity (measured by secchi depth) (metres)	> 5	< 3	3 to 5
v)Level of hypolimnion oxygen during summer stratification (%)	> 50	< 10	10 to 50

Table 2.3 Trophic state classification of lakes based on total P and N by Vollenweider (1968)

Trophic classification	Total P ($\mu g/l$)	Inorganic N ($\mu g/l$)
1.Ultra-oligotrophic	< 5	< 200
2.Oligo-mesotrophic	5 - 10	200 - 400
3.Meso-eutrophic	10 - 30	300 - 650
4.Eu-polytrophic	30 - 100	500 - 1500
5.Polytrophic	> 100	> 1500

(Source : D. Harper, 1992, pp 196.).

2.6 Classification Based on the Chemical Properties of Lakes

2.6.1 General

Lakes have been variously classified on the basis of the chemical nature of its water, its CO_2 content and calcium content. These classifications are given below.

2.6.2 Classification based on the chemical nature of lake water.

On the basis of the chemical nature of their waters, lakes can be classified as :

2.6.2.1 Acid Lakes

The water of these lakes generally have pH values of 6 and / or less (Berner et al., 1987). Acid lakes have a distinctive chemical composition. They have hydrogen - calcium - magnesium - sulfate waters. Sulfate concentration is generally 3 to 5 times than that in the fresh water lakes (Berner et al., 1987).

Fresh water lakes may become acid lakes due to acidification of dilute fresh waters or because of acid precipitation. Acidificaton of lakes occur in areas that are unusually sensitive to acid precipitation because of a characteristic bedrock geology and soil. They are underlain by weathering resistant igneous, and metamorphic rocks or non calcareous sandstone and have thin patchy acid soils, neither of which are conducive to acid neutralization. Many lakes may be naturally acid due to presence of organic acids particularly humic acids (Berner et al., 1987). Lakes fed by head water streams which are more acidic than large streams may become acid lakes.

Acid lakes are characterized by steep slopes and exposed bedrock with little vegetation and soil development. In this way they receive precipitation virtually unaffected by the soil.

The increased Ca and Mg concentrations in acid lakes are often accompanied by increased dissolved aluminium and heavy metal concentrations (Berner et al., 1987). Infact, the aluminium concentration of acid lakes tends to be higher than the similar non - acid lakes. The fish population in acid lakes is also less (Berner et al., 1987).

2.6.2.2. Saline Lakes

All saline lakes are formed by closed lakes under desert or semi arid conditions where the evaporation rate is too high and there is a lack of outflow to present the subsequent discharge of salts to the seas (Bowen, 1982).

There is no definite boundary to define saline lakes. According to Hardie et al., (1978), lakes with more than 5000 ppm dissolved solutes are considered as saline lakes. Some lakes are more saline than even the oceans. Whereas the oceans contain 35 $^{o}/oo$ salts, the Great Salt Lake, for instance, has a dissolved solid content exceeding this by a factor of four. The Dead Sea with 246 $^{o}/oo$ salt content is even more saline (Bowen, 1982). Some salt lakes are intermittent and exist for only a short period after heavy rains. With subsequent intense evaporation they disappear. Such lakes are usually formed after rains in dry regions and these temporary lakes are called Playas. Because of the saline nature of water of these lakes, these are also called Salinas. In the Black Rock desert of Nevada, a Playa lake appears and remains during winter and covers an area of 1200 sq. km or more. But its depth seldom exceeds few centimeters. (Bowen, 1982). Dissolved salts in saline lakes however can not be built up for ever and ultimately saturation is reached with respect to soluble minerals (Berner et al., 1987).

Saline lakes are often highly alkaline and exhibit a high pH which is higher than 10 (Berner et al., 1987). Saline lakes may contain a variety of salts and unusual aquatic life that have extraordinary tolerance to high salt concentrations. Saline lakes are the sources of economically important chemicals such as lithium, borax, potassium, zeolite etc.. An interesting characteristic of the saline lakes is the formation of unusual minerals like Mirabilite ($Na_2SO_4.10H_2O$) , Gaylussite [$CaNa_2(CO_3)_2.5H_2O$] and Analcime ($NaAlSi_2O_6.H_2O$) etc. (Berner et al., 1987).

Most favourable conditions for the formation of saline lakes are to be found in the rain shadow basins. Such basins provide the unique combination of high mountain acting as a precipitation trap but with arid valley floors. For example the saline lakes located east of the crest of Andes and Cordillerans of south and north America. The least favourable arid areas are deserts with low relief such as Sahara deserts. Saline lake brine are dominated by relatively few major solutes namely SiO_2, Ca, Mg, Na, K, HCO_3, SO_4 and Cl (Eugster et al., 1978).

Examples of saline lakes are Lake Magadi and Chad in Africa, Bosque Lake in British Columbia, Great Salt Lake of Utah, Dead Sea in Israel and Jordan (Eugster et al., 1978) and Sambhar Lake in India.

2.6.2.3 Fresh Water Lakes

All naturally occurring lakes are mostly fresh water lakes. These lakes also differ widely in contents but tend to assume the composite dissolved solid characteristic of the water of the inflowing streams. This is because of the balance between the inflow and outflow (Bowen, 1982).

The pH of fresh water lakes ranges from 6 to 8 and they generally have calcium - magnesium - bicarbonate waters (Berner, 1987).

2.6.3 Chemical classification of lakes based on their CO_2 content

On the basis of their CO_2 content Reid et al., (1976), have classified lakes as :

i) Soft Water Lakes

ii) Medium Water Lakes and

iii) Hard Water Lakes

2.6.3.1 Soft Water Lakes

These lakes are common in regions of low lands and bogs. They have a pH of 4 to 6. Their waters have a high free carbon dioxide content ; nearly about 200 ppm. The bound CO_2 as carbonate is low ; usually less than 9 to 10 ppm (Reid & Wood, 1976).

2.6.3.2 Medium Water Lakes

These lakes have a pH value which is around 7. The free gaseous carbon dioxide in these lakes varies widely, frequently showing supersaturation relative to the partial pressure of the gas in the atmosphere. The bound carbon dioxide of these lakes is upto 30 to 35 ppm. (Reid & Wood, 1976). These lakes show a moderately increased calcium concentration in the hypolimnion during stratification (Reid & Wood, 1976). The medium water lakes, though contain a relatively less mass of living matter per unit area, often harbour a greater variety of plants and animals. (Reid & Wood, 1976).

2.6.3.3 Hard Water Lakes

These lakes occur in regions where the substrata contain easily dissolved minerals. These lakes are characterized by negative values for free carbon dioxide due to withdrawl of bicarbonates at a higher rate than the carbonates are precipitated. These lakes have a high pH values of 8.5 and above. Bound carbon dioxide of these lake waters is over 35 to 40 ppm, often reaching 200 ppm or even more. Calcium and magnesium carbonate are often precipitated as marl (Reid & Wood, 1976).

