A REVIEW OF LAKE EUTROPHICATION AND MITIGATION MEASURES

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ABSTRACT

The process of aging of lakes is a serious problem in India because of eutrophication. Besides natural eutrophication, eutrophication due to various anthropogenic sources as a result of socio-cultural activities is a serious issue. The paper reviews different aspects of eutrophication, its impacts on water quality and aquatic biota. Lake classification based on nutrient management models is described to evaluate lake conditions and associated rejuvenation methods. The positive correlation between different groups of algae has been observed in relation to physico-chemical conditions of soil-water of lakes. Lake assimilative capacity in relation to water quality and sediment water interactions is illustrated for better understanding of the restoration of lake. Methods for rejuvenation of lakes are described emphasizing on the reduction of nutrients through anthropogenic activities.

INTRODUCTION

Lake is an ephemeral feature of the landscape and is a dynamic system. 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 V.T., 1964). Lakes are transitory features of the earth surface and each has a birth, life and death related to certain geological and biological processes. Most of the lakes are potential source of fresh water at high altitudes and also in plains. Water impounded in the lakes is used to meet domestic, agricultural and industrial needs. Apart from this, lakes also provide water for fisheries, and recreation. The physical, chemical and biological characteristics of lakes vary widely. Lakes vary physically in terms of light levels, temperatures and water currents; chemically in terms of nutrients, major ions and contaminants; biologically in terms of structure, population numbers and growth rates.

Human settlement in the drainage basin of a lake generally leads to discharge of point and non-point sources of pollution in the lake. Man made activities in turn accelerate runoff from the land surface and increase input of plant nutrients. Also, streams are used for disposing household wastes and sewage, adding to the nutrient load in the receiving water body. The addition of plant nutrients stimulates growth of algae and other biota, which stimulates fish and other organisms in the food web. Phosphorous and Nitrogen are derived from sewage, agricultural and livestock holding operations. This perceives negative effects on water bodies such as excessive algal and plant growth and impaired aesthetic quality of water.

CLASSIFICATION OF LAKES

Trophic status is a useful means of classifying lakes and describing lake processes in terms of the productivity of the ecosystem. Basins with infertile soils release relatively little nitrogen and phosphorous leading to less productive lakes, classified as oligotrophic or mestrophic. Watersheds with rich organic soils, or agricultural regions enriched with fertilizers, yield much higher nutrient loads, resulting in more productive or eutrophic (even hyper eutrophic) lakes.

Lakes have been classified according to their trophic state. A Eutrophic ("well-nourished") lake has high nutrients and high plant growth. An Oligotrophic lake has low nutrient concentrations and low plant growth. Mesotrophic lakes fall somewhere in between eutrophic and oligotrophic lakes. Each lake has a unique constellation of attributes that contribute to its trophic status. Three main factors regulating the trophic state of a lake are; (1) rate of nutrient supply (2) climate (3) shape of lake basin (morphometry).

EUTROPHICATION

Eutrophication has been defined as biological reaction of aquatic ecosystems due to nutrient enrichment and can lead to algal blooms, dissolved oxygen deficiency, fish death and other ecological changes. Active biological communities are developed and lake basins become shallower and more eutrophic as decaying plant and animal material accumulate at the bottom. Shallow lakes tend to be more productive than deep lakes because of the absence of stratification, thereby allowing nutrients to remain in circulation and accessible to plants. Nutrient loading from their watershed has a larger impact on Shallow lakes. However, deep lakes generally become physically stratified into three identifiable layers, known as epilimnion, metalimnion and hypolimnion causing the lake to stratify thermally without complete mixing (Brock, 1985). This prevents atmospheric oxygen from reaching the bottom waters leading to anoxic conditions. Studies of sediment cores have suggested that the algal productivity of Minnesota Lake (Heiskary, 1990) actually may have fluctuated a great deal during the past 12000-14000 years (the period since the last glaciations). The natural time scale for the aging of a lake from ultraoligotrophic to eutrophic state is of the order of thousands of years. However, a high rate of input of nutrients due to human activity can increase the rate of aging significantly resulting in eutrophic conditions developing after only a few decades (Brock, 1985). This is defined as cultural eutrophication (Vallentyne,1972). This occurs through poor management of the watershed and introduction of human wastes through septic systems disposal of wastewater in stream joining the lake. Such changes may occur over periods of only decades and are reversible if anthropogenic nutrient loading can be controlled. During 1960's this was a serious issue, exemplified by the hypertrophic condition of Lake Erie (Wright, 1980). Although it was pronounced "dead", it eventually returned to less eutrophic conditions, when major point sources were controlled in the early 1970's. Significant effects of eutrophication on lake ecosystem are mentioned below:

Increase in plant and animal biomass, increase in rooted plants growth, increase in water turbidity, increase in sedimentation rate, development of anoxic conditions (low dissolved oxygen levels), decrease in species diversity, change in dominant biota, increase in the frequency of algal blooms.

Some of the major consequences resulting from eutrophication of lakes can be classified as follows;

- Decrease in the amenity value of the water (e.g. it may become unsuitable for water sports, such as sailing or other recreational activities)
- Increased vegetation may impede free flow of water and movement of boats
- Depletion of dissolved oxygen levels at the bottom of lake

Under these anoxic conditions, anaerobic bacteria multiply which results in the release of hydrogen sulphide, methane, thioalcohols, ammonia, carbon dioxide etc. These conditions result in the lake becoming extremely unaesthetic and no longer remaining useful for any purpose.

NUTRIENT MANAGEMENT MODELS

Inorganic nutrients provide chemical building bodies for life in aquatic systems. Some nutrients are required in large quantities for cell development (macronutrients) such as carbon, oxygen, nitrogen, phosphorous, sulphur, silica and iron. Smaller quantities of micronutrients, like manganese, copper and zinc are also necessary. Nitrogen and phosphorous are the primary controllable nutrients and are present in point sources like untreated domestic sewage and industrial effluents and non-point sources like urban and agriculture runoff (Khallel, 1999). Carbon, as a macronutrient is often used as a measure of biomass and is an indicator of pollution level. Silicon has significance in the dynamics of phytoplankton, being a major structural element in the cell (Khallel, 1999).

Various nutrient loading models are tested on man made lakes and reservoirs and used to predict phosphorous dynamics in response to management options (Allen, 1983). Phosphorous concentrations in lake waters are found to be sensitive to reservoir operation. Jones and Bachman's, Walker's, Dillon and Kirchner's phosphorous models are tested on western lakes with similar morphometry and trophic status as determined by the U.S. Environmental Protection Agency (EPA) in National Eutrophication survey (Mahaman, 1980). All the models are found to be applicable to both long and short retention time lakes and have some merit for the examination of eutrophication (Tapp, 1978).

Lake min, Basins, Qual2k, Wasp 6, Mike 11 are some of the lake models available and are useful in nutrient management and monitoring in the lake ecosystem. Mike 11, (2000) model describes the cycling of carbon, nitrogen and phosphorous from inorganic to organic form and back to inorganic, as well as coupling to dissolved oxygen driven by hydrodynamics and external functions like light radiation, temperature and loads of organic matter and nutrients. These advance tools are useful in a long range of consequences of human interventions on lake environment.

Management of impacts on lake system due to of increased nutrients depends principally on the Vollenweider phosphorous loading relationship. Vollenweider and Kerekes (1980) discussed the historical perspectives of limnological research and loading concepts. Jones and Lee (1980) indicated that the USA Organisation for Economic Cooperation and Development (OECD) nutrient load eutrophication response model is applicable to deep lakes. The Dillon Rigler and Vollenweider input/output models used to predict the general trophic state following phosphorous abatement (Uttormark, 1980). A variation of the Vollenweider's model predicts the phosphorous and nitrogen concentrations in shallow and eutrophic lakes subjected to both external and internal loading and could be used in lake management (Osbome, 1980).

