LECTURE-3

Hydrological Monitoring of Lakes & Their Catchments: Water Quality, Bathymetry and Soils Properties

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INTRODUCTION

Water is a prime natural resource, a basic human need and a precious national asset. Planning, development and management of water resources need to be governed by national perspectives. As per the latest assessment (1993), out of the total precipitation, including snowfall, of around 4000 billion cubic metre in the country, the availability from surface water and replenishable ground water is put at 1869 billion cubic metre. Because of topographical and other constraints, about 60% of this i.e. 690 billion cubic metre from surface water and 432 billion cubic metre from ground water, can be put to beneficial use. Availability of water is highly uneven in both space and time. Precipitation is confined to only about three or four months in a year and varies from 100 mm in the western parts of Rajasthan to over 10000 mm at Cherrapunji in Meghalaya.

Water as a resource is one and indivisible: rainfall, river waters, surface ponds and lakes and ground water are all part of one system. Water is a scarce and precious national resource to be planned, developed, conserved and managed as such, and on an integrated and environmentally sound basis, keeping in view the socio-economic aspects and needs of the States. It is one of the most crucial elements in developmental planning.

The knowledge of hydrology of lakes is essential for their proper use and conservation. Lake has its hydrologic response. It has cause and effect relationship with the adjoining catchment. Because of storage of large mass of water, it moderates flood and climatic factors in the region. Also the deforestation, conversion of grassland to cropland, intensification of agricultural production, land amelioration etc. in the nearby catchment area affects the microclimatic and reduces evapotranspiration thereby increasing runoff and rates of erosion and siltation. Accelerated nutrient cycles and faster transport of soil particles increases sedimentation rate and lead to enrichment of lake water. Water quality is a measure of how deep you can see into a lake. It can be affected by pollution, erosion and other factors, including the removal of shore vegetation. Water quality studies are regarded as one of the thrust areas in the water resources sector, as envisaged in the National Water Policies 1987 & 2002 that "both surface water and ground water should be regularly monitored, and a phased program should be undertaken for improvements in water quality".

Water Quality Issue in National Water Policy 2002

- Both surface water and ground water should be regularly monitored for quality. A phased programme should be undertaken for improvements in water quality.
- Effluents should be treated to acceptable levels and standards before discharging them into natural streams.
- Minimum flow should be ensured in the perennial streams for maintaining ecology and social considerations.
- Principle of 'polluter pays' should be followed in management of polluted water.
- Necessary legislation is to be made for preservation of existing water bodies by preventing encroachment and deterioration of water quality.

Definition of Lake:

Lake is an ephemeral feature of the landscape and is a dynamic system. It is because that erosion and deposition begin to destroy lakes from the moment they appear. There are about 3 million lakes in the world and most of them are located in the Northern Hemisphere. According to Zumberge and Ayers 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"(Chow, 1964). Lakes are transitory features of the earth surface and each has a birth, life and death related to certain geological and biological processes. Their life expectancy may vary from a short spell of two floods to millions of years. Lakes are the potential source of fresh water at high altitudes. The water stored in lakes is used for fulfilling domestic, agricultural and industrial needs. Apart from these, lakes also provide water for fisheries, transport, recreation and hydro electric power generation. From the geologic point of view, a lake consists of two distinct parts, the basin and the water body. It is obvious that the latter could not exist without the former and both should be taken into account in any workable definition. In Finnish practice, the minimum area of a lake is considered to be 0.01 km^2. As a summary, a water body should fill the following requirements to be a lake:

- It should fill or partially fill a basin or several connected basins.
- It should have essentially the same water level in all parts with the exception of relatively short occasions caused by wind, thick ice cover, large inflows, etc.
- It should have so small an inflow to volume ratio that considerable portion of suspended sediment is captured.
- It should have a size exceeding a specified area, e.g. 0.01 km^2at mean sea level.

Lakes and Reservoirs Pollution Pathways

The following pathways assume special significance in the case of lakes and reservoir pollution:

- Riverine sources: pollutants in solution in the inflow or adsorbed onto particulate matter, or both. The cumulative input is the sum of contaminants from all of the rivers draining the watershed into a lake.
- Groundwater sources: groundwater systems polluted from point and diffuse sources flowing into rivers, and directly into lakebeds.

- Atmospheric sources: direct wet and dry atmospheric deposition of contaminants to the lake surface and wash off of similar pollutants from the land. This latter process is defined as secondary cycling.

Thus, the lakes serve as traps for pollutants carried by rivers and groundwater draining the watershed. The pollutant concentration in the lake usually builds up due to evaporation of water from the lake's surface unless there is a natural flushing with good quality water.

WATER QULITY MONITORING

Selection of water quality variables

Water quality monitoring is expensive, and resource committed to unnecessary water quality characteristics may be at the expense of a successful experimental design. Therefore, the selection of water quality variables to include in a project requires consideration of several factors, which include: the study objectives, the type of water resource, the use or classification of water body, the type of non point source activity, the difficulty or cost in analysis of the variable, and water quality problem. The description is given below:

(a) Objectives: A properly stated objective assists in defining the water quality variables to monitor. In fact, selecting the water quality variables may result in a redefinition or clarification of the objectives in a feedback manner. The constraint part of the objective may specifically mention the water quality variables.

(b) System Type: The type of water resource being studied also influences the variables selected. Table-1 indicates that the appropriate variables of interest differ primarily between subsurface systems, such as soil water and ground water, and surface water systems, including lakes, streams, and wetlands. For example, chemical nutrients may be important to all systems, but particulate forms of nutrients are meaningful only for lake, stream, and wetland systems and not for soil water or ground water systems.

Table 1. Water quality variable groups by water resource system type matrix

Variable	**Lake**	Stream	Wetland	Ground water
PHYSICAL				
Dissolved oxygen	√	√	√	
Discharge	√	√	√	√
Salinity	√	√	√	√
Secchi disk transparency	√			
Specific conductance	√	√	√	√
Suspended solids	√	√	√	
Temperature	√	√	√	

Total dissolved solids	√	√	√	√
Turbidity	√	√	√	
CHEMICAL				
BOD_5	√	√	√	
Inorganic non-metals: Cl, F		√	√	√
Nutrients: N, P dissolved total or particulate	√	√	√	√
Metals: Ca, Mg, Na, K, As, Cd, Cr, Co, Cu, Fe, Hg, , Pb, Mn, , Ni, Zn	√	√	√	√
Ph	√	√	√	√
BIOLOGICAL				
Bacteria	√	√	√	√
Chlorophyll "a"	√	√		
Invertebrates	√	√	√	
Fish	√	√		
Macrophyton	√	√	√	
Periphyton	√	√		
Plankton (algae)	√	√		
Protozoa	√	√		

(c) Designated use: Variable selection may be modified by the intended or designated use of water body (US EPA, 1981b). A water body being used for recreation, including aesthetic uses, might emphasize variable associated with sediment, nutrients, toxic and biological characteristics because all these are visual or affect visual characteristics of water bodies. However, water having an irrigation use might not include biological variables (Table 2). Water intended to be used for drinking, recreation, or fisheries might include analysis of biological and toxic substances.