These lakes contain high living matter per unit area than soft water lakes. The percentage of calcium and magnesium are 53 % and 34 % of the total cations present respectively. The increase of these ions in hard water as compared to the soft waters, takes place at the expense of two alkali metals ; sodium and potassium. The hypolimnion of hard water lakes characteristically contains a greatly increased load of calcium (Reid & Wood, 1976).

R. Cushmann et al., (1980), have used following boundary values :

i) Very Hard Water Lakes : 180 to above 240 mg of Ca CO_3 / litre

ii) Hard Water Lakes : 120 to 180 mg of $CaCO_3$ / litre

iii) Moderate Water Lakes : 60 to 120 mg of $CaCO_3$ /litre

iv) Soft Water Lakes : less than 60 mg of $CaCO_3$ / litre

Examples :

Very Hard Water Lakes : Lake North-West Ohio & South-East Michigan U.S.A.

Hard Water Lakes : Lake Michigan, U.S.A.

Soft Water Lakes : Lake Superior, U.S.A.

2.6.4 Classification of lakes on the basis of calcium content

Reid & Wood , (1976), report that W. Ohle, a German limnologist, proposed a following scheme of lake classification in 1934 on the basis of their calcium content.

2.6.4.1 Poor Lakes

They have calcium content of less than 10 mg / litre.

2.6.4.2 Medium Lakes

These lakes have calcium content between 10 to 25 mg / litre, and,

2.6.4.3 Rich Lakes

In these lakes the calcium content is more than 25 mg / litre.

2.7 Classification of Lakes Based on Presence or Absence of Outlets

2.7.1 General

Reid and Wood, (1976), have given the following classification of lakes on the basis of presence or absence of outlets :

2.7.2 Open Lakes

These lakes posses some form of outlet. The effluent may be a stream which drains the lake or drainage or may be by seepage into the basin substrata in the form of groundwater.

Open lakes serve as settling basins for sediments introduced by improving streams, because the tributary loses its carrying capacity as it enters the calm water of lake. The water in the effluent stream usually is clear than that in the influent stream attesting to the settling action of the lakes. Salts are removed with the stream outflow or seepage and lake remains fresh.

Example : Lake Geneva in the Western Alpines (Reid & Wood, 1976).

2.7.2 Closed Lakes

These lakes lack outlets and lose water mainly by evaporation. They are formed under extremely diversified conditions such as by tectonic rifting, block faulting or thrusting by volcanic cratering or lava flow damming with vegetation or sediments such as landslides or barrier bars or by wind deflation etc.. In arid and semi arid regions streams often flow into lakes without effluents. Under high evaporation and low precipitation these are usually saline.

Example : Salt Lake in Great Basin of Western U.S.A. (Reid & Wood, 1976).

2.7.4 Seepage Lakes

These are form of closed lakes. In these lakes water passes out as groundwater discharge. These lakes may come across an extreme drop of water level and occasional complete emptying due to lowering of water table or solution of a portion of the basin, permitting drainage into underground channels or the opening of a previously clogged channel to sub-surface. These conditions are generally come across in limestone areas (Reid & Wood, 1976).

According to Lin et al., (1986), out of the 14,000 lakes in the state of Wisconsin ; U.S.A., 10,000 are seepage lakes and many are quite low in alkalinity.

Ferguson and Zoemensky (1981) have given the following brief classification,

i) Open or Exorheric Lakes - lakes having outlets.

ii) Closed or Endorheric Lakes - lakes lacking outlets.

iii) Intermittent or Ephemeral Lakes - in these lakes there is outflow but only during high water stages.

Whereas, as early as in 1934, Birge and Inday studied 529 lakes and classified them into two types, reports Thurman, (1985). These are,

i) Seepage Lakes

These lakes do not have stream draining into or out of them. They are recharged by groundwater only and are characterized by low concentrations of both organic and inorganic matter. They have low P.O.C. (particulate organic carbon) which is 1.09 ml / litre (Thurman, 1985).

ii) Drainage Lakes

In these lakes surface water is the major input. These lakes do have outlets. They contain more inorganic and organic matter. They have greater average concentration of P.O.C. which is 1.5 ml / litre (Thurman, 1985).

2.8 Classification Based on the Geometric Shape of the Lakes

2.8.1 General

Lakes vary widely in size and shape. The form of a lake is a function of its origin unless the lake is reshaped by a geological or organic process.

Under this classification lakes can be classified as,

I) Irregular Lakes and

II) Geometrically Shaped Lakes.

2.8.2 Irregular Lakes

These lakes lack a definite geometrical shape. They are formed mostly by glacier action or action of the continental ice or scouring of rocks by glaciers or by deposition of debris by a retreating glacier with subsequent damming of streams.

Most of the lakes are originally irregular in shape. However, they may change their shapes due to intrinsic processes such as currents, sedimentation and freezing and other external factors like human activity (Reid & Wood, 1976).

2.8.3 Geometrically Shaped Lakes

These lakes have some geometric shape. A descriptive terminology developed by Hutchinson in 1957,(vide Reid & Wood, 1976) distinguishes seven principle forms. These are,

2.8.3.1 Circular Lakes

These lakes are circular in shape. They are mostly of volcanic or meteoric origin especially craters and calderas. These could be also typical solution sinks like dolines in Florida (Reid & Wood, 1976).

2.8.3.2 Sub-circular Lakes

They are sub-circular in shape and are mostly formed due to valley glaciation. They include cirque and tarns (Reid & Wood, 1976).

2.8.3.3 Elliptical Lakes

These lakes are elliptical but they are very unusual.

Example : Carolina Bay Lakes (Reid & Wood, 1976).

2.8.3.4 Sub-rectangular Lakes

Lakes of tectonic origin situated in grabens usually show an elongate, angular surface form of roughly rectangular shape. (Reid & Wood, 1976).

Examples : Lake Tahoe (Reid & Wood, 1976).

2.8.3.5 Dendritic Lakes

Lakes having many arms or embayments are called dendritic lakes. They are formed when a very highly branched stream valley is impounded by the development of a dam (Reid & Wood, 1976).

2.8.3.6 Lunate Lakes

These lakes are having crescent shaped basins. Generally ox-bow lakes formed in a mature river are lunate (Reid & Wood, 1976,).

2.8.3.7 Triangular Lakes

These lakes are triangular in shape and are generally seen in the coastal regions when the barrier beach or sand spit develops across the mouth of a stream valley.

2.9 Classification Based on the Water Balance of Lakes

This classification is of importance for the hydrological studies of lakes because it is based on a hydrological parameter of lakes unlike most of the other classifications. It was proposed by Szesztay in 1974 (vide Kuusisto, 1985). According to him the lake classification based on the water balance can help in detecting the changes in the water levels of the lakes both manmade and natural. His classification considered the following three factors,

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

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

3. The magnitude of the mean annual flux (F) which is the sum of the inflow plus precipitation (F) or the sum of outflow and evaporation (F).

He has divided the lakes into nine classes. The classification is presented in Figure 7.