Trophic state determination is an important aspect of assessment of water quality in a lake. Trophic state is a measure of the degree of plant material in a body of water. It is usually measured using one of several indices of algal biomass (weight), water transparency (Secchi depth), algal chlorophyll and total phosphorous. The Trophic Sate Index (TSI) values of Carlson (1977) range from 0 to greater than 100, where each 10 units represent a doubling in transparency and total phosphorous. Suggested TSI limits to classical trophic state terminology are:

Trophic state		**TSI limits**
Ultraoligotrophy	:	(0-20)
Oligotrophy	:	(20-40)
Mesotrophy	:	(40-50)
Eutrophy	:	(50-70)
Hypertrophy	:	(>70)

The boundary conditions for classification of lake and reservoirs as defined by the OECD (1982) are presented in Table1. Chlorophyll-a is a measure of the total phytoplankton content and is an important parameter in lake classification and its status. The Secchi depth is a measure of the degree of transparency of water and is a function of the algal concentration and the concentration of dissolved components.

Table 1. OECD Boundary values of cake classification (1982)

Trophic Level	**Total P mg/L**	**Mean Chlorophyll-a µg/L**	**Max Chlo-a µg/L**	**Mean Secchi Depth m**	**Minimum Secchi Depth m**
Ultra–Oligotrophy	<4.0	<1.0	<2.5	>12.0	>6.0
Oligotrophy	<10.0	<2.5	<8.0	>6.0	>3.0
Mesotrophy	10-35	2.5-8	8-25	6-3	3-1.5
Eutrophy	35-100	8-25	25-75	3-1.5	1.5-1.7
Hypereutrophy	>100	>25	>75	<1.5	<0.7

(Source: Eutrophic status of Hussainsagar lake in Hyderabad, Er. P. S. Kelkar, 2002, Journal of the Institution of Engineers (India), Vol.83.)

The limiting nutrient concept is based on the assumption that under given cell stoichiometry of aquatic plants, the nutrient rate will control the maximum amount of plant biomass. In freshwater systems, the limiting nutrient is usually phosphorous (Perkins, 2000) and studies have mostly been concentrated on indices of limitation (Vrba, 1995). In phosphorous limited condition algae have been observed to use phosphatase enzyme to utilize organic phosphorous

Whitton, 1996). Vollenweider (1983) proposed the total nitrogen to total phosphorous ratio of 9:1 for proper growth of phytoplanktons. Consequently water bodies or lakes with total nitrogen to total phosphorous ratio greater than 9 are considered to be potentially phosphorous limited whereas those less than 9 are nitrogen limited. The studies by Salas, et al (1990) concluded that, by using the nitrogen to phosphorous ratio concept, the majority of the warm water tropical lakes and reservoirs were observed to be phosphorous limiting. Although in some cases other factors, such as light could be limiting factor in view of the high observed levels of both nitrogen and phosphorous.

WATER QUALITY IMPACTS ASSOCIATED WITH EUTROPHICATION

Assimilative capacity is the range of concentration of a substance or mixtures of substances that will cause no deleterious effects upon the receiving water bodies. The lake ecosystems have certain assimilative properties regarding anthropogenic wastes. Anthropogenic wastes may be of non-point sources or point sources e.g. from upstream tributaries after rainstorms, from die-off of aquatic plants, from pulses of urban storm water, direct runoff of lawn fertilizer, or from leaky lakeshore septic systems. Significant amounts of available nitrogen may be deposited during rainfall due to soil erosion. Nitrogen and phosphorous may also come from fertilizers from agriculture fields.

Water quality of lake is highly affected by increasing nutrient loading. Profuse algal growth cause bad taste and odour (Verma, 2002). Excessive macrophytes growth loses the open water zone and hence with increased turbidity Secchi depth goes down. Dissolved oxygen becomes limiting factor for the survival of fish and fish food. Some kinds of blue green algae are not eatable by zooplanktons and hence food chain efficiency reduces. In the bottom of the lake toxic gases e.g. ammonia, H_2S production cause loss of fish habitat. Also some blue green algae synthesize toxins which are harmful to fish habitat.