Table 2. Water quality variables groups by intended water resource use

Variable	Intended use			
	Fish	Recreation	Irrigation	Drinking
PHYSICAL				
Dissolved oxygen	√			√
Discharge				
Salinity	√		√	√
Secchi disk transparency	√	√		
Specific conductance			√	√
Suspended solids	√	√	√	√
Temperature	√			
Total dissolved solids	√		√	√
Turbidity	√	√	√	√
CHEMICAL				
BOD_5	√			

Inorganic non-metals: Cl, F	√		√	√
Nutrients: N, P dissolved total or particulate	√		√	
Metals: Ca, Mg, Na, K, As, Cd, Cr, Co, Cu, Fe, Hg, , Pb, Mn, , Ni, Zn	√	√	√	√
PH	√		√	√
BIOLOGICAL				
Bacteria		√		√
Chlorophyll "a"	√			√
Invertebrates	√			
Fish	√			
Macrophyton	√			
Periphyton				
Plankton (algae)	√			√
Protozoa		√		

(d) Pollution Sources: The non point source of the water quality problems also influences variable selection, as will certain activities for those sources. The major non point source category include:

- agriculture
- construction
- landfill
- mining
- silviculture
- urban

(e) Analysis difficulty: The difficulty or cost of analysis should be considered when selecting water quality variables. When water quality characteristics are highly related, but the analysis cost of one is much cheaper than the other, the less expensive variable could be selected. For example, analysis of turbidity is less costly than suspended soils, both of which are less expensive expensive than total solids. Also, nitrate nitrogen is cheaper than ammonia nitrogen or total Kjeldahl nitrogen because digestion of the sample is not required.

(f) Water quality problem: Finally, the water quality problem itself influences the variables to sample. Eutrophication problems require monitoring of several physical, chemical, and biological characteristics. Excess algae might suggest sampling of dissolved oxygen and temperature, flow for mass balance purposes, turbidity or Secchi disk transparency, nutrients, plankton abundance/type, and chlorophyll "a" concentrations. Because many of these variables are related, not all would be needed to detect changes. Also, an index, such as Carlson's Trophic State Index (TSI) could be used (Carlson 1977). It combines some of these variables.

Prioritising of water quality variables

Because virtually hundreds of water quality variables exist and are therefore candidates for monitoring, a method for prioritising their selection is important. The general approaches for prioritising water quality variables are ranking, activity matrices, correlations, and probability of exceeding standards. The first three have been discussed below:

(a) **Ranking:** According to this criterion, variables higher in the hierarchy would be selected over lower-ranked variables. Sanders et al. (1983) suggest a hierarchical approach of:

- **Primary-** water quantity variables that serve as a carrier of water quality, e.g., discharge, volume, head
- **Secondary-** water quality variables that are the result of aggregated effects, e.g., temperature, pH, conduction, dissolved oxygen, turbidity, anions, cations
- **Tertiary-** water quality variables that produce aggregated effects, e.g., radioactivity, suspended matter

(b) **Activity matrices:** The water quality variable matrices given Tables 1-2 serve as a second method in selecting water quality variables.

(c) **Correlations:** Correlations between variables can be used to reduce the variable list. A number of water quality variables are often correlated. Total phosphorus often is highly related to ortho-phosphorus. In lake systems, total phosphorus has been reported to be highly related to Secchi disk transparency and chlorophyll 'a' (Reckhow & Chapra, 1983). Other variables that might be expected to exhibit correlations are conductivity and dissolved solids, and suspended solids and turbidity. Since these variables may be highly related, one variable could be dropped from the monitoring program or monitored less frequently. The equation for calculating correlations is given below:

$$r=\frac{\Sigma(Xi - Xm)(Yi - Ym)}{\surd\{\Sigma(Xi - Xm)^2\,\Sigma(Yi - Ym)^2\}}$$

Where,

Xm and Ym = the means of the variables X and Y respectively
Xi and Yi = individual values of variables X and Y, respectively

To use correlation coefficients, some monitoring data would have to be available either from a previous study or from preliminary monitoring in the watershed of interest. As an example, Muddy Bay is experiencing impairment caused by excessive sedimentation and eutrophication. Both nitrogen and phosphorus are believed to contribute to the problem. Prioritisation of water quality variables based on correlation coefficients is given in Tutorial (Ex. 1a).

Types of water quality sampling

If water quality did not vary in space or in time, there would be little reason to collect more than one sample to describe the quality of a particular water body. However, water quality does vary spatially and temporarily. The four types of water quality samples that can be collected are grab, composite, integrated or continuous. The sample type selected is governed by the study objectives, the variable to sample, and whether concentration or mass is the desired outcome. The sample type are discussed below:

(a) **Grab Samples:** A grab sample is a discrete sample that is taken at a specific point and time (APHA, 1989). Grab samples may not be representative of the water quality of the body of water being sampled. Samples at a single location in a lake or a single well are really grab samples. Grab samples can be collected manually by hand or automatically with a sampler.

(b) **Composite Samples:** A series of grab samples, usually collected at different times and lumped together, are considered composite samples. However, composite samples typically are taken only at one point.

(c) **Depth Integrated Samples:** A specific type of grab sample is a depth integrated sample (USGS, 1977). Such a sample may account for stratification induced changes with depth, but temporal variations could not be integrated. Depth integrated samples may be appropriate for both lake and ground water systems. In lakes, depth integration can be achieved by sampling each lake strata, by obtaining a sample of the entire water column with a hose, or by automatic devises or pulleys that collect at different depths over time.

(d) **Continuous Samples:** Continuous sampling is rare in non point source pollution studies and is typically used for research. Continuous monitoring can be used for any water quality variable that is measured using electrometric methods, eg. Temp., pH, EC, DO etc.

Sampling frequency and duration

The most frequently asked questions when developing a water quality monitoring study are *"How many samples and for how long?"* Unfortunately, the correct response is: *"It depends."* Several factors affect the frequency of sampling. They include the objectives of the study, the types of water body being studied, the data variability, and the available resources. Sampling frequency is also affected by the aquatic system being studied. In general, the variance is greater; therefore, more samples are needed for studying stream than for lakes. Apart from this, financial resources typically limit the sampling frequency, although time, people, and laboratory capability can also limit sampling frequency. The primary sampling techniques to define sampling frequency are random sampling and stratified random sampling. The stratified random sampling relevant to the lake monitoring has been described.

Stratified random sampling: Instead of each water quality sample having the equal chance of being collected, there may be advantages to dividing the population of water quality samples into sub groups that are each more homogeneous than the whole data set. Samples could be taken from each subgroup or strata. This type of sampling is termed *Stratified Random Sampling.* More samples are allocated to subgroups that have greater variability. The appropriate example for stratified lakes would be **groping by strata in lake (epilimnion, metalimnion and hypolimnion).** Stratified random sampling is given in the Tutorial (Ex.-1b). The sample size for stratified random sampling can be calculated from the relationship (Reckhow & Chapra, 1983):

$$n=\frac{t^2(\sum wiSi)^2}{d^2}$$

Where, n = the total number of samples

t= Student's "t" at n-1 degree of freedom

wi= the proportional size of stratum I

Si= the standard deviation of the water quality data for stratum I

d= the difference from the mean

The number of samples for each individual stratum is determined from:

$$ni=\frac{nwiSi}{\sum(wiSi)}$$

Where, ni= the number of samples for stratum I

PRESENTATION OF WATER QUALITY DATA

Graphical representation of the concentrations of different ions in a water samples have been developed from time to time. Such graphical patterns make understanding easier and quicker. Some of them are bar graphs, patterns drawn on radial co-ordinates, stiff's pattern, cumulative percentage composition, Schoellers' logarithmic plotting and trilinear diagrams. A few common graphical presentation are given below:

(I) Piper's Trilinear Diagram: Piper classification (1953) is used to express similarity and dissimilarity in the chemistry of different water samples based on dominant captions and anions. The Piper diagram combines three distinct fields for plotting, two triangular fields at the lower left and lower right respectively, and an intervening diamond shaped field. Each apex of a triangle represents a 100 percent concentration of one of three chemical constituents. Major ions are plotted in two base triangles of the diagram as cation and anion percentages of milli-equivalent per litre. Total cations and total anions are each considered as 100 percent. The respective cation and anion locations for an analysis are projected into the diamond shaped area which represents the total ion relationship (Fig. 1).

