CHAPTER 2

LITERATURE REVIEW

2.0 LITERATURE REVIEW

2.1 Phytoplankton

The plant and plant-like organisms form the phytoplankton (phyton in Greek means a plant). Plankton is the assemblage of organisms which carry out all or a major part of their growth and reproduction in the open waters of the sea, lakes, pools and rivers. The phytoplankton consists almost wholly of algae. The photosynthetic activity of phytoplankton in open water helps to increase the concentration of oxygen in water. Phytoplankton is the main producers in most freshwater environments and thus, provides the principal energy base for many aquatic food webs (McCormick & Cairns, 1994).

2.1.1 Algae as environmental indicators

Whitton (1975) reported that certain species of algae may be regarded as 'indicators' of particular types of pollution, but this concept has limited value. However, conspicuous growths of a few species do appear to provide some guides to environmental conditions. He mentioned that a large growth of *Cladophora* and *Euglena mutabilis* would probably indicate nutrient eutrophication and acid mining waste respectively. Malea and Haritonidis (2000) noted that the presence of *Ulva rigida* (green algae) in the seawater was due to lead ions.

Algae respond rapidly to a wide range of pollutants and possess many desirable attributes as indicators of ecosystem integrity and environmental change, most notable the following (McCormick & Cairns, 1994):

(a) algae are a ubiquitous and ecological important group in most aquatic ecosystems;

(b) algae are sensitive to a broad range of environmental stressors;

(c) algae provide relatively unique information regarding ecosystem condition compared with animal indicators;

(d) algae respond rapidly to changes in environmental conditions:

(e) the use of algal assemblages facilitates establishment of a historical benchmark or other reference point for estimating pre-disturbance conditions;

(f) algae provide a cost-effective monitoring tool in terms of information gained per unit effort.

Algae also respond rapidly to a wide range of pollutants. They provide potentially useful early warning signals of deteriorating conditions and the possible causes. Shifts in the relative abundance of algal species and density can be used to detect the environmental changes (Patrick, 1994). The Trophic Diatom Index was established for monitoring in rivers (Kelly *et al.*, 1995). Yap *et al.* (1997) reported that higher population biodiversity and lower cell number were found at the upper stream areas of Sg. Selangor and Sg. Bernam which were less polluted compared to the downstream areas with lower population biodiversity and higher cell number.

2.2 Factors that influence phytoplankton distribution

2.2.1 Natural factors

Natural factors that can affect the phytoplankton distribution in the lakes are soil types and geochemistry of the catchment area which include the location, climate and hydrology of the area.

2.2.1.1 Climate

The weather conditions of the catchment area are influenced by the geographical location which determines water temperature, precipitation and solar energy. All of these factors are important in controlling phytoplankton productivity.

Generally, the nearer to the equator, the greater is annual productivity because the water bodies receive relatively constant amount of solar energy throughout the year. There is high correlation between phytoplankton photosynthesis and availability of light energy. A seasonal fluctuation pattern of *Chlorella* in open ponds was reported by Babel *et al.* (2002). Temperature influenced the gross primary productivity in Kodayar aquatic system where temperature decreases 1°C for every 240 m change in altitude (Murugavel and Pandian, 2000). In addition, with increasing altitude, there is a decrease in atmospheric pressure, implying that oxygen saturation is lower. Hence, the dissolved oxygen (DO) level in the Kodayar lakes increases with decreasing altitude. Water temperature may be a limiting factor for blue-green alga such as *Cyclindrospermopsis rachiborskii* (Babel *et al.*, 2002)

Experiments carried out by Cura (1981) indicated that light was controlling the nitrate up-take and its relationship to growth rate of phytoplankton. In addition, light intensity has long been recognised to affect the succession of phytoplankton. Toner (1981) found that there is a strong correlation in phytoplankton standing crop at Mount Hope Bay, Massachussets with a combination of light intensity and wind.

Low turbidity during dry season and higher concentration of SiO_2 during the rainy season changed the phytoplankton species distribution in Lake Victoria, Kenya (Lung'ayia *et al.*, 2000).

2.2.1.2 Geology and physiography of the catchment area

Chemical composition of lake waters are influenced by the geological composition, size and topography of the drainage basin. However, the availability of chemical substances which can dissolve in the water is unknown. Therefore, mineral contents of freshwater can vary within a wide range due to the differences in the regional geochemical and climatic conditions. The weathering rate of minerals is increased by increasing temperature, increasing acidity, an active percolation of water and the presence of oxygen (Moss, 1988). Sedimentary rocks are built from mixed particles, they are often porous, presenting a large surface area for water to percolate and therefore have much more widespread effect on freshwater chemistry.