The subdivision of the i - and O - axes into three equal parts defines nine classes of lakes viz. I-E, I-OE, I-O, IP-E, IP-OE, IP-O, P-E, P-OE, P-O.

Lakes belonging to the class I-O are characterized by the dominance of inflow and outflow. They generally have a highly unstable water balance. Usually they also have a high value of the annual flux, F. Most of the man made lakes fall in this class. Lakes coming under P-E class are climate controlled. Their water levels change in accordance with the climatic fluctuations. Lakes of the classes P-OE, P-O and IP-O usually have small catchment area and are seen in humid areas only. The class P-E contains lakes which are dominated by precipitation and evaporation. Closed lakes come under this category.

Kuusisto (1985) suggests that additional water balance parameters like the ratio of the mean annual flux, F to the volume of the lake, the ratio of the mean annual inflow to the volume of the lake and the range of water storage, either absolute or relative, should also be considered for classifying the lakes on the basis of the water balance.

2.10 Other Minor Classifications of Lakes

Apart from the major classifications of lakes discussed so far, there are a few more classifications given by some scientists. But these classifications are of relatively less importance.

Winter (1977) reports that Bogoscovsky (1966)

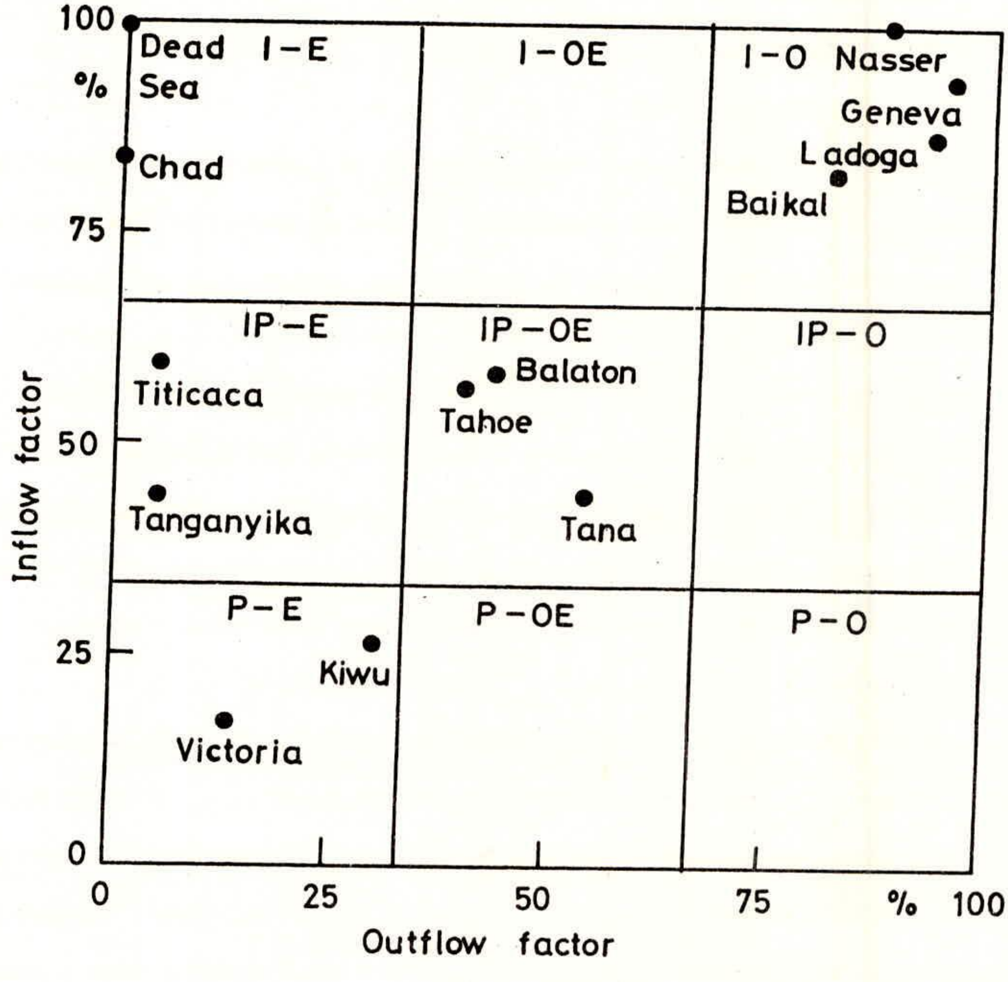

FIG. 7 – CLASSIFICATION OF LAKES BY WATER BALANCE CRITERIA (AFTER KUUSISTO, 1985)

grouped the lakes of Russia on the basis of the components of hydrologic budget into two types ; those that have outflow predominant and those that have evaporation predominant. In this classification, reports Winter, the subtypes within each major group are based on surface water inflow, outflow, precipitation - evaporation relationship. Groundwater inflow and outflow are not directly considered.

Winter (1977) has also given the classification proposed by Born et al.,(1974), based on the hydrologic aspects of lakes. They suggest two broad types of lakes ; those dominated by groundwater and those by surface water. Each group is subdivided according to the efficiency of the lake water system that is high or low (Winter, 1977). (Due to the unavailability of the original literature the above classifications are not discussed at length).

Depending upon D. O. (dissolved oxygen), a lake can be oxic if it contains dissolved oxygen and anoxic if it doesn't (Henderson ,1979).

Besides all the classifications discussed so far, lakes are classified in the following two ways also. But the lack of information on the exact boundary conditions inhibits detailed discussion on these classification. These are,

2.10.1 Classification based on the size of lakes

2.10.1.1 Classification based on the surface area / volume

Lakes are generally classified on the basis of its surface area or volume as small lakes, large lakes and very large lakes.

Generally lakes have a surface area of less than 250 sq.km (Bowen, 1982). Considering this as an average , lakes with surface area less than 250 sq. km can be considered as small lakes and those having more as large lakes. Although according to M. Munawar (1987) lakes with surface area of more than 500 sq. km are called large lakes. There are, however, some lakes with more than thousands of sq. km surface area. These can be considered as very large lakes. For example Lake superior which has an area of almost 80,000 sq. km (Bowen, 1982). While classifying the lakes on the basis of volume, Nace adopted the figure of 10 cu. km or more for accepting a lake as large.

2.10.1.2 Classification based on the depth of water

On the basis of the depths of their waters, lakes can be classified as very shallow, shallow, deep and very deep lakes. The average depth of lakes is about 30 m (Bowen, 1982). So lakes with depths less than 30 m can be considered as shallow lakes and those having depths of more than 30 m can be considered as deep lakes. However, there are some lakes which have a depth of only a few metres. These can be considered as very shallow lakes. On the contrary ,there are some lakes which have depths of greater than thousand of metres for example Lake Baikal in Russia which has maximum depth reaching 1700 m. Such lakes can be considered as very large lakes.

2.10.2 Classification of lakes on the basis of altitudes

Lakes can be classified as high altitude and low altitude lakes depending upon their altitudes above the mean sea level. But an exact boundary value to demark between the two is not known.