Essential nutrients such as the bioavailable form of phosphorous and nitrogen (dissolved phosphate, nitrate and ammonium) typically increases in the spring from accumulated nutrients in the bottom. Concentrations of nutrients typically decrease in the epilimnion during summer stratification as algae take up nutrients. When the algae die and settle out eventually nutrients are transported to the hypolimnion. During this period any "new" input of nutrients into the upper water may trigger a "bloom" of algae (Seven, 1989).

Phosphorous especially when in the form of ionic orthophosphate (PO_4^{3-}) is widely accepted as being the critical nutrient in determining the degree of lake eutrophic conditions. But in some cases inorganic nitrogen (NH_4^+ or NO_3^-) can be the limiting nutrient. The significance (Campbell, 1981) of phosphorous is evident from the fact that 1 g of phosphorous give rise to at least 100 g of algae which in turn require 150 gm of oxygen for aerobic degradation. A lake's biological characteristics are determined in large part by physical characteristics including temperature, light transparency and abundance of inorganic nutrients (Winfield, 1988) [Nitrogen, Phosphorous, Carbon], which results into the enrichment of periphyton standing crop, species composition and primary production in an oligotrophic soft water lake.

SEDIMENT WATER INTERACTIONS IN THE LAKE

Bottom sediments have long been acknowledged as a potential source of phosphorous nutrients to the overlaying water of lakes and impoundments. In shallow lakes, the intense sediment water contact gives an extra dimension to the eutrophication problem. Much of the phosphorous that has been absorbed by the sediment during eutrophication can be released to the water column. The impact of release from sediments is found to depend on the dissolved oxygen concentration at the sediment water interface (Simon, 1983). Originally, it was thought that phosphorous is relatively immobile in sediments and that the only source of phosphorous available to the overlaying water is contained at the sediment surface (Hayes, 1952). Studies also suggest that phosphorous can be mobile in anoxic sediments Hynes, 1970, Krom, 1980). Thus, sediments may act as a phosphorous reservoir. This internal loading can cause a delay of many years in the response to restoration.

As the sediments build up in eutrophic lakes, so does the potential phosphorous reservoir. Substantial amounts of nitrogen can disappear from shallow lake as a result of denitrification (Jenson, 1992). The relatively high sediment temperatures in summer may lead to an increase in mineralization rates and consequently to an increased release of nutrients into water column from the sediments.

A study on 27 Danish lakes (Soudergaard, 1993), that had received a substantial reduction in nutrient loading due to restoration measures, showed that even 4 – 16 years after the reduction in loading, decrease in nutrient concentration in most lakes was less than expected. Sediments start acting as a source rather than a net sink of phosphorous and keep releasing phosphorous to the lake water. Phosphorous content of sediments is indicative of potential internal loading (Kelkar, 2002). Assuming a homogeneous well-mixed system with no exchange between sediment and water, it derived through modeling studies that it takes about three times the hydraulic retention time to reduce the surplus phosphorous in the lake water by 95%.

The average nitrogen to phosphorous ratio of 17:1 for sediment in the lake (Gibbons, 1981) indicates that phosphorous is the limiting nutrient (Schindler, 1978) in this ecosystem. One of the mechanisms is the release of phosphorous associated with macrophyte pumping (Roy, 1972; Wetzel, 2001; Carignan, 1980) and senescence (Solski, 1962; Funk, 1975). The other mechanism of phosphorous translocation is diffusion (Krom, 1980; Berner, 1977). Other factors may play a secondary role, e.g. sediment agitation, benthic disturbances and enzyme hydrolysis.