2.2.1.3 Hydrology

Hydrology refers to movement of water from the catchment. Generally, in a tropical area, the greater the quantity of rainfall, the greater the quantity of water and nutrients transported to a waterbody. However, it might not continue to increase indefinitely with the increasing rainfall (Ryding & Rast, 1989).

2.2.2 Anthropogenic factors

The catchment may be altered by human activities such as forest removal, cultivation, land clearing, fertilisation, industrial and waste disposal. The removal of vegetation cover for these human activities may upset the land ecosystem which conserves nitrogen and phosphorus. Forest harvesting results in direct removal of nitrogen in forest biomass, alters mineralisation and nitrification rates and increases water and nitrogen fluxes from catchments (Lepisto, 2000). The change from forest to agriculture can led to increase in stream concentration of total phosphorus and soluble orthophosphate by about ten-fold and total nitrogen about five-fold (Moss, 1988).

Point sources of pollution like sewage treatment plants become a major source of nutrient load into a waterbody. Rapid urbanisation has caused the increase of sewage treatment plant facilities and also the risk of poorly treated sewage being discharged into water bodies. Lake Washington in the United State experienced severe phytoplankton problems resulting from sewage inputs (Edmondson, 1972).

Non-point sources are mainly due to geologic and physiographic factors that affect lake water quality. A higher nutrient load was correlated with increase of urban and agricultural land usage. Human alterations and disturbances of a watershed can result in greater nutrient export to a receiving water body. Removal of vegetation can disrupt nutrient cycling processes, resulting in an accelerated loss of ions from the drainage basin to a lake in the basin (Ryding & Rast, 1989).

2.3 Freshwater phytoplankton distribution patterns

Reynolds (1984) highlighted the importance of understanding the patterns of distribution of phytoplankton and the scales of spatial and temporal heterogeneity with the fluid environment, as well as phenomena that contribute to their existence. The environments inhabited by plankton are obviously heterogeneous and the spatial and temporal scales of availability are interlinked.

2.3.1 Vertical distribution

Discontinuities in spatial distribution of phytoplankton that persist for hours or days are known as vertical planes. According to Reynolds (1984), the specific vertical distributions can vary substantially with depth, with time and in relation to physical segregation of the water column. In addition, the observable patterns are isolated instance in a dynamic process of change. The patterns become increasingly complex when gradients of light attenuation or nutrient availability are superimposed.

Nutrients and light availability in the water column account for the higher initial algal density at the bottom while a more dilute community can be observed at the surface. Therefore, mixing events contribute to a more even vertical distribution of the community (Mataloni, 2000). However, the vertical distribution of phytoplankton in Lake Solumsjo was due to thermocline rather than light conditions (Danilov & Ekelund, 2001).

Reynolds (1984) reported that various interactions occur between organisms either negatively, positively or neutrally buoyant in water layers.

2.3.1.1 Non-motile, negatively buoyant algae

Reynolds (1984) described planktonic diatoms as under this category because they are usually negatively buoyant and spontaneously increase their mean intrinsic rate of sinking under certain conditions.

A given density gradient increases with its depth beneath the surface. The breakdown of limnetic density gradient depends on the spontaneous weakening of the gradient itself as depth is increased. It is possible to distinguish between major segregation of water masses into epilimnia, metalimnia, and hypolimnia which survive as mutually separate entities for months, and the formations at layers nearer the surface which may survive only for hours or at most, days on end. The depth range in which short term micro-stratification can persist will often depend largely upon the wind speeds experienced and changes of heat content in the upper layers. The stronger the gradient, the greater wind speed is required to overcome it.

Reynolds (1984) concluded that prolonged suspension of non-motile, non-buoyant cells would be resisted by shallow micro-stratification. It is no coincidence that diatoms tend to be favoured in well-mixed water columns where micro-stratified density gradients are transient.

2.3.1.2 Positively buoyant algae

The vertical distribution of buoyant organisms especially some of the planktonic cyanobacteria are potentially to float in water column rather than to sink. The mechanisms of bloom formation are dependent upon the coincidence of three pre-conditions:

(a) pre-existing population;

(b) significant proportion of the organism containing sufficient gas vesicles to render them buoyant; and

(c) stability of the water column.

2.3.1.3 Neutral buoyant algae

Organisms where effective density is more nearly similar to that of the suspending water position. They may transiently approach isopycny against strong external density gradients. The motile algae control movement so that they can migrate towards light.

2.3.2 Horizontal distribution

Reynolds (1984) noted that patchiness in the horizontal distribution of phytoplankton occurs frequently. It is necessary to relate the sizes and longevities of the patches both to the process, which contribute to their formation and survival and the generation times of phytoplankton. Phytoplankton exhibits a longitudinal distribution, with highest concentration in the upstream zones under the direct influence of Paranapanema River, and low concentrations towards the dam in Brazil (Nogueira, 2000).