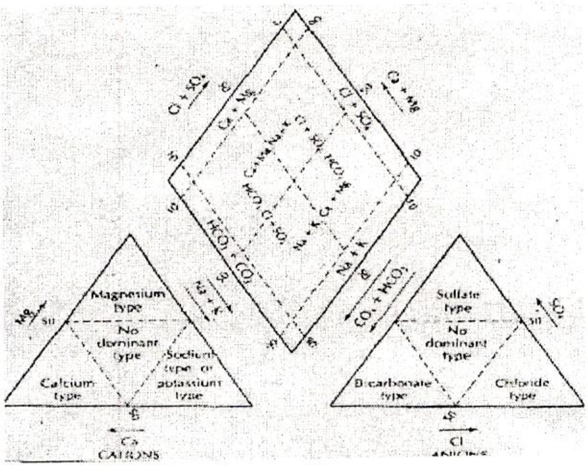

Fig. 1. Piper's Trilinear Diagram

(ii) Stiff Diagram: Stiff (1951) system uses four parallel horizontal axis and one vertical axis. Four cations are plotted on one side and four anions on the other side of the vertical axis in meq/l. The vertices of the polygon are connected to give a shape characteristic of the type of water. In Stiff's diagram, a polygonal shape is created from four parallel horizontal axes extending on either side of a vertical zero axes (Fig. 2). The use of the lower horizontal bar with iron and carbonate is optional in many waters.

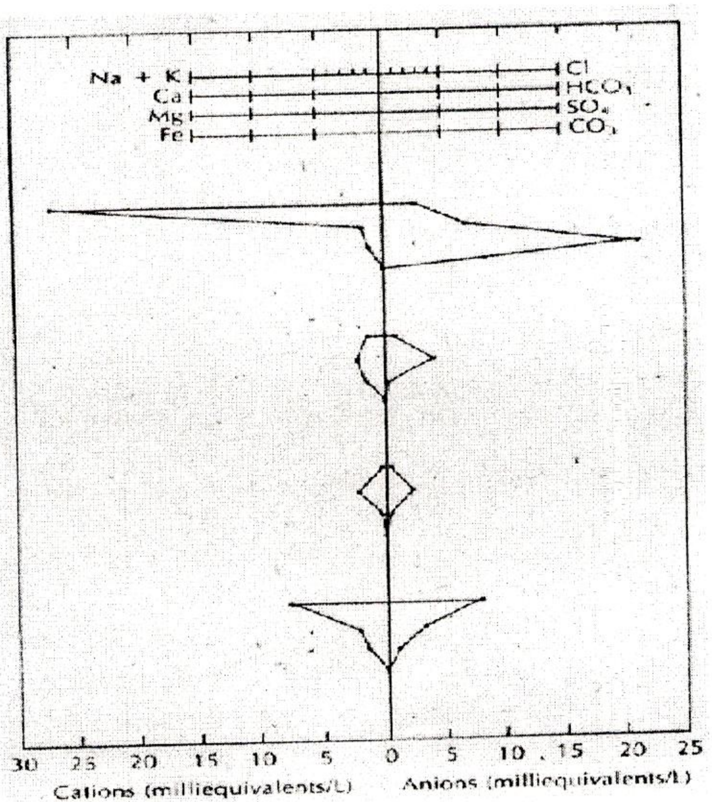

Fig. 2. Analysis presented by Stiff patterns

(iii) U.S. Salinity Laboratory Classification: The U.S. Salinity Laboratory diagram (U.S.D.A, 1954) is used to study the suitability of water for irrigation purposes (Fig.3). It is most popular method for determining the suitability of irrigation water. The U.S. Salinity diagram is a combination of salinity and alkalinity (sodium) hazards plotted on X and Y-axis, respectively. The salinity hazards are expressed in terms of electrical conductivity of water in micro-mhos/cm at 25 ^{0}C and alkali hazards are expressed in terms of sodium adsorption ratio (SAR).

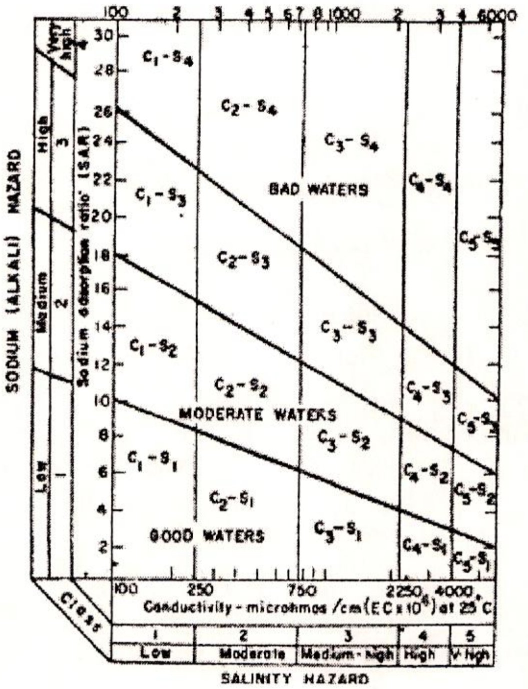

Fig. 3. USDA classification of irrigation waters

EUTROPHICATION OF LAKES

Natural lakes are formed due to some geological process which creates a depression, which is latter filled with water to become a lake. In case of reservoirs, these depressions are artificially created by damming a river valley. At birth, all lakes are deficient in nutrients and hence, are unable to support aquatic life. However, since lakes, both manmade and natural, are bodies of standing waters, the relative lack of motion of the lake water makes their basin (the depression that is filled with water), a sediment trap. Thus, sediments and other material brought with the inflow gets accumulated in them. Sedimentation fills the lakes, slowly turning them first into ponds and swamps and then into marshy lands and ultimately into terrestrial systems causing their extinction. Thus, after their formation, with passage of time nutrients brought by sediments from the catchment and from other sources, get accumulated in them and their productivity increases. Through bacterial and other decompositions of the sediments, the water bodies become further rich in nutrients on which phytoplankton thrive. With increase in phytoplankton and food supply, the zooplankton and other forms of animals also increase. Thus, there is an overall increase in the species diversity and biological productivity. This process is called eutrophication. It, thus describes the biological effects of an increase in concentration of plant nutrients on lakes manifested through the excessive growth of aquatic plants, both attached and planktonic to levels that are considered to be an interference with desirable water uses. Three general designations of productivity are used for lakes. Lakes with low productivity are called oligotrophic, those with intermediate productivity are called mesotrophic and the ones with high productivity levels are referred to as eutrophic.