A complete classification of lakes based on factors related to lake hydrology is yet to be developed. However, one of such attempts has been made by Winter in 1977 who tried to classify the lakes in North Central U. S. according to their interaction with atmospheric water, surface water and groundwater using the approach of developing a general classification by considering many variables related to lake hydrology with the goal of identifying independent variables upon which to base the classification system. He has however not grouped the lakes into well defined groups or classes.

As can be seen from the various classification systems of lakes discussed so for , a classification system for lakes which can be used for hydrological studies has not been developed hitherto. Most of the classifications consider physics, chemistry and biology of lakes and as such are biased towards the need of the study area although it is true that factors related to lake hydrology are generally not clearly understood. Most of the classifications are also based on a single variable and hence inadequate as Winter (1977) points out,

" classification based on few variables are usually optimal with respect to those variables but are not likely to be of general use. It is generally true that systematic classification have to be modified as additional variables based on many variables are more likely to be of widespread use but might not be totally satisfactory for any purpose."

Thus, there is a need to identify and evaluate the relative importance of relative factors that control lake hydrology especially those that control the interaction of lakes and groundwater and the residence time of lakes to develop a classification system which will be used to apply the results of the study of a lake in one class with confidence to the other lakes in the same class as is rightly observed and told by Winter.

3.0 **Lakes of India**

The statistics of the total lake water resources of India are not available. Studies which are of interest to hydrologists have been undertaken on different lakes of the country by various agencies. The summary of the information available of some of the important lakes of India is presented below.

3.1 Andhra Pradesh

i) Kolleru Lake

It is also called as Colair lake. It is situated 50 km east of Vijaywada at 0 - 5 m altitude. The latitude is $16^{\circ}30'$ - $16^{\circ}45'$N and longitude is $81^{\circ}05'$ - $81^{\circ}20'$ E. It is a large, shallow, freshwater lake with associated marshes; between Krishna and Godavari rivers. The lake exists due to the growth and coalescence of the Godawari and Krishna deltas on either side, leaving a body of sea water in the middle. It is elliptical in shape. The area of the lake is 90,000 ha at the maximum flooding. Maximum depth of the lake is 3 m. The lake is of recent origin. The climate is tropical monsoon climate. Water level in the lake fluctuates. The lake sometimes receives a small quantity of the sea water through Upputeru River. The pH of the lake water is 7.2 - 8.2. The lake shows higher values of alkalinity, hardness and nitrates. Sedimentation in the lake is high. The lake bed is rising at 2.5 cm/yr. The dissolved oxygen content of the lake water is low. Part of the lake is included in the Kolleru Sanctuary established in 1976. Major threats to the lake include expansion of the agricultural area, large agricultural and industrial effluents, large withdrawl for irrigation and bounding and restriction of water inlet.

ii) Pakhal Lake

It is situated 40 km to the east of Warangal at 85 - 90 m height. The latitude is 17°57'N and the longitude 80°00'E. It is a small freshwater lake created in 16 th century. The area of the lake is 1500 ha. It is fed by numerous ephemeral and semiperennial streams. Pakhal wildlife sanctuary was established in 1976 having an area of 86205 ha. Lake Loknavaram lies 20 km to the north of the Pakhal lake.

iii) Pulicat Lake

This lake lies 45 km north of Madras at an elevation of 0 - 10 m. The area of the lake is 72,000 ha. The climate of the area is a tropical monsoon climate. The latitude and longitude of the lake are 13°25' - 13°55' N and 80°03' - 80°19' E respectively. It is the second largest salt lagoon in India. 46,100 ha of the lake is in A.P. and the remaining in T.N. It is fed by two rivers. The lake is separated from the Bay of Bengal by Sriharikota island. There are numerous swamps to the north of the lake having an area of about 20,000 ha. Pulicat Lake Sanctuary has been established.

3.2 Assam

i) Deepar Bheel

It is situated at a distance of 10 kms from Guwahati to it's south - west. The climate of the lake area is humid tropical monsoon climate. Its a permanent freshwater lake. The altitude of the lake is 53 m. The latitude of the lake is 26°05' - 26°09' N and its longitude is 91°36' - 91°45' E. The area of the lake is 4,000 ha. The depth of the lake at the maximum flooding is 4 m. and drops down to 1m in dry season. The main sources of water for the lake are rivers Basistha, Kalmani & monsoon runoff. The lake drains into Bramhaputra river. Half of the lake dries in winter and the shore is converted into rice fields. The forests to the south of the lake are being felled resulting in the soil erosion and siltation. The runoff water carries agricultural fertilizers and pesticide load. There is a proposal of a Bird Sanctuary at the bheel. The lake is proposed for domestic sewage disposal which may have disastrous effects on the wetland ecosystem. The lake water is presently used for the drinking purpose.

ii) Sareswar Bheel

It's a shallow freshwater lake on the flood plains to the north of the river Brahmaputra at a distance of 35 kms north north east of Dhubri. The area of the lake is 1700 ha and it's elevation is 55 m. The latitude is $26^{o}20'$ N and the longitude being $90^{o}05'$E. The climate of the area is a humid tropical monsoon climate. The depth of the lake at maximum flooding is 4 m. and falls to 1 m during dry season. The exposed shoreline is converted to rice fields. A Bird Sanctuary is proposed at the lake.

3.3 Bihar

i) Chaurs of Bihar

These are numerous small freshwater lakes covering an area of 100 to 200 ha. These lakes are mostly ox-bow lakes. They are fed by monsoon and overflow by rivers. Dry out completely in summer. The climate of the lake area is the tropical monsoon climate. The maximum depth of these lakes is 1.5 m in monsoon. The lakes are at an altitude of 30 - 75 m. The lakes are situated between $25^{o}15'$ - $27^{o}00'$N latitudes and $84^{o}10'$ - $88^{o}10'$E longitudes. River Gandak lies to the west of the lakes and Mananda to the east.

ii) Khabartal Lake

It's the largest freshwater lake of North Bihar. It'a an ox-bow lake formed by the meander of the Gondak River. The lake covers an area of 7400 ha at the maximum flooding and 300 - 400 ha in the late summer. The lake is situated at an elevation of 45 m and between 25°35' N latitude and 86°10 'E longitude. The climate of the lake region is the tropical monsoon climate.

3.4 Goa

i) Mayem Lake

Lake Mayem is located in Bicholim ; 33 kms from Panji. It's a freshwater lake surrounded by hills having active iron mines. The latitudes of the lake is 15°34' N and it's longitude is 73°56'E. The area of the lake is 960 ha. The depth of the lake is more than 20 m. Shallower zones are warm monomictic. Transparency of the lake water is maximum at 110 cm in May and is minimum in monsoon. The pH of the deep water is more than the surface water. Dissolved oxygen is more in surface water. Iron mines contribute to siltation.