2.3.2.1 Small-scale patchiness

At the finest readily-measured scales, discontinuities are inevitable, patchiness at the smaller scale may appear either integrated within or further differentiated between larger and more stable patches. An individual organism is unlikely to adopt a permanent position relative to the flow but to be transported elsewhere. Small-scale variations are important to the understanding of larger-scale patchiness in lakes.

2.3.2.2 Large-scale patchiness

Maintenance of large-scale patchiness must depend partly upon the positive 'feedback' provided by net population change, whether this is strictly reproductive, enhanced or otherwise by point sources of nutrient enrichment or due to local different removal rates. A patch will be maintained as long as which the patch is diffusively eroded at its edges (Reynolds, 1984).

2.3.2.3 Advective patchiness

Advective patchiness in small basins is consequent upon the interaction between behaviour in the vertical distribution and take effect on the stable, advective flows, patterns generated by light winds and return currents (Reynolds, 1984).

2.3.3 Temporal variations in abundance and composition of phytoplankton

Seasonal changes in the abundance and composition of phytoplankon may be observed to occur on temporal scale measured in weeks or months, during which mean specific population densities may increase or decrease through 6 - 9 orders of magnitude (Reynolds, 1984). The temporal variations of phytoplankton primary production in Barra Bonia Reservoir showed the existence of an extremely dynamic system, characterised by a trophic level that changes itself all the time (Calijuri & Dos Santos, 2001). Phytoplantkon abundance is subject to a lasting and overriding control by chronic nutrient deficiency, the peak biomass occurring when the physical conditions are most favourable. Unni and Pawar (2000) reported that temporal changes with absence of most diatoms, were due to increase of sewage pollutants in the environment.

2.3.4 Periodicity and change in phytoplankton composition

The composition of phytoplankton communities and the relative abundance of component species undergo continuous changes and on varying scales. This is in response to advective mixing processes through annually recurrent cycles of compositional change that accompany underlying cyclical fluctuations in isolation, temperature and vertical differentiation of the environment, to longer term floristic changes where one reconisably recurrent cycle is supplanted by another (Reynolds, 1984).

2.3.4.1 Seasonal periodicity of phytoplankton

Reynolds (1984) explained the variations in the abundance and species compositions of phytoplankton that occur in a given lake through a given twelve-month period often repeated in the following year. Where the same phytoplankton species will be prominent at the corresponding stages while individually, each will tend to increase or decrease on a specific annual cycle. However, the precise timing may be varied from year to year and dominant species at any given stage will not always be the same.

In lakes at lower latitudes generally with higher irradiance intensities, surface temperature are correspondingly higher and temperature-controlled density gradients will be potentially more stable. Seasonal changes were related to water temperature where the total phytoplankton densities of *Nitzschia* sp. *Merismopedia glauca*, *Scenedesmus bijugatus*, *Pediastrum* sp. and *Lepocinclis* sp. on the River Mahanadi were influenced by water temperature as reported in the study carried out by Unni and Pawar (2000). Greater density differences per unit temperature rise occur in warm water. Here, gradients may develop rapidly and generate instability in the phytoplankton. At any one time and over the season *Spirogyra* populations may consist of different morphological forms which respond to temperature and irradiance. High temperatures and variable light may cause several filament forms to disappear, exacerbated by disintegration of the floating mats (Berry & Lembi, 2000).

2.3.5 Longer-term floristic changes

The long-term changes in composition and annual cycles of phytoplankton may due to factor like climate, catchment vegetation, land use, nutrient loading, natural autochthonous limnological processes, as well as their interactions. Reynolds (1984) reported that the changes in the above environmental conditions may cause the responses as follows:

(a) increased biomass production on the growth medium. The greater the alleviation of nutrient limitation, so the regulation moves towards physical processes related to more frequent alterations in the light climate. Naturally abrupt changes in column mixing inevitably have greater relative effect on the optical depth of surface layers rendered turbid by suspended phytoplankton and hence on specific growth, loss rates and competitive selection.

(b) a significant and sustained increase in the loading of limiting nutrients on a lake. Biologically recycling processes may assist the stimulus to be carried through the entire annual sequence. However, if the augmentation of nutrient loading continues to rise slowly or is sharply raised to a new level, these will cause:

  (i) fast-growing species to have an opportunity to build up large populations in subsequent years and depress the growth of the competitors.

  (ii) dominance of 'ungrazed' species if fast-growing species are also the potential food supply of zooplankton.