Trophic state determination is an important aspect of lake surveys. Trophic state is not the same thing as water quality, but trophic state certainly is one aspect of water quality. Trophic State is a measure of the degree of plant material in of a body of water. It is usually measured using one of several indices (TSI) of algal weight (biomass): water transparency (Secchi Depth), algal chlorophyll, and total phosphorus. The TSI values of Carlson (1977) range from less than 0 to greater than 100, where each 10 units represents a doubling in Transparency or a halving of Total Phosphorus. TSI limits to classical trophic state terminology are (Table 3a):

Table 3a. TSI Limits of Trophic Condition

Trophic Condition	TSI Limits
Ultra-Oligotrophy	0-20
Oligotrophy	20-40
Mesotrophy	40-50
Eutrophy	50-70
Hypereutrophy	>70

In accordance with the definition of trophic state given above, the trophic state index (TSI) of Carlson (1977) uses algal biomass as the basis for trophic state classification. Three variables, chlorophyll pigments, Secchi depth, and total phosphorus, independently estimate algal biomass.

Calculating the TSI: The index is relatively simple to calculate and to use. Three equations are used: Secchi disk, TSI (SD); chlorophyll pigments, TSI (CHL); and total phosphorus, TSI(TP). The simplified equations are below:

$$\mathbf{TSI\ (SD) = 60 - 14.41\ ln\ (SD)}$$

$$\mathbf{TSI\ (CHL) = 9.81\ ln\ (CHL) + 30.6}$$

$$\mathbf{TSI\ (TP) = 14.42\ ln\ (TP) + 4.15}$$

The units for chlorophyll (CHL), Secchi Depth (SD) and TP are same as given in Table-3b.

Relating Trophic State to the State of the Waterbody

Any trophic state index gains value when it can be correlated with specific events within a waterbody. Below is a table of attributes that could be expected in a north temperate lake at various TSI values. Some characteristics, such as hypolimnetic oxygen or fisheries may be expected to vary with latitude and altitude and the table may not place these changes in the proper TSI category.

Table-3b: A list of possible changes that might be expected in a north temperate lake as the amount of algae changes along the trophic state gradient.

TSI	**Chl (ug/L)**	**SD (m)**	**TP (ug/L)**	**Attributes**	**Water Supply**	**Fisheries & Recreation**
<30	<0.95	>8	<6	**Oligotrophy:** Clear water, oxygen throughout the year in the hypolimnion	Water may be suitable for an unfiltered water supply.	Salmonid fisheries dominate
30-40	0.95-2.6	8-4	6-12	Hypolimnia of shallower lakes may become anoxic		Salmonid fisheries in deep lakes only
40-50	2.6-7.3	4-2	12-24	**Mesotrophy:** Water moderately clear; increasing probability of hypolimnetic anoxia during summer	Iron, manganese, taste, and odor problems worsen. Raw water turbidity requires filtration.	Hypolimnetic anoxia results in loss of salmonids. Walleye may predominate
50-60	7.3-20	2-1	24-48	**Eutrophy:** Anoxic hypolimnia, macrophyte problems possible		Warm-water fisheries only. Bass may dominate.
60-70	20-56	0.5-1	48-96	Blue-green algae dominate, algal scums and macrophyte problems	Episodes of severe taste and odor possible.	Nuisance macrophytes, algal scums, and low transparency may discourage swimming and boating.

70-80	56-155	0.25-0.5	96-192	**Hypereutrophy:** (light limited productivity). Dense algae and macrophytes		
>80	>155	<0.25	192-384	Algal scums, few macrophytes		Rough fish dominate; summer fish kills possible

Other TSI Indices

Nitrogen: Other indices have been constructed to be used with the basic three. Since nitrogen limitation still classifies a lake along Naumann's nutrient axis, the effect of nitrogen limitation can be estimated by having a companion index to the Total Phosphorus TSI. Such an index was constructed by Kratzer and Brezonik (1981) using data from the National Eutrophication Survey on Florida lakes. This index is calculated using the formula:

$$\text{TSI (TN)} = 54.45 + 14.43 \ln \text{(TN)}, \text{ Nitrogen in mg/L}$$

Macrophytes: The TSI in its present form is based solely on algal biomass. It is therefore blind to macrophyte biomass and may, therefore, underestimate the trophic state of macrophyte-dominated lakes. This is a serious drawback that needs to be addressed. The solution could be very simple. Canfield *et al.* (1983) proposed a method to measure the total phosphorus content of lakes. The total macrophyte biomass in the lake is estimated by the equation:

$$\text{TSMB} = \text{SA} \times \text{C} \times \text{B}$$

Where TSMB = total submersed macrophyte biomass, SA = lake surface area, C = percent cover of submersed aquatic macrophytes, and B = average biomass collected with a sampler.

CONTROL AND MANAGEMENT OF EUTROPHICATION

The need to manage and restore the culturally eutrophic lakes has mainly arisen to avoid the untimely death of lakes. However, before we proceed to the aspect of overcoming this problem, it is important to understand the terms like management and restoration as they are commonly associated with the lake conservation programmes. Cookes et al. (1993) have differentiated between these terms. Restoration, according to them is an active attempt to return an ecosystem to an earlier condition following degradation, resulting from any kind of disturbance. Restoration involves repair of ecological damage, a return of species and processes to their former states, and is holistic in its approach to returning the lake and its watershed (including surrounding wetlands) to an approximation of pre-disturbance conditions. Management, on the other hand, involves an attempt to remedy, or improve, or change conditions, usually of some specific lake component, often with human uses in mind. Management often does not deal with the causes of the lake's disturbance but with ameliorating the effects of some of the symptoms. The focus is usually on a specific community, species, or problem.

Most eutrophication control and management efforts so far have been concentrated on limiting, diverting, or treating the excessive nutrient, organic, and silt loads as the first most obvious step toward protection and restoration of a lake. In some lakes, where it is not economical to use them or where they are insufficient to produce immediate and long lasting improvements due to internal recycling of nutrients, techniques to manipulate or alter one or more internal chemical, biological, or physical processes or conditions, have been tried to restore or rehabilitate the water bodies. Thus, eutrophication control techniques can be broadly categorized as those involving the control of external phosphorous load and in-lake eutrophication control methods. Control of external phosphorous load deals with controlling the major sources of phosphorous in the drainage basin, before the nutrients reach the lakes. Various techniques to achieve this include phosphate elimination by chemical precipitation using aluminum or iron salts or lime during the sewage treatment process; restriction of detergent phosphates; and controlling land use changes. Other methods involve the treatment of influent water by techniques like construction of pre-reservoirs; physical or chemical treatment of the influent tributary before reaching the lake by flocculation; direct addition of phosphorous -precipitating chemicals such as iron salts to the influent waters; and filtration of tributary water through an aluminum oxide filter (activated alumina columns). External phosphorous can also be controlled by simply diversion of the wastewater without any treatment, in case of localized point sources. This may, however, give a temporary solution and carry the problem to some other location. Another method is the use of seepage trench.

Unlike the direct methods which control the basic cause of eutrophication, the in-lake eutrophication control methods deal with control and manipulation of the nutrients within the lakes. Although these methods are less effective compared to the direct methods and hence, may be needed to be repeatedly applied, they are however, relatively economical (Clasen et al., 1989).