3.5 Gujrat

i) Ajwa Lake

It is located in Vadodara at an elevation of 50 - 60 m. The lake has an area of 200 - 300 ha. It provides water for irrigation and domestic use. The lake is situated between 22°24'N latitude and 73°24' E longitude. The lake area has a dry tropical monsoon climate.

ii) Hiran Lake

Situated between 21°00' - 22°30' N latitudes and 70°31' - 70°10' E longitudes, Lake Hiran is a shallow lake. The water is used for irrigation and domestic purpose. The climate of the area is dry tropical monsoon climate.

iii) Khijadia Lakes

These are the group of three shallow freshwater lakes situated between 22°32' N latitude and 70°08' E longitude at a distance of 10 km north east of Jamnagar. These lakes are fed by monsoon runoff. A deep channel connects the outflow from these lakes with a tidal channel running down to the sea. Two of the three lakes are bunded. All lakes dry in summer. The main lake is declared as Bird Sanctuary.

iv) Nalsarowar Lake

Located at 60 kms south west of Ahmedabad, this is a large ,shallow, freshwater lake. Previously it was an arm of the sea in the low area between Saurashtra and Gujrat. It is situated between 22°47' N latitude and 72°03' E longitude. It covers an area of 11,500 ha. It has an extensive marshes and reed beds surrounding it. The lake is entirely dependent upon the monsoon rainfall. It dries completely in dry years. It has many islands. Water of the lake is fresh in winter and slightly brackish in summer. The elevation of the lake is 11.5 m and the climate of the lake area is dry tropical monsoon climate. Nalsarowar Bird Sanctuary has been established in 1969.

v) Pavagadh Lake

The lake is located in Vadodara at an elevation of 50 - 60 m. It's area is 100 ha. The latitude is 22°29' N and the longitude is 73°22' E. The lake provides water for the domestic use and irrigation. The climate is dry tropical monsoon climate.

vi) Yadhwan Lake

This lake is situated at an elevation of 50 - 60 m between the 22°29' N latitude and 73°29' E longitude in Vadodara. The lake basin covers an area of 400 ha. The climate of the lake region is dry tropical climate. The lake is a source of water for irrigation and also provides water for the domestic purposes.

3.6 Haryana

i) Lav - Kush Tirath

Located in between $29^{o}55'$ N latitude and $76^{o}00'$ E longitude, its a small fresh water lake on the plains of north west Haryana, 95 kms west north west of Karnal. Its is situated at an altitude of 230 m. The area of the lake basin is 8 ha. The climate of the area is dry tropical monsoon climate.

ii) Sultanpur Jheels

These are a group of shallow fresh water lakes having total area of 144 ha located at 15 kms west of Gurgaon. The latitude and the longitude of the lakes are $28^{o}28'$ N and $76^{o}55'$ E respectively. The altitude is 220 - 230 m. The climate of the region is monsoon climate with very scanty rainfall. The lakes flood during monsoon and heavy rainfall. The siltation in the lakes is on the increasing scale. There is an excavation of the sand for lime industry. Planting of the salt tolerant species in surrounding area and restoration is proposed to reduce erosion. It was declared as Bird Sanctuary in 1971.

3.7 Himachal Pradesh

i) Renuka Lake

Its a long, narrow, oblong shaped lake flanked by two parallel steep hills running east west ; 173 kms south west of Shimla. The altitude is 645 m. The latitude of the lake is $30^{o}36'$ N and it's longitude is $77^{o}27'$ E. The length of the lake is five times the width. Maximum depth, once 25 m, is reduced to 13 m only due to siltation. The maximum length of the lake is 1050 m. Maximum breadth is 204 m. The length of the shoreline is 3214 m. Shoreline development index is 2.155 m. Surface area of the lake is 17694.88 sq. m. Total volume of the lake is 991335.38 cu. m. Mean depth of the lake is 5.66 m. Development of volume index is

1.305 m. Area of the catchment is 254.3 ha. The lake is fed by monsoon and perennial underground seepage water. One fourth of the total lake area is covered by marshes. The lake is monomictic with a distinct stratification during May - October. Overturn commences in November. 90 % of the total catchment area is under the subtropical deciduous reserved forest cover. The climate of the lake area is subtropical monsoon climate. Renuka Lake receives an average annual rainfall of 1,500 mm and the mean maximum temperature reads 38^{o} C.

3.8 Jammu & Kashmir

i) Dal Lake

Its a fresh water lake situated at an altitude of 1587 m between $34^{o}06'$ N latitude and $74^{o}52'$ E longitude in the flood plain of Jhelum river in eastern part of Srinagar city at the foot of Zabarvan mountains. The area of the lake is 1670 ha. The lake comprises four basins viz. Hazaratbal, Bod Dal, Lokut Dal and Nagin Lake and a myriad of inter-connecting channels. The lake has been extensively reclaimed to form man made islands separated by canals and areas of water covered by floating gardens. The inflow channel known as the Telbal Nalla enters the lake from the north and brings water from a high altitude Marsar lake. During its downward journey the inflow stream collects large quantities of silt from the denuded catchment and deposits it in the northern basin of the lake. A number of ephemeral water channels enter the lake from human settlement and discharges large quantities of wastes. Within the lake basin itself there are a number of springs but their location has not been so far charted. Towards the south-west side an outflow channel discharges the lake water into a tributary of Jhelum river. A small canal connects the Dal Lake with the Anchor Lake and acts as an additional outflow channel.

The total area of the Dal catchment is 346 sq km. The total open water area of the lake, once 23.4 sq. km, has shrunk to 12.4 sq. km in 118 yrs. The shrinkage is attributed to heavy siltation and urbanization. km. The water volume of the lake is $10.43 * 10^6$ cu. m. 80 % Of the inflow to the lake is supplied through the Telbal Nalla and 20 % through precipitation. The quantity of water supplied through springs is negligible and is considered equal to the amount lost in seepage.

The lake suffers from great eutrophication and siltation. Principal nutrients in the lake water are nitrogen and phosphorus. Sediment is mainly organic in nature, composed of large quantities of lacustrine and marl. Increased quantity of suspended material has caused considerable reduction of the secchi depth. All basins of the lake do not conform to a single pattern of thermal behaviour. There are marked horizontal and vertical thermal variations. pH of the lake water varies from 8.2 and 8.5. If proper control measures are not taken the lake is expected to be converted into marshy land or swamp in 70 to 80 years. The climate of the area is arid.

ii) Halgam Rakh Lake

Located 30 kms north west of Srinagar, its a small fresh water lake on the flood plains of Jhelum. The lake is covered with dense reed bed. The area of the lake is 1400 ha. The maximum depth of the lake is 1.25 m. The latitude of the lake is $34^{o}15'$ N and its longitude is $74^{o}31'$ E. The rate of siltation and eutrophication in the lake are highly increasing. The summer climate is warm and dry and the winter is cold and wet.

iii) Hokarsar lake

Its a permenent eutrophic lake with very turbid water. It is situated at a distance of 10 kms to the west of Srinagar.