  (iii) anoxic conditions due to increased hypolimnetic oxygen uptake as eutrophication advances and biological production increases.

  (iv) reduction in light penetration, increasing average optical depth, biasing the outcome of interspecific competition in favour of 'shade' species.

Initially, the additional nutrient load may stimulate the chlorophytes to produce larger standing crops but as growth becomes limited by the photic conditions, the environment is opened to exploitation by the more 'eutrophic' species. The latter become more established, in extremes, the chlorophytes disappear from the lake.

2.3.6 Seasonal succession

Reynolds (1984) defined succession as a biological concept implying a strongly predetermined bias in the sequence in which species or species-groups will dominate a community. The advancing succession is typically characterised throughout by increasing species diversity and increasing production per unit area but declining productivity. An initially clear water column, autotrophic phytoplankton responds, within the limits of light and temperature, by increasing its biomass rapidly; the community composition will be biased in favour of faster-growing species which may become dominant. This high productivity may continue for some time but progressively, light penetration is reduced, production becomes restricted to a declining volume of water and, though those organisms placed well within the illuminated zone may still maintain a high rate growth, the productivity of the entire biomass is bound to fall. Moreover, as nutrients are depleted from the productive zone, the competitive species are those that are better adapted to nutrient scarcity or to low average insulation. Generally, a combination of resource limitation and predation plays the primary role in phytoplankton succession.

The successional trend may be interrupted at any time by externally imposed perturbations which significantly alter the physical structure of the environment. The most important of these are wind-induced mixing episodes, especially where these both randomize the vertical distribution of the existing species and recharge the surface waters with nutrients. Temperature is a major driving force for the seasonal succession of phytoplankton communities in Lake Baikal (Richardson *et al.*, 2000). Cyanobacteria are more productive in warmer waters while diatoms are dominant in cooler waters (Coles & Jones, 2000). While warmer temperature is the main factor in seasonal succession of diatoms, light for attached diatom communities appears more important in high irradiance species than low irradiance species as was observed in the successional sequence (Tuji, 2000). The role of temperature in contributing to seasonal succession lies partly in the fact that temperature may determine a differential appearance of cells from resting stages. This provides a suite of species for growth at a given time. Light intensity does not affect this differentiation process (Cura, 1981).

The dynamics of phytoplankton succession required the knowledge of nutrient-phytoplankton-zooplankton relationships because zooplankton can affect changes in nutrient availability through faecal deposition of soluble nitrogen and phosphorus which promotes the growth of phytoplankton (Olden, 2000).

2.3.7 Grazing

Three major groups of freshwater zooplankton such as protozoa, rotifera and crustacea are believed to feed upon planktonic algae (Reynolds, 1984). Reynolds also reported that their activity deplete the standing stock of phytoplankton, hence may have a significant effect upon their dynamics and population ecology. The dynamics of the phytoplankton are determined by the product of the biomass of their standing populations, their individual feeding rates, the capacity of the 'algal' growth rate and net loss due to the demand of grazers. Therefore, if the phytoplankton wanes, the zooplankton is likely to be affected by limited food and might experience mortalities. However, not all the phytoplankton is readily available to the grazers and the proportion of those that are inedible, usually the larger forms and often the blue-green algae, tends to increase with increasing lake fertility (Moss, 1988).

Cura (1981) reported that there are two obvious mechanisms by which zooplankton grazing may affect the phytoplankton. These two mechanisms are:

(a) controlling the population size and hence initiation and termination of a bloom; and;

(b) selective grazing for one species over another at different seasons and hence facing changes in seasonal succession.

The most obvious impact of zooplankton is through direct grazing of algae, resulting in a reduction in overall phytoplankton biomass (Lambert *et al.*, 1986).

2.4 Features of a lake controlling the production of phytoplankton

2.4.1 Thermal stratification and temperature

Moss (1980) commented that a lake surface roiled by wind causes a well mixed environment in the water, with parameters like temperature and chemistry being much the same throughout, is rarely true. In many circumstances, temperature differences develop down the water column and divide the lake into layers which do not mix. This stratification also causes differences in water chemistry with depth. In warmer climates, direct stratification is referred to as the upper layer (epilimnion), the lower layer (hypolimnion) and a transitional zone (metalimnion) between the two layers. In the tropics, the temperature ranges between epilimnion and hypolimnion by only a few degrees, from around 29°C to 25°C. Temperature treatment in some freshwater red algae in culture, produced pigment contents that were different because most freshwater red algae had the best growth under low irradiance, confirming the preference of freshwater red algae for low light regimes (Zucchi & Necchi, 2001). These might be due to the photosynthetic enzymes and other enzymes being temperature dependent. Zucchi and Necchi (2001) also showed that the fluctuation of light and temperature influenced the rate of photosynthesis in the diatom *Skeletonema.*

2.4.2 Light

It is no doubt that light is important for photosynthesis. Light intensities which are insufficient to saturate immediate photosynthetic requirements are unlikely to support maximal growth rate (Reynolds, 1984).