The major in-lake eutrophication control methods include:

- Nutrient inactivation through direct addition of phosphorous precipitating chemicals to lakes;
- Flushing of lake water;
- Hypolimnetic aeration;
- Artificial circulation;
- Selective withdrawal of hypolimnetic water;
- Lake level drawdown;
- Covering bottom sediments;
- Dredging;
- Harvesting of macrophytes;
- Bio-manipulation and
- Use of algaecide (eg. copper sulphate) or herbicide

As has been mentioned earlier, a lake may have a considerable non point source of nutrient as well. For the control of non point source of nutrients, the suggested method is the construction of wetlands around lakes, at or near the mouth of inflowing river (Mitsch, 1994).

All these techniques of in-lake eutrophication control have been developed to treat different symptoms, although control of excess algae is more or less a common goal. For example hypolimnetic aeration and artificial circulation are done to control foul odours, fish kill and algal blooms. Algaecides is used to control toxic algae. Herbicides are used to control excessive growth of macrophytes. Bio-manipulation is used to control excess algae as well as macrophytes. Sediment covering helps in controlling foul odours, fish kills as well as algal blooms. Like dredging, it also helps in preventing nutrient release from sediment to lake waters (Khobragade, S.D., 2006).

BATHYMETRY AND MORPHOMETRIC CHARACTERISTCS

Lake morphometry deals with the quantification and measurement of lake forms and form elements. Morphometric data are of fundamental importance in most limnological and hydrological projects. Bathymetric map of a lake is source of most morphometric data. It is constructed from hydrographic surveys conducted with echo-sounding equipment. Hydrographic surveys may be conducted with different techniques and for various purposes, e.g. to meet requirements for safe navigation. In such cases the accuracy of every detail and depth value is essential. For fishing purposes it is of interest to know the bottom roughness. For scientific purposes, in hydrological, limnological and sedimentological contexts, it is of primary interest to have a bathymetric map illustrating the general morphology of the basin as well as major topographical features.

Bathymetric survey: The range-line method is most widely used for medium to large lakes/reservoirs. Range line method usually requires relatively lesser field work and is therefore, it become less expensive than the other methods e.g. contour method. In this method, number of cross sections, called ranges, are selected to survey the lake. The most important is measurement of bed elevation at many known locations in the lake. These measurements are almost always made by measuring the water depth beneath a boat and the exact location of the boat on the lake's surface. So, two basic types of measurements are required, (i) location measurements/Sounding tracks (ii) depth measurements.

Location measurement: The basic measurement required for a lake/reservoir survey is the location of the cross sections (range line/sounding track) and points of depth measurement. It requires a base map of the lake with locations of cross section points around the lake. The location points around the lake are helpful in positioning the cross sections on the map for bathymetric survey. To get the base map of the lake along with the location of cross section points, survey of the lake surface area is to be carried out.

Plane Table Surveying, also called plane tabling, is a method of surveying in which field work and office work is done simultaneously on a plane table. The field observations are taken and recorded side by side on the sheet fixed upon the plane table and a map of the area is obtained. It is commonly employed for small and medium scale mapping. The equipment essentially needed for plane tabling is a plane table or drawing board which carries a drawing sheet and is mounted on a tripod stand and an alidade which provides line of sight and a straight graduated edge. The accessories to the plane table are a trough compass, which is used for marking the direction of the magnetic meridian on the sheet of the plane table, and a plumbing fork or U-frame with a plumb bob, used for centering the table. Besides these, the other accessories are drawing sheet, a water proof cover to protect the drawing sheet and drawing instruments like pencils, eraser and scale etc. Traversing is the main method of plane tabling and is similar to that of compass or theodolite traversing. It is used for running survey lines of a closed or open traverse. The detail may be located by offsets taken in the usual manner or by radiation or by intersection method of plane tabling. After completion of the plane table survey, surface area of the lake is determined using digital planimeter and graphic method.

Depth Measurement: The simplest way of measuring the water depth is to use a sounding weight or a pole to obtain it directly. The other method is use of sonic sounding equipment. Sounding weight can be fabricated of iron plate or angles. To determine the sedimentation rate on the basis of bathymetric survey, the shape and weight of sounding weight should be in record for future survey. Sonic sounding equipment for measurement of depth is preferred on most reservoir and lakes. The scientific depth sounding equipment currently available can be used to provide a continuous record or chart of the bottom profile. The basic components are a recorder, a transmitting and receiving transducer and a power supply. By careful calibration, a high degree of bottom profile accuracy can be maintained. The ultrasonic ecosounders are widely used for depth measurement. The principle of echo sounder is simple. An acoustic signal is sent from the transducer and is received back as an echo from the bottom. The time of travel of signal is measured and depth is calculated.

Important morphometric parameters of bathymetric surveys:

Maximum Length: Maximum length of lake is the line connecting the two most remote points on the shoreline. In regular basins this line is generally straight and concurs with the maximum effective length. It may not cross land, but it may cross islands.

Maximum Width: Maximum width of lake is defined by the straight line at a right angle to the maximum length which connects the two most remote extremities on the shoreline without crossing land. Island may be crossed.

Maximum and Mean Depth: Maximum depth (D_{max}) is the greatest known depth of the lake. Mean depth is ratio of lake volume to lake area i.e.

$$D = \frac{V}{a}$$

where, V= lake volume, m^3, a = lake area, m^2
The D-value is a most useful parameter, e.g., in models describing the productive and the trophic status of lakes.

Total Lake Area: Total lake area is area of the lake plus the area of all islands, islets and rocks within the limits of the shoreline. This area value is generally determined with a planimeter.

Volume*:* Volume of the lake may be determined by plotting the depth area map and the area under the curve obtained may be planimetered or otherwise measured. In another method, the area enclosed by successive pairs of depth contours are averaged and multiplied by the contour interval to yield a series of volume elements which are summed (Zumberge and Ayers, 1964).

$$V_{A1A2} = \frac{h}{3}(A_1 + A_2 + \sqrt{A_1 A_2})$$

V_{A1A2} is volume between two adjacent depth contours, h distance apart, A_1 is the area enclosed by the upper and A_2 is area enclosed by the lower. Summation of the results of repeated successive use of the above equation will yield lake volume.

Slope: Slope of the lake basin shows pattern of lake sharpness in the bank and flatness of the lake bottom. It also reveals the pattern of sediment accumulation in different zone. Another important aspect of the study is the identification of origin of the lake. Slope of the lake basin between the adjacent depth contours and mean slope of the entire lake can be computed by using the following formula (Zumberge and Ayers, 1964).

$$S = \frac{1}{2}(C_1 + C_2)\frac{I}{A_a}$$

Where C_1 and C_2 are the lengths of the contours, I is contour interval, and A_a is area of the bottom included between the two contours. The mean slope of the basin can be defined by

$$S = \left(\frac{1}{2}C_0 + C_1 + C_2 + \dots\dots\dots\dots\dots\dots + C_{n-1} + \frac{1}{2}C_n\right)\frac{d_m}{nA_0}$$

Where C_0, C_1 etc., are length of the contours, n is the number of contours, d_m is the maximum depth, and A_o is the surface area of the lake.

The Hypsographic Curve - The hypsographic curve, also called the depth- area curve, is constructed by putting the depth of lake on the negative ordinate and the cumulative area of the lake on the positive abscissa. The hypsographic curve represents certain elements of the form of the basin and it may also be used in graphic determinations of the lake volume.