The lake area is 1300 ha. The lake is situated between 34°05' N latitude and 74°43 ' E longitude. It was once an ox - bow lake surrounded by fresh water marshes on the flood plain of Jhelum. The lake is suffering from heavy siltation. The maximum depth of the lake is 2.5 m. Summer is warm and dry and winter is cold and wet.

iv) Mirgund Lake

This lake is located 15 kms west north west of Srinagar between 34°08' N latitude and 74°38' E longitude at an elevation of 1580 m, on the flood plains of Jhelum. The area of the lake basin is 300 ha. Its a shallow fresh water lake with reed beds. The maximum depth of the lake is 1.05 m. The lake is facing the problems of increasing siltation and eutrophication. The climate of the lake area shows warm and dry summer and cold and wet winter.

v) Pangong Tso Lake

Its a narrow brackish lake in the upper drainage basin of Indus River, 100 kms east south east of Leh, Ladakh. The area of the lake basin is 65,000 ha. The altitude of the lake is 4218 m. It's latitude is 33°50' N and the longitude being 78°35' E. The climate is arid climate. The lake has a protected high altitude cold desert National Park.

vi) Shallabugh Lake

Its a shallow fresh water lake located at 16 kms north west of Srinagar.The area of the lake is 750 ha. The altitude of the lake is 1580 m. It's latitude is 34°01' N and longitude is 74°42' E. The main threats to the lake are siltation, eutrophication and encroachment of the agricultural land.

vii) Tso - Kar

Once a large fresh water body, it is now contracted into two water bodies ; 100 kms south south east of Leh, Ladakh. The two water bodies are Startsapuk - Tso and Tso - Kar. The former is brackish water body and the latter is hype saline. It is fed by perennial springs and snow melt. It becomes almost fresh in summer. It is surrounded by peaks of about 7,000 m on all sides. The area is 20,000 ha. It is situated at an altitude of 4530 m. The latitude and longitudes between which it has been situated are $33^{o}18'$ N and $78^{o}00'$ E respectively.

viii) Tso Morain Lake

Its a closed lake fed by springs and snow melt. The area of the lake is 12,000 ha. The lake is located between $32^{o}50'$ E latitude and $78^{o}20'$ E longitude at an elevation of 4511 m ; 160 kms south south east of Leh, Ladakh. The lake water, originally fresh, is now brackish to saline. The lake area has reduced considerably. The climate of the lake area is arid.

ix) Wular Lake

Situated 40 kms north west of Srinagar, its a large fresh water lake. The area of the lake is 20,000 ha. Its altitude is 1580 m. The latitude of the lake is $34^{o}20'$ N and it's longitude is $74^{o}33'$ E. The lake is silting rapidly in south east portion where Jhelum enters. The maximum depth of the lake presently is 40 m. The area has a warm and dry summer and cold and wet winter.

3.9 Kerala

i) Pookot Lake

Its a natural water body of about 7.5 ha, situated in the Western Ghats. The catchment of the lake is 40 ha in area and is separated from adjoining catchment by a chain of hills rising to the order of 800 m above mean sea level. The slopes of the northern and eastern sides of the catchment are 80 and 56 m/km. The elongation and circulatory ratios are 0.4 and 0.2

respectively. The average annual rainfall in the catchment is 4433 mm and the number of rainy days are 140. About 60 % of the rainy days are in the south-west monsoon and 30 % of the rainy days in the north east monsoon. The streamflow into lake begins in June and continues upto December. Maximum flow is during south-west monsoon period thereafter sudden reduction in flow is observed in September. The runoff coefficient reaches the maximum value during the month of August (ranging from 0.91 to 0.98) and then steadily decreases with the begining of south-west monsoon and again picks up in the peak of north-east monsoon in October (ranging from 0.91 to 0.94).

ii) Vembanad Lake

This lake is situated in the higher reaches of the coastal back waters of Cochin. Originally 70,000 ha, the lake area has now been reduced to only 8,000 ha due to reclamation for agriculture. The elevation of the lake is 0 - 5 m. The lake is situated between $9^{o}30'$ to $10^{o}20'$ N latitudes and $76^{o}13'$ to $76^{o}50'$ E longitudes. The climate of the lake region is humid tropical climate.

3.10 Madhya Pradesh

i) Chandpatta Lake

It is situated in Madhav National Park ; 5 kms east of Shivpuri. The area of the lake is 200 ha and its maximum depth is 12 m. The altitude at which the lake is situated is 450 m. The latitude and longitude of the lake are $25^{o}26'$ N and $77^{o}42'$ E respectively. The climate of the lake region is dry tropical mansoon climate. Water level in the lake flactuates during dry and wet season by 2 m. The lake is bunded along eastern shore. It supplies water for irrigation. The lake area is given protection under wildlife protection act of 1972.

ii) Dihaila Jheels

Located at 50 kms west north west of Shivpuri, these are shallow fresh water lakes. The total area of the jheels is 370 ha. The altitude is 227 m. The latitude of the lakes is 25 35' N and their longitude is 78 05' E. The maximum depth of the lakes is 3 to 5 m. The water level drops in the dry season and the lakes may become totally dry in draught years. Presently the water of the lake is being used for irrigation. Intensive grazing and siltation are the major threats to the lakes. It has been declared as Waterbird Sanctury. The climate of the area is tropical mansoon climate.

iii) Upper Bhopal Lake

Its a shallow lake situated between two rising hills. The lake is located in north west part of Bhopal city at an elevation of 523 m above mean sea level. The latitude and the longitude of the lake are $33^{o}17'$E and $77^{o}21'$N respectively. The water of the lake is used for drinking purpose. On the western side of the lake strong winds are always blown in between the two ridges. The level of the water in the lake fluctuates. During south west monsoon the lake is filled up with water and during the rest of the year water level is gradually reduced. Maximum water level is reached during August - September and the minimum in June. The water level is affected by evaporation, percolation and leakage through the dam, regular draw off by water works authorities and the unauthorized draw off by cultivators. Because of shallow depth, its fluctuating water level and the wind direction, there is a daily mixing of water column. There are well defined periods of thermal stratification, mixing and isothermy that influence community, respiration and photosynthesis rates. The maximum temperature of the lake is 32^{o}C in June and the minimum is 18.5^{o}C in January. The pH of the lake water varies. The maximum pH of 8.9 is reached in June and the minimum of 7.8 in September. The alkalinity is 32 ppm in June whereas it is not traceable during rest of the period. It has been observed that there is gradual reduction in bicarbonate in the surface layers. The bottom layers contain more bicarbonate than the surface indicating bacterial action at the bottom deposits. The changes in bicarbonates are found to be greatest in the uppermost strata. The data for the lake shows that the maximum difference in O_2 content between the surface and the bottom layers is 3.1 mg/l observed in the day time and the minimum difference is 0.1 mg/l in the early morning hours. These two facts indicate that there is stratification during day time and turnover or circulation in early morning. The thermal stratification is not seasonal but diurnal. The lake is polymictic. The lake is heavily under the influence of human activities because of rapid urbanization of Bhopal city.