Moss (1988) defined the euphotic depth as the water depth at which photon flux density falls to around 10 μmol $m^{-2}s^{-1}$ and the euphotic zone as the layer of water above it. At values around 10 μmol $m^{-2}s^{-1}$, the energy absorbed in photosynthesis in an algal cell just balances the maintenance energy needs of the cell. Net photosynthesis is then zero and no new production can occur. The euphotic depth for phytoplankton corresponds to that at which about 1 % of the surface light still remains. Surface photon flux density may vary from zero in the polar winter to about 2400 μmol $m^{-2}s^{-1}$ on the equator under full sun. Growth rate was slightly higher under low fluctuating light for *Nitzschia*, under high fluctuating light for *Anabaena*; and lower under low fluctuating light for *Sphaerocystis* and *Phormidium*, greater effect of fluctuating light was when fluctuations were between limiting and saturation or inhibiting irradiances (Litchman, 2000). In addition, shading was an over-riding factor controlling periphyton biomass accrual on the artificial substrata with nutrients playing a relatively minor role where diatom prevailed in streams with shade higher than 57%, whilst filamentous green algae occurred more frequently in open streams subject to high irradiance (Morisch, 2001).

A crude measure of the depth of the euphotic zone may be obtained by dangling a weighted, flat white disc into the water and recording the depth (z_s) at which it just disappears to an observer at the surface. This depth is a measure of the transparency of the water and although it varies with the observer and surface conditions, it does bear an approximate relationship to the depth of the euphotic zone: z_{eu} = 1.2 - 2.7 (mean 1.7)z_s (Moss, 1988).

2.5 Photosynthetic activity of phytoplankton

Photosynthetic rate in phytoplankton is measured either from the uptake of dissolved ^{14}C-labelled CO_2 into algal particles or from the net change in the dissolved oxygen of suspending medium.

2.5.1 Light-limited photosynthesis

Reynolds (1984) reported that shorter wavelengths of photosynthetically active radiation, penetrate to relatively greater depths, and sustain the light-limited photosynthesis. Phytoplankton is able to regulate their photosynthetic efficiency by varying their pigment contents. The phytoplankton grown under continuously low irradiances have relatively higher photosynthetic efficiencies than those grown under high light because of their higher relative pigment content. Under light-limited conditions cyanobacteria may be more efficient photosynthetically (Coles & Jones, 2000).

2.5.2 Light-saturated photosynthesis

The photosynthetic rate is said to be light-saturated when the increment in photosynthesis rate is uncoupled from light, reaching a maximum (P_{max}) at some vertical distance below the surface. This means no further increase in light will enhance photosynthetic rate. However, the P_{max} is largely independent of the intensity and spectral composition of the photosynthetically-active radiation (Reynolds, 1984).

2.5.3 Light-inhibited photosynthesis

Photo-inhibition is due to ultraviolet radiation which has a directly inhibitory effect upon the photochemical systems, and damage the organic structures in the cells, including the thylakoids and chlorophyll. The plastids may also experience shrinkage as high oxygen concentrations may accelerate these processes (Reynolds, 1984). Algae may tolerate sub-lethal irradiances for short periods with recovery often involving renewed synthesis of chloroplasts, replacement of thylakoids and slowly in the reactivation of the photosystem. Coles and Jones (2000) found that degree of photo-inhibition in the cyanobacteria was not strongly dependent on temperature.

2.5.4 The effects of temperature

Algal photosynthetic rates are influenced by temperature because the cellular processes are temperature dependent (Reynolds, 1984). Temperature and photon flux density are important factors for quantifying growth as well as photosynthesis (Coles & Jones, 2000), with rates accelerating with increasing temperature between 25°C and 40°C. The rates typically increase according to non-linear, exponential functions, with the rate increases per 10°C rise in temperature generally described by Q_{10} values. Most algae probably reach their optimal growth rate in the range 20 °C to 25°C but many thermophilic species may continue to increase with temperature up to the range of 35 °C to 45°C.

2.5.5 The effect of carbon supply

Photosynthetic activity which takes up dissolved carbon dioxide from the water at a faster rate than fresh supplies can invade from the atmosphere, can cause significant carbon depletion. As the depletion progresses, there is an upward drift in the pH as the equilibrium between dissolved CO_2, bicarbonate (HCO^{-3}) and carbonate (CO_2^{-3}) moves in favour of the latter. Potentially, photosynthetic rate may be limited by the carbon depletion per se, the shift in the dominant carbon species present and by the high pH. Therefore, photosynthetic rate reduction occurs at pH > 10.