The Volume Curve - The volume curve illustrates the relationship between depth and volume in the same way as the hypsographic curve shows the relationship between depth and area. The cumulative volume at each depth level is given on the positive abscissa and the depth on the negative ordinate.

SOIL PROPERTIES IN CATCHMENTS

Lake has its hydrologic response. It has cause and effect relationship with the adjoining catchment. Because of storage of large mass of water, it moderates flood and climatic factors in the region. Also the deforestation, conversion of grassland to cropland, intensification of agricultural production, land amelioration etc. in the nearby catchment area affects the microclimatic and reduces evapotranspiration thereby increasing runoff and rates of erosion and siltation. Accelerated nutrient cycles and faster transport of soil particles increases sedimentation rate and lead to enrichment of lake water. So, various physical, chemical and biological inputs manifested through the hydrology of the catchment area and affects the quality and quantity of the lake water.

To understand hydrology of a particular area, all factors which affect hydrologic cycle should be studied. Soil characteristic is one of them. The soil physico-chemical properties are required for many hydrological studies and simulation of flow process. These properties are basic input for developing an integrated watershed management program or models. Soil studies of various basins are necessary in designing of irrigation canals, and agricultural planning. In order to determine soil physico- chemical properties of a watershed, field and laboratory works are essential.

Soil Sampling: Soil Sampling is one of the most important and foremost step in collection of representative soil samples for physico-chemical analysis. Moreover the integrity of the sample must be maintained from the time of collection to the time of analysis. Undisturbed and disturbed soil samples are required in the analysis of soil for various physical parameters. The undisturbed soil samples are taken by driving ring of 53*55 mm (contents 100 cc) for determining permeability in the laboratory. For determining of bulk density and specific gravity of soil undisturbed, uncompacted soil samples should be taken using core samplers. While, disturbed soil samples are taken to determine moisture contents, porosity, water holding capacity, textural analysis and moisture retention studies using pressure plate apparatus. The depth wise soil samples to cover root zone are preferred in various studies. The field investigation to study important hydrological soil properties are given below:

(i) Infiltration: The movement of water from the surface into the soil is called infiltration. The phenomena of infiltration plays an important role in hydrologic studies as the understanding of the same enables us to estimate more effectively the amounts of runoff originating from precipitation and the results thereof can be applied more confidently to the design problems. The infiltration data is used to estimate of rainfall excess from the given precipitation so as to have an idea of the resulting flood. The infiltration characteristics of the soil is one of the dominant variables influencing irrigation. Infiltration rate is the soil characteristics determining the maximum rate at which water can enter the soil under specific conditions, including the presence of excess water. It has the dimensions of velocity. The actual rate at which water is entering the soil at any given time is termed the infiltration velocity. The rate of decrease is rapid initially and the infiltration rate tends to approach a constant value. The nearly constant rate that develops after some time has elapsed from the start of irrigation is called the *basic infiltration rate*. The typical values of basic infiltration rates for two bare soil conditions are given in Table-4. In this table, condition A is for well aggregated soils with high organic mater, open granular structure, and no evidence of surface sealing. Condition B is for poorly aggregated soils with low organic matter contents and a thin sealed layer at the surface.

Table 4. Basic Infiltration Rates for Two Bare Soil Condition (James, 1988)

Soil	Basic infiltration rate for	
	Condition A, mm/h	Condition B, mm/h
Coarse sand	19-25	8.9
Fine sands	13-19	6.4
Fine sandy loam	8.9-13	5.1
Silt loam	6.4-10.2	3.8
Clay loam	2.5-7.6	2.5

Accumulated infiltration, also called cumulative infiltration, is the total quantity of water that enters the in a given time. Infiltration rate and accumulated infiltration are the two parameters commonly used in evaluating the infiltration characteristics of soil. For design purposes, the relationship between infiltration rates and elapsed time are usually expressed by the following empirical equations:

Horton's model:

$I=I_c+(I_0-I_c)e^{-kt}=a+be^{-kt}$

Kostiakov's model:

$I=bt^{-c}$

Philip's model:

$I=(1/2)st^{-0.5}+b=b+ct^{-0.5}$

Green & Ampt's model:

$I=k(1+\alpha S_c/Y)=b+c/Y$

Where,
I= infiltration capacity, cm/hr
I_c= final constant (basic) infiltration capacity, cm/hr
I_0= initial infiltration capacity, cm/hr
Y= Cumulative infiltrated water in depth
t = elapsed time
α= porosity
s= Sorptivity as defined by Philips (1957)
S_c= Capillary suction as defined by Green & Ampt (1911)
a,b,c,k are constants used in respective infiltration models.

Under naturally, undisturbed condition in the forest, infiltration capacity is almost always high enough to preclude natural overland flow (surface runoff, in general). Occasionally under particularly intense storms, on this saturated soils, surface runoff for short distance may be observed, but such condition are rare. If the soil surface is severely disturbed, infiltration rates may suffer drastic reductions, some times to as low as zero. With varying degree of disturbance and protection, infiltration may recover to pre disturbance rate especially with adequate protection and occurrence of frost which restores permeability. Commonly used methods for determining infiltration capacity are hydrography analysis and infiltrometers studies. Infiltrometers are usually classified as rainfall simulators or flooding devices. Flooding infiltrometers are usually rings or tubes inserted in the ground. Water is applied and maintained at a constant level and observation are made on the rate of the replenishment required.

(ii) Water Holding Capacity: The water holding capacity of soil depends upon the physical and chemical nature of it. When the soil is absolutely saturated with water, so that water fills all the pores between the particles of soil and there is no air space (as in case of aquatic sediments), the soil is said to be at its maximum water holding capacity or saturation. The tension of water at saturation capacity is almost zero and it is equal to free water surface. It can be calculated using following formula:

$$\text{WHC (\%)} = \frac{(W_2-W_1)-(W_1-W_0)}{(W_1-W_0)} * 100$$

Where, WHC is water holding capacity; W_0 is weight of empty box (g); W_1 is weight of box with dried soil (g); W_2 is weight of box with water saturated soil (g).

(iii) Dry Bulk Density: The dry bulk density of the soil is defined as the dry weight of a unit volume of it, and is expressed as g/cm^3. Normally the bulk density ranges from 1.1 to 1.5 g/cm^3 for medium to fine textured soil and from 1.2 to 1.65 g/cm^3 for coarse textured soil, but its is slightly higher in case of alkaline saline soils. The soils with high bulk density are inhibitive to root penetration, and have low permeability and infiltration. The bulk density is inversely related to pore space of soil.

$$\text{Bulk density (g/cm}^3\text{)} = \frac{\text{Weight of soil (g)}}{\text{Volume of soil (g)}}$$

(iv) Moisture Content: Among most frequently determine soil characteristics is water content and is defined as the ratio of weight of water to weight of soil in a given mass of soil. The water content is generally expressed as a percentage and it may also be expressed as a fraction. In this study, the moisture content was determined using oven drying method.