Nitrogen does not show strong resilience to reduction efforts as described for phosphorous. It does not accumulate in the sediment that can strongly and disappears as gas into atmosphere under anaerobic conditions (Kelkar, 2002). Sediment surface is very important site for denitrification. Jenson and Cowerkers (1994) showed that for Danish Shallow lakes, 77% of accumulated nitrogen disappeared through denitrification. Mineralization of organic material at the sediment surface may be an important source of carbon for the water column of shallow lakes and phytoplankton growth is probably rarely limited by carbon (Vadstrup, 1995). An oxidizing environment at the sediment water interface normally inhibits the diffusion of phosphorous into the overlaying water column, and that inhibition is best described by the relationship between iron and phosphate (Theis, 1978).

EUTROPHICATION INDICATORS

Common indices for classifying the trophic status of a lake, particularly the Secchi disc transparency, can be misleading because Secchi disc transparencies and chlorophyll-'a' concentrations do not correlate well (Lambou, 1982). Total phosphorous has the most practical correlation in both lotic and lentic samples (Peters, 1982). God Frey (1982) concludes that due to the use of phosphate detergents, changes occurs in phosphorous loading patterns, which are responsible for increase in spring and summer algal crops and composition of the phytoplankton assemblage. Phytoplankton indices and Palmer's pollution indices are the most important measure of eutrophic indicator genera Sullivan, P.F and Carpenter, S.R. (1982).

The relationships among nutrient loading, algal biomass and lake clarity were documented clearly by Vollenweider (1976). This represented a milestone in lake management because it allowed managers to predict the outcome of nutrient control strategies (Walker, 2000). The watershed forms the natural unit for nutrient management. The models are based on empirical data relating to watershed nutrient loading and nutrients to algal biomass that provide a conceptual framework which links nutrient supply to lakes with phytoplankton biomass and water clarity.

The nature and quality of biological species, particularly phytoplankton community on which whole aquatic population depends in a water body, are dependent on its physico-chemical characteristics such as pH, conductivity, nutrients, BOD, alkalinity, hardness, and also on its nature such as stagnant lakes or moving water (Malammanavar, 1996) (Table 2). According to Munawar (1974) and Hegde (1988) more concentrations of nitrate and oxidisable organic matter are responsible for the growth of algae. Similarly algal blooms present in the lake results in the precipitation of carbonate of calcium and magnesium from bicarbonate causing the higher alkalinity. According to Manawar (1974) phosphate is released into media when it has low concentration of oxygen and high concentration of carbon dioxide. Possibly this may favour the dominant growth of *Euglena elastica*, cyanobacteria (Hedge, 1986; Metting, 1983). Blue green algae live in high pH due to increased ability of organic and inorganic nutrients (Lund, 1945; Lund, 1947; Mitra, 1961). Excessive growth of certain algal species such as *Anabaena, Aphanizomenon, Microsystis, Oscillatoria, Scenedesmus, Pediastrum, Stigeoclonium, Melosira, Fragillaria* is known to indicate nutrient enrichment of water bodies (Palmer, 1969; Kumar, 1990).

Diversity of plankton depends on physico-chemical characteristics of water. In oligotrophic water, diversity of plankton is high. With increasing levels of pollution, such as mesotrophic and eutrophic conditions, diversity of plankton decreases due to less ability to adapt adverse conditions (Washington, 1984). The water bodies receiving organic pollution, normally showing index values below 1 can be devoted as eutrophic. R.C. Trivedi (1981) proposed a correlation between diversity of planktons and degree of pollution. He stated that the water body having diversity index above 4 is clean water. Diversity index of 3 – 4 indicate light pollution, 2 – 3 and < 2.0 indicate moderate and heavy pollution respectively (Table 3).

Table 2. Different groups of algae according to different physico-chemical conditions

Group / species	Physicochemical condition
Scenedesmus	Sewage contamination
Ankistrodesmus	Chloride
Euglenoid	Chloride
Euglenoid flagellates	pH 7-2, more chloride
	NH_3, Organic matter, Iron
Microcystis	pH 9.6, more chloride
	Very high organic matter
Green algae	Nitrates, Phosphates high
Volvocales	High alkalinity
Chlorococcales	High, pH rich DO
Cyanophyceae	Nitrate content high
-do-	Calcium very high
Euglenophyceae	Nitrate & Ammonia
Bacillariophyceae	High conductivity, Nitrate, Silicate

(Source: Algae as ecological indicators of water quality, Dr. J. P. Verma, Ecology of polluted waters, Vol.1, 2002).