2.6 Nutrient requirements

Reynolds (1984) classified the twenty elements in the tissues of algae into macronutrients and micronutrients. Macronutrients consist of C, O, H, N, P, S, K, Mg, Ca, Na and Cl, each constitute ≥ 0.1% of the dry ash-free dry weight. Micronutrients include Fe, Mn, Cu, Zn, B, Si, Mo, V and Co, are present in traces (≤ 0.1% by weight). However, there is exception to the classification where Si is a major component of the cell wall for Chrysophyta and diatoms and is referred to as macronutrient. The 20 elements are required for the phytoplankters' growth but only C, N and P is likely to limit the growth rates (Moss, 1988). The variations in the chemical composition of natural waters might be important in regulating the abundance, composition and the geographical and periodic distribution of phytoplankton (Reynolds, 1984).

2.6.1 Nutrient uptake

Reynolds (1984) reported that the nutrients obtained by phytoplankton from the external medium in simple inorganic compounds or ions to assemble into the structures of living cells. Uptake by autotrophic organisms is limited to sources which are both soluble and diffusible, they may pass through the semi-permeable membrane into the cell but many soluble complexes and insoluble polymers are unavailable. In addition, dissolved nutrients present in water must be maintained within the cell. Therefore, passive diffusion rarely meets the uptake requirements of the cell because the diffusion gradients are in reverse direction. Moreover, the concentrations of nutrients are subject to variation in space and time. Thus growing populations have the possibility of one or other of its nutrient sources becoming unavailable or unobtainable because it is too diluted. The low concentrations of nutrients present in water require active, energy-requiring uptake mechanisms that involve specific enzyme-transport system to concentrate them into the cells (Reynolds, 1984; Moss, 1988).

2.6.2 Phosphorus availability

In aquatic systems, bioavailable phosphorus is introduced primarily as a consequence of aqueous leaching from the hydrological catchment. Clearance of land and ploughing its surface weakens the phosphorus retentivity of catchment. The quantities of usable phosphorus available are related firstly to the geochemistry of the catchment and the mineral deposits present, then to rates of their erosion, which will be influenced by geomorphology, climate and hydrology (Reynolds & Davies, 2001). In water, phosphorus usually occurs in the oxidized state, either as inorganic orthophosphate ions (HPO_4^{2-}, PO_4^{3-}, $H_2PO_4^-$) or in organic. The dissolved orthophosphate are available for biological metabolism without further breakdown (Tchobanoglous & Burton, 1991). Dissolved phosphates are derived from weathering of phosphatic minerals e.g. apatite present in catchment soils and are generally present in aqueous concentrations within the range 0.1 to 1000 $\mu g\ PL^{-1}$. Fluctuations of phosphorus concentration may due to seasonal variations in supply and biological transformation in the waters and are present in particles of varying sizes ranging down to colloidal and organic compounds (Reynolds, 1984).

Moss (1988) reported that phosphorus enters water bodies as inorganic ions and polymer, organic phosphorus, living micro-organisms and dead detritus. The sum of all the forms of phosphorus, total phosphorus (P_{tot}) is a reasonable measure of the fertility of a water. A infertile lake may have only about 1 $\mu g\ P_{tot}\ L^{-1}$ while most fertile may have 1000 $\mu g\ P_{tot}\ L^{-1}$ or more.

Phosphorus is removed mainly through soil sorption processes which are slow and vary based on soil composition and through plant assimilation and subsequently burial in the litter compartment. Ammonia is removed largely through microbial nitrification (aerobic) and denitrification (anaerobic), plant uptake and volatilisation. Nitrate is removed largely through denitrification and plant uptake. However, denitrification is the primary removal mechanism. Therefore, phosphorus removal rates are variable and typically behind nitrogen.

Reynolds and Davies (2001) reported that phosphorus is a primary agent in causing eutrophication.