The undisturbed samples were collected and weighed, w, at site and brought to soil laboratory in plastic covers, collected soil were kept in a oven (105^0-110^0 C) for about 24 hours so that it become perfectly dry. Its dry weight, wd, is then measured and water content is calculated from below equation:

$$\text{M.C (\% db)} = [(w-wd)/(wd)]*100$$

(v) Particle Size Distribution: The relative proportion of sand, silt and clay determines the soil texture. The percentage of various sizes of particles in a given dry soil sample is found by a particle size analysis or mechanical analysis. By mechanical analysis is meant the separation of a soil into its different size fractions. The mechanical analysis is performed in two stages: (a) sieve analysis, and (b) sedimentation analysis or wet mechanical analysis. The first stage is meant for coarse grained soils only, while the second stage is performed for fine grained soils. In general a soil samples may contain both coarse grained particles as well as fine particles, and hence both the stages of mechanical analysis may be necessary.

The textural analysis is performed for disturbed sample oven dried and these oven dried samples of soil is separated into two fraction by sieving it through a 4.75 mm IS sieve. Sieving should be performed on the soil sample passing through 4.75 mm IS sieve by arranging largest aperture sieve at the top and the smallest aperture sieve at the bottom. The sieves used for fine sieve analysis are: 2 mm, 1 mm, 600, 425, 300, 212, 150 and 75 micron IS sieves. A receiver is kept at the bottom and a cover is kept at the top of the whole assembly. The proportion of the soil sample retained on each sieve is weighed and the percentage is calculated on the basis of total weight of dried soil sample taken.

The material passing through 75 micron sieve is used for sedimentation analysis using hydrometer. The results of particle size analysis using both fine sieve analysis as well as hydrometer analysis are plotted to get a particle size distribution curve with the percent finer (N %) as the ordinate and the particle diameter as the abscissa with the diameter being plotted on a log arithmetic scale. Fig.4 presents the textural classification chart for 12 main textural classes. In Fig.4, the dotted lines indicate the method of determining the textural class of a soil containing 18% clay, 36% silt and 46% sand. The three lines join at a point A which lies within the class 'loam'.

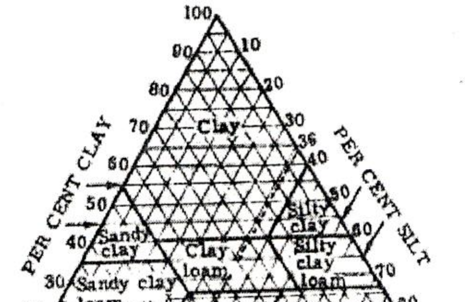

Fig. 4. USDA soil textural classification chart.

(vi) Permeability: Permeability is defined as the property of a coarse material which permits the passage or seepage of water (or other fluids) through its interconnecting voids. A material having continuous voids is called permeable. Gravel are highly permeable while stiff clay is the least permeable, and hence such a clay may be termed impermeable for all practical purposes. The various factors affecting permeability include grain size, properties of the pore fluid, void ratio of the soil structural arrangement of the soil particles, entrapped air, and foreign matters, adsorbed water in clay soils. The qualitative relation of permeability and texture of soils is given in Table 5. Darcy showed experimentally that the rate of water q flowing through soil of cross - sectional area A was proportional to the imposed gradient i or

$$q/A \sim i, \text{ then } \quad q = kiA$$

The coefficient of permeability has been called " Darcy's coefficient of permeability" or "coefficient of permeability" or permeability or even hydraulic conductivity. The study of seepage of water through soils is important for the engineering problems involving flow of water through soils such as seepage under dams, the squeezing out of water from a soil by the application of load, and drainage of sub grades, dams, and back fills. The effective strength of the soil is often controlled by its permeability. The coefficient of permeability can be determined by the following method:

(a) Laboratory methods:

(i) Constant head permeability test.
(ii) Falling head permeability test.

Permeability can be determined in the laboratory by direct measurement with the help of ICW Laboratory permeameter, by allowing water to flow through soil sample either under constant head or under variable head. Permeability can also be determined directly by field test using In-situ Guelph Permeameter. In laboratory, most common method for determining the permeability is ICW laboratory permeameter, which is constant head type equipment. For this, undisturbed soil samples are collected from field by driving a stainless steel cylinder of size 53*55 mm (content 100 cc) and collected soil samples are brought to laboratory. Top and bottom of the ring sample were checked to determine whether they have not been sealed up. Spot seals are removed by taking away tiny particles with the point of a knife, so that pores and root passage are reopened and it should be kept in a water basin for two days, the water level in the basin must remain approx. 1 cm below the top of the sample ring. K-factor can be expressed with a formula in ICW Lab Permeameter as below:

$$K = 144(Q.L)/(h.F1)$$

Where,

K, coefficient of permeability in m/day
Q, quantity of through-flowing water per unit time (cm^3/min)
L, length of the sample (m)
h, level difference inside/outside the ring or ring holder (m)
F1, area of cross section of the soil sample (cm^2)

Table 5. Textural Classes of Soils and Permeability

General Texture	Textural Classes	Permeability
Clayey (Heavy)	Clay	Very Slowly
	Silty Clay	
	Sandy Clay	
Moderately Clayey	Silty Clay Loam	Slowly

	Clay Loam	
Loamy (medium)	Sandy Clay Loam	Moderately
	Silt Loam	
	Loam	
	Very Fine Sandy Loam	
Sandy (light)	Fine Sandy Loam	Rapidly
	Sandy Loam	
	Loamy Fine Sand	
Very Sandy	Loamy Sand	Very Rapidly
	Fine Sand	
	Sand	

(vii) Moisture Retention Characteristics of Soils: Pressure plate Apparatus (Soil Moisture Equipment Co., USA) is generally used to test the soil moisture retention characteristics of soil samples (Fig.5). For this analysis, soil samples should be dried, powdered and passing through a 2mm sieve. Samples thus prepared are used for determining the moisture retention against 0, 0.1, 0.33, 0.5, 0.7, 1.0, 3.0, 7.0, 10.0 and 15.0 bars respectively. Each of these samples should be tested against 0.5 bar & 1.0 bar by 1 bar plate, whereas 2.0 bar and 3.0 bar with 3 bar plate as well as 15.0 bar with 15.0 bar plate and test should be replicate thrice. The apparatus should be under continuous operation i.e. from the placement of water soaked (saturated) sample in the chamber till the end of the testing i.e. soil moisture and the pressure applied reaching to an equilibrium.

Samples taken out of the pressure chamber are weighed on a high precision micro balance to record the moist weight of samples. These weighed samples were placed in the oven at 105 deg Celsius till the weight become constant on drying. Samples taken out of the oven were placed in the deccicator for cooling and dry weight was recorded by weighing it on the same microbalance.