3.11 Maharashtra

i) Lonar Lake

Located at 140 kms from Aurangabad, in Buldana district, it is supposed to be the largest and oldest lake of meteor origin in the world, though there is a difference of opinion regarding its origin. It is believed to have been originated 50,000 years back. It is a circular depression, having a dimeter of 1800 m at the rim and 1200 m at the water level, the area of waterspread being a little over 1 million sq. km. It is about 100 m deep. The bottom is 50 m being of highly weathered trap , overlain by silt and 5 to 8 m of brine. The saline water contains CL, CO_2, HCO_3, SO_4, Na, K, Ca, SiO_2 and B. No appreciable amount of Ni, Co, Cr or V are found. The rim around the lakes stand 5 or 6 m above the surrounding country, the trap appearing to dip away from the depression. No appreciable fracturing or shattering is noticed in the rocks nor have any high - pressure minerals been detected in and around the rim, though the ratio of the diameter to depth is suggestive of meteoric impact. Gravity and magnetic surveys of the lake and surrounding area by the Geological Survey of India did not reveal any appreciable anomalies. The lake may therefore be merely a collapse structure.

3.12 Manipur

i) Logtak Lake

Its a large lake which is constantly shrinking. It is situated 20 kms south west of Imphal, in upper drainage basin of Manipur river. The area of the lake is 26,000 ha. The elevation of the lake is 770 m. The latitude and the longitude between which the lake is situated are $24^{o}35'$ N and $93^{o}50'$ E respectively. The lake is drained by Manipur river. 4000 ha of the lake is already reclaimed for agriculture. The inflow to the lake contains domestic sewage, fertilizers and pesticides. The lake water is used intensively for irrigation and domestic purpose. The climate of the area is tropical mansoon climate.

3.13 Orissa

i) Chilka Lake

Its a large, shallow, pear shaped, brackish lake being 70 km long and 52 km broad. The maximum area of the lake is 16,500 ha and the minimum area of the lake is 89,100 ha. The depth varies in different seasons. It is 0.9 m to 2.6 m in dry season and 1.8 to 3.7 m in mansoon. The lake is situated at 150 kms distance to the south west of Cuttak betweemn $19^{o}28'$ to $19^{o}54'$ N latitudes and $85^{o}06'$ to $85^{o}35'$ E longitudes. The lake is seperated from the Bay of Bengal by a 200 m wide sandy ridge which is 71 km long and 32 km wide. Rivers Daya, Bhagavati and eight other rivers flow into lake from north. Inflow rate of the silt is 13 million tonnes per year. There is an inflow of fresh water in mansoon and sea water in dry season. There are extreme cyclic changes in salinity of the lake water. It varies from 0.1 to 36 ppt. The salinity of the lake water starts increasing in the month of November and reaches peak in April - June. The south eastern sector shows less flactuation in salinity. The pH of the lake water varies from 6.8 to 9.7. The shore area of the lake is being encroached and reclaimed for prawn culture. There is eutrophication of the lake due to mercury rich effluents. The lake was given sanctury status in 1973. It was declared the wetland of international importance in 1981 under the Ramser Convention.

3.14 Punjab

i) Harike Lake

Located 55 kms south of Amritsar at an elevation of 210 m, its a shallow water storage reservoir at the confluence of Sutlej and Beas rivers. The area of the lake is 4,100 ha. The latitude is $31^{o}10'$ N and the longitude is $74^{o}56'$ E. 70 % of the lake water surface is covered with Water Hyacinth Acute soil erosion and silting are the major problems the lake is facing. Maximum depth of the lake is 2 m. Bird Sanctury wass established in 1982.

3.15 Rajasthan

i) Chhata Lake

Situated in the tropical mansoon climatic regions of Rajasthan, 100 kms south south east of Delhi, these are three descrete water bodies ; Nari, Sankhi and Kamai. Nari and Sankhi are natural lakes while Kamai is a tank. The total area of the lakes is 3,000 ha. They are situated at an altitude of 190 m between 27°45' N latitude and 77°40' E longitude. They are fed by mansoon runoff and irrigation canals. Sankhi is shallower and saline with maximum depth of 30 cms. Lake NAri is slightly brackish with maximum depth of 60 to 80 cms. All the three water bodies usually dry up in May.

ii) Salt Lakes

Sambhar Lake, Phulera Lake and Didwana Lake

These are three saline lakes. They are situated at an altitude of 360 m. Lake Sambhar lies between 27°00' N latitude and 75°00' E longitude ; on the border of Jodhpur and Jaipur, 64 km to the west of Jaipur city. Phulera Lake lies between 27°12' N latitide and 74°34' E longitude whereas Lake Didwana lies between 26°52' N latitude and 75°11' E longitude, 65 km to the north west of Sambhar. Lake Sambhar is the largest of the three with an area of 23,300 ha and length of 32 km. The area of lake Phulera and Lake Didwana are 200 ha each. Sambhar Lake is fed by seasonal rivers Bandi and Medha and several other streams. About 7,800 ha of the eastern arm of Sambhar Lake is devoted for salt production while 20 % of Didwana Lake is used as salt pans. The saline mud in Sambhar lake is 22 m deep and is underlain by Aravalli schist. The greater part of Sambhar Lake in summer is covered by a thin white crust of glistening common salt. The sediments below are saturated with brine. It is estimated that in the upper 4 m of the mud in the lake, whose average salt content is about 6 %, there would be roughhly one million tons of salt per sq. m. Sambhar Lake contains practically no magnesium salts. Potassium salts are absent in Didwana Lake. Sodium sulphate is present in Sambhar and Didwana. Water level of these lakes fluctuates from few cms to a maximum of 2 m. Sambhar Lake often dries in early summer. All the three lakes are surrounded by sand flats and dry thorn shrubs. Sambhar lake is facing the problem of siltation. The climate of the lake region is tropical mansoon climate.

The other salt lakes of Rajasthan include Lake Pachbhadr; 100 km south-west of Jodhpur, Lake Chhapar near Sujangarh and Lake Lunkaransar in Bikaner.

3.16 Tamil Nadu

i) Pulicat Lake

Its a shallow salt water lagoon just near to Madras City. It is 60 km long and 5 - 15 km km wide, but the average depth is only 2 m. It is seperated from the sea by a bar, on the seaward side of which is a shoal which may represent the sediments formerrly deposited here by the old Palar river. The area in which there are islands in this lake is inundated during the mansoon. The marine silt in the islands contain thin layers of gypsum deposited from the sea water during recent times.