2.6.3 Nitrogen availability

The potential sources of nitrogen available to algae include nitrate, nitrite, ammonium ions and certain dissolved organic nitrogenous compounds such as urea, free amino acids and peptides which are essential in the synthesis of amino acids and proteins of algae cells. However, more than 90% of the nitrogen in soils is present in organic forms not available to plants (Lepisto, 2000) but some cyanobacteria are able to fix atmospheric nitrogen dissolved in the water (Reynolds, 1984). Three processes contributing to nitrogen retention are denitrification, sedimentation and uptake by aquatic plants (Saunders & Kalff, 2001). Reynolds (1984) also reported that in receiving waters without substantial inputs from agricultural soils, ground water and treated sewage effluent, the concentrations of nitrates may range from 10 to 1000 $\mu g\ N\ L^{-1}$. Nitrite which can be produced both chemically or by bacteria either reducing nitrate or oxidising ammonium is present at low concentrations $< 60\ \mu g\ N\ L^{-1}$. Nitrate and nitrite have to be reduced prior to assimilation, in reactions catalysed by nitrate-reductase and nitrite-reductase. Therefore, ammonium is the most energetically favoured source of inorganic nitrogen. However, Serigio *et al.* (2002) found that different chemical forms of nitrogen may influence the growth nitrogen uptake seen to be strongly species-specific.

2.6.4 Silicon availability

Reynolds (1984) reported that all phytoplankton require small amounts of silicon involved in protein and carbohydrate synthesis. Diatoms especially must strengthen their cell walls with amorphous silica polymer. The requirement of silicon becomes ecologically important and unique for diatoms and availability of silicon have potential to regulate the growth of the diatoms in the lakes and species composition.

Silicon is present in most natural water as solid or colloidal silicate polymers, derived from catchment soils or recycled from biogenic sources such as dead diatoms. Depolymerisation leads directly to the formation of soluble monomeric orthosilicic acid ($SiOH_4$), the soluble reactive silicon that is probably the only fraction available to diatoms and other phytoplankton (Reynolds, 1984). A regression analysis of monthly net sediment SiO_2 release on water temperature suggested that temperature was the only factor significantly related to SiO_2 release (Gibson, 2000).

2.6.5 Other nutrients

Reynolds (1984) reported that other nutrients involved in regulating species composition and abundance is either minor or it is unclear. Calcium ions are often the most abundant cations in freshwater. Calcium acts as a central role in the pH-carbon dioxide-bicarbonate system which influences the supply of photosynthetically-available carbon and capacity of the water to buffer fluctuations in pH, hence, controlling photosynthetic activity and phytoplankton species composition.

In addition, magnesium, potassium and sodium are present in quantities far exceeding algal requirement in nature, thus rarely considered to have an important influence on algal ecology. Iron also has been considered as an important trace metal for phytoplankton. However, excesses of both manganese and copper inhibit many algae and copper sulphate is still widely used as an algicide.

2.7 Eutrophication

Eutrophication is known as the state of a water body which is manifested by an intense proliferation of algae and higher aquatic plants, and their accumulation in the water body in excessive quantities (Ryding & Rast, 1989). Enrichment of an aquatic ecosystem with plant nutrients can be accelerated by human activities (Robarts & Southall, 1977).

Eutrophication due to excessive algal growth may destroy the pristine environment of our lakes. Eutrophication is one of the major environmental problems, affecting about 30 – 40 percent of the world's lakes and reservoirs (UNEP, 1991). All the lakes have a finite life span from a few years to millions of years, sooner or later they will be filled with sediment and, if left alone, be replaced by terrestrial communities (Harper, 1992). Water quality is one of the main concerns for lake management. Excess nutrient inputs into lakes due to human activities may result in the deterioration of water quality of the lakes.

The effects of eutrophication are considered negative in many places around the world, and often reflect human perceptions of good versus bad water quality. Die-off and settling of plant growth results in sediment oxygen demand, which tends to reduce dissolved oxygen levels due to the decomposition process (Lund & Lund, 1995). The effects of eutrophication which may be detrimental to aquatic life, are compounded by large day-night fluctuations in dissolved oxygen due to photosynthesis and respiration.

One of the significant consequences of increasing eutrophication in water is the abundant growth of autotrophic organisms, especially of green and blue-green algae (Matulova 1979). The low grazing rate by filter-feeding zooplankton on blue-green algae results in the accumulation of algal biomass in eutrophic lakes. Increased phytoplankton crops may cause amenity problems in terms of loss of clear water, becoming commercially important (Moss, 1988).

Howarth (1988) indicated that phosphorus and nitrogen tend to be the limiting factors for phytoplankton in freshwaters and marine waters respectively. In most non-eutrophic lakes phosphorus is usually the nutrient which limits algal growth (Robarts & Southall, 1977). However, it is believed that nitrogen is the primary nutrient which limits the maximum algal biomass levels in tropical systems (Ryding & Rast, 1989). It is because the tropical systems often develop extremely low N:P ratios, thereby favouring the dominance of N_2-fixing blue-green algae. Phytoplankton utilises inorganic nitrogen sources like ammonia and nitrate; however, the former is preferred (Bates, 1976). Soluble reactive phosphorus or orthophosphate is another nutrient that promotes algal growth (Chapra, 1997). The recent announcement by the Estuarine Research Federation, United States indicated that silicon and iron also play an important role in causing coastal eutrophication (Pelly, 2000).