The phytoplankton community attributes, viz. total count, different species and groups act as indicators of water quality and organic pollution. The bacillariophyceae (diatoms) is the indicator of oligotrophic waters (clean water, Standard methods, and 1998). With the increase in pollution levels, the succession occurs as follows

Bacillariophyceae> Chlorophyceae > Pyrrhophyceae > Cyanophyceae > Euglenophyceae

Table 3. Correlated diversity index with various degrees of pollution as suggested by Trivedi (1980)

Condition	Diversity Index (d)
Clean water	4
Light pollution	3 – 4
Moderate pollution	2 – 3
Heavy pollution	<2.0

Diversity per individual = $d = -\Sigma Pi \log_2 Pi$

Where Pi = Probability that any individual selected at random, belongs to i^{th} species {Source: Use of diversity index in evaluation of water quality,R. C. Trivedi, , CPCB, 1981.}

LAKE RESTORATION

Alum treatment has been proved very efficient in control of algal bloom and turbidity in lake waters (Doke, 1995; George, 1992). The precipitation of phosphorous help to keep the phosphorous fixed in the sediment and can no longer be used as food by algal organisms

(Eilen, 1985). Removal of sediment layer to reduce release of phosphorous and toxic substances can do a great deal towards lake restoration. Restoration of lake may include biomanipulation, hydrological adjustments like water level manipulation, complete draw down and if possible, flushing and dredging.

Important restoration operations for control of point and non-point sources of nutrients in lake are:

- Diversion of dry weather flow entering the lake through inlet nallahs
- Ban on all activities that causes pollution of the lake
- Removal of algal matter to reduce the environmental problems
- Sewage treatment with tertiary treatment to remove phosphorous and nitrogen
- Desludging to remove accumulated organics, nutrients and heavy metals.
- Aeration to accelerate biological reactions and elimination of anoxic conditions.

Reduction of nutrient loading is a first logical step in restoration of eutrophic lake. Restoration of lake may take very long time and eutrophic conditions may prevail even if anthropogenic activities are reduced drastically. Other practical eco-technological measures that can be taken to change the state of lake may include aeration to make up oxygen depletion in hypolimnion. The aeration system accelerates the digestion of the organic bottom deposits that stimulate excessive weed and algae growth (Alan, 2001). It reduces anoxic conditions by bacterial seeding which speeds up digestion. Aeration is a practical solution for taste and odour control and to evaluate aeration effect on H_2S and CH_4 levels (Ashley, 1983). Reduction of accumulated CO_2 due to aeration decreases Ca, Mg, HCO_3 and PO_4 through $CaCO_3$ co-precipitation (Mcqueen, 1983).

CONCLUSION

Introduction of point and also the non-point sources of contamination have a significant effect on lake ecosystem. From various studies it is seen that application of nutrient management models are useful to evaluate lake conditions and associated rejuvenation methods. Vollenweider's phosphorous loading relationship and input/output models may help to predict the general trophic state following phosphorous abatement. Lake assimilative capacity in relation to water quality is very much useful towards the correlation between deposition of nutrients and water quality assessment. Thus one can evaluate the critical nutrient load in determining the degree of lake eutrophic conditions and limiting nutrient concept. Sediment water interactions are furthermore useful for the studies of internal loading, in the response to lake restoration. The relationship between nutrient loading and algal biomass is a milestone in lake management because it allows predicting outcome of indices and nutrient control strategies. Various diversity indices and nutrient indices depend on physico-chemical characteristics of water. Modern tools of mathematical models describe the growth of biological species, oxygen conditions as a consequence of organic loading, available nutrients and hydraulic conditions of lake. Ecotechnological measures like aeration, sediment removal, phosphorous precipitation and inactivation, nutrient removal by advanced treatment and nutrient diversion need to be adopted to rejuvenate the lake.

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