3.16 Uttar pradesh

i) Bhimtal Lake

Situated at an altitude of 1345 m, its the largest Kumaun lake. Ita a perennial lake, irregular in shape, lying between 29°21' N latitude and 79°34' E longitude. The maximum depth of the lake is 24.75 m and the minimum depth is 12 to 13 m. The shoreline index for the lake is 1.67 and its development index is 1.74 The total volume of the lake is $4245 * 10^3$ m^3.

ii) Dahar Jheel

Situated in the dry tropical mansoon climate, at the confluence of Ganga and Ramganga Rivers, its a shallow fresh water lake. It lies between 27°19' E latitude and 79°59' N longitude. The area of the lake is 500 ha. The depth of the lake is less than 1.5 m. The lake is flooded in mansoon.

iii) Haidergarh and Madha - ki Jheel

These lake are shallow fresh water lakes located 50 kms south east of Lucknow. The lakes are associated with marshes. The area of Haidergarh lake is 100 ha and that of Medha - ki Jheel is 1,600 ha. The lakes are situated at an altitude of 100 m. The latitude of the lake is $26^{o}35'$ E and its longitude is $81^{o}15'$ N. The lakes are subjected to mansoon flooding. The lakes are polluted with domestic and agricultural wastes. They often dry out by the end of the dry season. The climate of the area is a typical Gangetic plain tropical mansoon climate.

iv) Khuraptal Lake

This lake is situated at an elevation of 1620 m between $29^{o}23'$ E latitude and $79^{o}26'$ N longitude. The maximum length of the lake is 400 m. Maximum width is 275 m and its maximum depth is 12 m. Its a perennial lake.

v) Lakes of eastern U. P.

These are numerous small lakes bounded by Ghagara river to the north and Ganges to the south. The altitudes of these lakes is 100 m. The latitude and longitude are $25^{o}10'$ to 26^{o} 20' N and $81^{o}00'$ N to $84^{o}45'$ E respectively. These lakes supply water for irrigation and domestic purpose.

vi) Malawatal Lake

This lake is situated in the Kaesa river which is a tributory of Gaura river, at an altitude of 1040 m. It is presently in the river form. The lake is situated between $29^{o}24'$N latitude and and $79^{o}38'$E longitude.

vii) Mohri Sothna Jheels

These are small freshwater lakes with an area of 300 ha. The laititude of the lake is $27^{o}56'$N and its longitude is $79^{o}11'$E. The climate of the lake region is dry tropical mansoon climate.

The lake depth is less than 1.5 m. The lake is flooded in mansoon.

viii) Nainital Lake

Located between the $29^{o}24'$N latitude and $79^{o}23'$N longitude, its a perennial lake. The lake is situated at an altitude of 1937 m. The area of the lake is 5.85 sq. km. The lake is surrounded by high hills. There is a submerged island running across the centre of lake dividing it into two basins. Lake depth has been reducing. The maximum depth of the lake was 27.45 m in 1899, 26.75 m in 1969 and 25.70 min 1979. Mean depth of the lake was 21.43 m in 1899, 20.64 in 1969 and 18.55 m in 1979. Volume of the lake was $7425.20 * 10^{3}$ cu. m in 1899, $6808 * 10^{3}$ cu. m in 1969 and $5907.50 * 10^{3}$ cu. m. The development of volume index is 2.25. Shoreline index is 1.48. The lake has a subcircular shape. The marked reduction in it's areal extent is because of the siltation of the deeper portion. The surplus water goes to Balia river.

ix) Naukuchiatal Lake

Situated at a distance of 5 km from Bhimtal Lake, in Nainital district, its the deepest and most voluminous of the Kumaun lakes of the lesser Himalaya. The latitude of the lake is $29^{o}32'$N and it's longitude is $79^{o}21'$E. The altitude of the lake is 1320 m. It is a perennial Lake. It has an irregular shape. The maximum areal extent of the lake is 90 ha. Lake basin is a conical deep trough with flat bottom. Basin walls have steep slope. North west corner of the lake is a deltaic plain which is marshy and swampy. Mean depth of the lake is 21.89 m. Maximum depth of the lake is 41.25 m. It has a small artificial outlet leading to Bhimtal gadhera. To the north west of the lake is the Nal - Damayanti lake - 4 which, previously a lake, is now in the form of a tank. The lake faces a threat not only to the quality of its water but to its very existance also, from the rapid growth of the human activities in the catchment area of the lake. The excess water of the lake is used for the irrigation and drinkng purpose in loweer valley villages.

x) Nawabganj - Priyadarshani Bird Sanctury

This is a permenent, shallow, freshwater lake with adjecent riparian forest on the upper Gangetic plains, 45 kms east of Luckknow. The latitude of the lake is $26^{o}50'N$ and the longitude is $81^{o}10'E$. It's altitude is 115 m. It is fed by mansoon runoff. The area of the lake is 600 ha. Average depth of the lake is 1 to 1.5 m. The water level in the lake fluctuates. The lake dries in early summer. The climate of the region is typical Gangetic plain climate. The lake is getting polluted from nearby towns.

xi) Punatal Lake

It is also called Gauratal Lake. Its a closed lake situated at an elevation of 1360 m between $29^{o}21'N$ and $79^{o}32'E$ latitude and longitude respectively. The lake is circular in shape. It is fed by mansoon. Surplus water is exited through suubterrain and recently constructed canal. Maximum depth of the lake is 25.10 m. The mean depth is 17.17 m. Development of volume index is 2.05. Total volume is $1854.4 * 10^{3}$ cu. m. The lake basin is a conical trough. The basin walls are very steep. Floor is flat. Northern and southern parts are shallow. Its a perrenial lake.

xii) Pyagpur and Sitadwar Jheels

Located at a distance of 100 km to the north east of Lucknow, in the typical gangetic plain tropical mansoon climate, these are fresh water lakes with associated marshes, situated some 20 km apart on the plain between Rapti and Ghagra rivers. The lakes are situated between $27^{o}25'N$ latitude and $81^{o}48'E$ longitude. The area of the lakes are 2800 ha and 150 ha respectively. The lakes are shallow. The maximum depth of the lakes varies from 1 to 3 m. Sitadwar lake dries in dry season. The main threat to the lakes is from agricultural exploitment and extensive fishing.

xiii) Sattal Lake

Situated at an elevation of 1300 m, its an irregular lake. Maximum depth of the lake is 21.5 m and minimum depth is 10.53 m. Total volume of the lake is 2598.50 * 10^3 cu. m. Development of volume index is 1.47. Lake basin is trough shaped with walls being convex towards the water surface. It has three distinct parts seperated by sediments. Recently an embankment is constructd to increase capacity.

xiv) Sauj Jheel

This is a small frshwater lake situated at the confluence of Ganga and Ramaganga rivers. The depth of the lake is less than 1.5 m. The area of the lake is 400 ha. The latitude of the lake is 27^{o}10'N and the longitude is 79^{o}11'E. The climate of the region is dry tropical mansoon climate. The lake is flooded in mansoon due to low depth.

xv) Sheoja and Gaundial Jheeels

These are smalll freshwater lakes situated at the confluence of the Ganga and Ramaganga rivers. The lakes are situated between 27^{o}05'N and 79^{o}11'longitude. The total area of the lakes is 500 ha.

xvi) Sukhtal Lake

This lake is located to the north east of Khurpatal. It seems to have been the part of Nainital Lake . The latitude of the lake is 29^{o}23'N and the longitude of the lake is 79^{o}26 'E. The length of the lake is 350 m. Maximum width is 110 m. The lake is situated at an altitude of 2000 m.

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