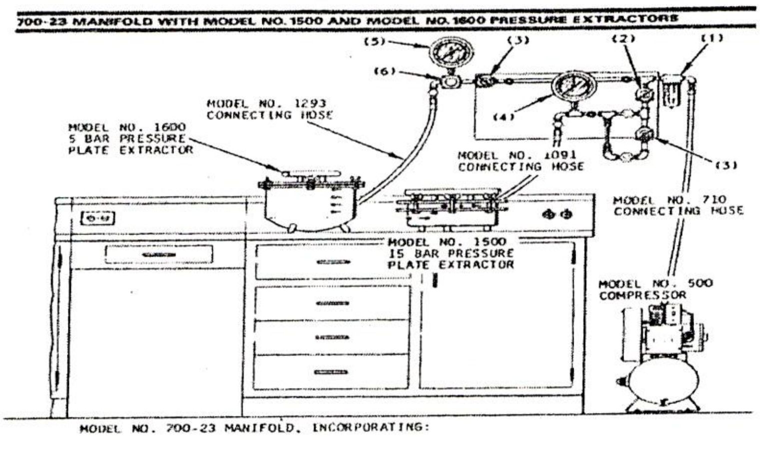

Fig.5. Laboratory Set up for 15 Bar Ceramic Plate Extractor and 5 Bar Extractor (Soil Moisture Equipment Corporation, 1983)

Moisture by weight was determined from the initial and dry weight of the sample. Moisture content at 0 bar (saturation) should also be determined using prescribed procedures. Then data of % moisture (dry weight) on ordinate and soil suction (bars) on abscissa is platted, which termed as moisture retention curves. These curves are extremely important in soil research and in development of practical, effective irrigation practices. The soil moisture tension at field capacity varies from soil to soil, but it generally ranges from 1/10 to 1/3 atmospheres. The moisture tension of a soil at the permanent wilting point ranges from 7 to 32 atmospheres, depending on soil texture, on the kind and condition of the plants, on the amount of soluble salts in the soil solution, and to some extent on the climatic environment. The determination of moisture content at 15 atmosphere tension which is the usually assumed value of permanent wilting point, can be done by the pressure membrane apparatus. The typical moisture characteristics curves of clay, loam and sandy soil are given in Fig. 6.

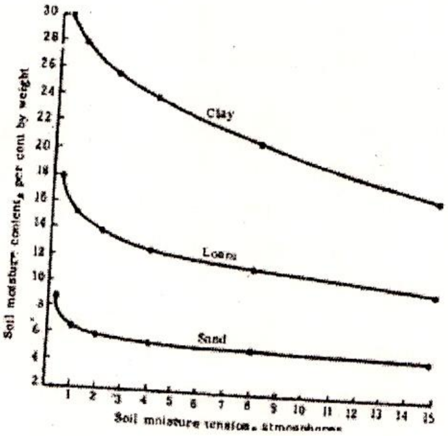

Fig. 6. Moisture characteristics of common soil types (Source: Michael, 1990).

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TUTORIALS

Problem-1

Question (a): *In a preliminary water quality monitoring program, the 8 water quality variables were monitored in a watershed (USA). Based on the cost of data, these analyses would cost a total of $ 40.45 per site visit. If budget is limited to $ 25 to monitor water quality per sampling period. Prioritise the water quality variables based on the correlation matrix analysis of the variables? The water quality variables include:*

- Turbidity
- Total Suspended Solids (TSS)
- Volatile Suspended Solids (VSS)
- Total Phosphorus (TP)
- Orthophosphate (OP)
- Total Kjeldahl Nitrogen (TKN)
- Ammonia Nitrogen (NH_3)
- Nitrate Nitrogen (NO_3)

Solution:

Step I: Preparation of a matrix of variables (v) and observation sites (n) for representing into a data matrix of dimension v×n.

Step II: Analyse the data matrix using the Eq. for correlation coefficients (r):

$$r=\frac{\sum(Xi-Xm)(Yi-Ym)}{\sqrt{\{\sum(Xi-Xm)^2\sum(Yi-Ym)^2\}}}$$

Where,

Xm and Ym = the means of the variables X and Y respectively
Xi and Yi = individual values of variables X and Y, respectively

Calculating the Attributes of above Eq.

Xi	Yi	(Xi-Xm)	(Yi-Ym)	(Xi-Xm)(Yi-Ym)

1	1			
2	2			
3	3			
.	.			
.	.			
.	.			
.	.			
N	N			
Xm=Xi/n	Ym=Yi/n	Σ(Xi-Xm)	Σ(Yi-Ym)	Σ(Xi-Xm)(Yi-Ym)

Step III: Test of Significance of correlations (r):

Computed values of correlation coefficients (r) may be evaluated using "t" tests at the desired levels of significance (eg. 1% , 5% levels of significance for n-2 degree of freedom). A "t" test for the significance of "r" is given by (Davis, 1986):

$$t = \frac{r\sqrt{(n-2)}}{\sqrt{(1-r^2)}}$$

Significant Correlation: *If "t" calculated is* ***greater than*** *"t (table) value at selected level of significance, otherwise non significant.*

Step IV: Preparation of matrix of correlation coefficients

Correlation matrix (r)

	Turbidity	**TSS**	**TKN**	NO_3	**TP**
TSS	0.577	1.000	-	-	-
VSS	0.764	**0.855**	-	-	-
NH_3	-	-	**0.836**	0.281	-
NO_3	-	-	-0.057	1.000	-
OP	-	-	-	-	**0.915**

Step V: Prioritising of Variables

The Table 2 indicates that, the correlations between TP and OP, TKN and NH_3, and TSS and VSS are **significant** and very high. **Adequate monitoring could be achieved by choosing TSS, Total P, and TKN for less than $25 to meet sedimentation and eutrophication objectives (USDA, 1996).**

Question (b): Determine the total number of samples and the number of samples within each stratum to be within 10% of the true mean at the 95% confidence level for phosphorus. The overall mean was 0.04 mg/L total phosphorus. The Preliminary sampling resulted following parameters of water quality for a stratified lake (Mudd Lake, USA) during the summer:

Lake Strata	Thickness		Standard deviation
	(ft)	(%)	(mg/L)
epilimnion	14	35	0.012
metalimnion	6	15	0.005
hypolimnion	20	50	0.010

Solution: The sample size for stratified random sampling can be calculated from the relationship (Reckhow & Chapra, 1983):

$$n = \frac{t^2(\sum wiSi)^2}{d^2}$$

Where,

n = the total number of samples
t= Student's "t" at n-1 degree of freedom
wi= the proportional size of stratum I
Si= the standard deviation of the water quality data for stratum I
d= the difference from the mean

The number of samples for each individual stratum is determined from:

$$ni = \frac{nwiSi}{\sum(wiSi)}$$

Where, ni= the number of samples for stratum I

Step I: First Iteration

$$n = \frac{(1.96)^2[(0.35)(0.012) + (0.15)(0.005) + (0.50)(0.010)]^2}{[(0.10)(0.04)]^2} = 23.8 = 24$$

We observe that the value of "t" used 1.96 (for >120 d.o.f) is not the same for n-1 (24-1) degree of freedom and 95% confidence level obtained in step I. Hence, we go for

2nd Iteration using new value of "t". Remember new "t" at 23 d.o.f and 95% confidence level is 2.069.

Step II: Second Iteration

$$n=\frac{(2.069)^2[(0.35)(0.012)+(0.15)(0.005)+(0.50)(0.010)]^2}{[(0.10)(0.04)]^2}=26.5=27$$

Now, allocate the 27 samples among the 3 strata by:

$$n\text{ (epilimnion)}=\frac{27(0.35)(0.012)}{[(0.35)(0.012)+(0.15)(0.005)+(0.50)(0.010)]}=11.4$$

$$n\text{ (metalimnion)}=\frac{27(0.15)(0.005)}{[(0.35)(0.012)+(0.15)(0.005)+(0.50)(0.010)]}=2.0$$

$$n\text{ (hypolimnion)}=\frac{27(0.50)(0.010)}{[(0.35)(0.012)+(0.15)(0.005)+(0.50)(0.010)]}=13.6$$

Therefore **11, 2, and 14 samples** should be taken from the epilimnion, metalimnion and hypolimnion, respectively.