Information on the nutrient concentration and trophic response is important if a water body is to be restored or maintained at the desired trophic state. Data on the species composition are additional information usually gathered. However, specific algal species may not be useful as eutrophication indicators in tropical water bodies because of the normally wider range of habitats available in these systems (Ryding & Rast, 1989).

The blue-green algae produce low molecular weight toxins which are hazardous to humans and animals health (Codd *et al*, 1995). There are about 3164 recorded cases of human poisoning and 148 reported death cases due to harmful algal blooms in the Asia-Pacific (Corrales & Maclean, 1995). High nutrient loads from point and non-point sources leading to blue-green algal blooms occur during summer at Carcoar Dam (White *et al.*, 1994).

The blue-green algae can survive up to 10 years and some even up to 25 years in a desiccated soil (Trainor, 1985).

2.7.1 Natural eutrophication

It was assumed that oligotrophic lakes were 'primitive' and that they naturally 'evolved' into eutrophic ones. Reynolds (1984) elucidated that lakes do age, over relatively short periods of geological time, as catchment-derived silts are washed an accumulated as lake sediment. Thus, even supposing that no change occurs in the amount of nutrients reaching a basin, its effect becomes more concentrated in the diminishing volume of the lake while the reduction in the hypolimnetic volume accentuates the severity of oxygen depletion during the stratified period. This process has been defined as natural eutrophication.

2.8 Wetlands

Wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static, flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six metres. This Ramsar definition of wetlands is internationally accepted (Davies & Claridge, 1993). The wetlands in Malaysia include lakes, rivers, mangroves, peat swamps and freshwater swamps; and most of the areas come under the jurisdiction of either the State Government or other forms of protection such as forest reserves (Burhanuddin, 1994). The total area of wetlands in Malaysia is estimated at 3.5 to 4.0 million hectares or 10% of the land area (Malaysia Wetland Working Group, 1986).

Generally, the wetlands system has been categorized as either free water surface (FWS) or subsurface flow (SF) types (Crites, 1994). A FWS system consists of basin or channels with a natural or constructed subsurface barrier to minimise seepage. Emergent vegetation is grown and wastewater is treated as it flows through the vegetation and plant litter. A SF system consists of channels or basins that contain gravel or sand media which will support the growth of emergent vegetation. Wastewater flows horizontally through the root zone of the wetland plants about 100 mm to 150 mm below the gravel surface. Treated effluent is collected in an outlet channel or pipe.

Many wetlands were constructed to minimise the negative impacts of pollutants from urban and agricultural runoff (Kadlec & Hey, 1994), sewage treatment plants (Bavor & Andel, 1994), mining (Eger, 1994), industries (Davies & Cottingham, 1994), landfill leachate (Martin & Moshiri, 1994) and aquaculture wastes (Norhanizan & Chee, 2001). All the studies conducted by the researchers indicated that the wetlands effectively improved the water quality.

Wetlands retain the highest proportion of total nitrogen loading, followed by lakes and then distantly by rivers (Saunders & Kalff, 2001). An artificial wetland constructed to purify recreational wastewater proved to be very effective in removal of nitrate (NO^{3-}) and orthophosphate ($O\text{-}PO_4$) up to 92% and 82% respectively (Vincent, 1994). Shi and Wang (1991) also discussed the effectiveness of wetlands in controlling the nutrients from wastewater using aquatic plants.

Lakes are open systems where they exchange energy and mass with the environment. Lakes contain only very small part of about 0.01% of the global amount of water (Jorgensen & Vollenweider, 1989). The state of the lake is influenced by the variables which are either controllable (in and outflow of water, nutrients and toxic substances) or non-controllable (precipitation, wind, solar radiation etc); and depends on the use of internal variables e.g. phytoplankton, nutrients and fish concentration. These physical and chemical as well as different biological factors must be taken into account when considering the functioning of lacustrine ecosystems.

Polymitic lakes (e.g. Putrajaya Lake) are located near the equato and are characterised by continuous mixing depending on the morphometry and climatic conditions, and low temperature and density gradients.

2.9 Putrajaya wetlands and lake

The development of Putrajaya Lake was divided into two phases (Phase 1A and Phase 1B). Construction of Phase 1A lake was started in March 1997 and completed in September 1988. The inundation of the lake commenced in October 1998 and reached the final normal water level of 21.ORL in January 1999 (Norazmi, 2000). The Phase 1B lake is still under construction and targeted to be completed by the end of 2003.

The Putrajaya wetlands is one of the biggest man-made wetlands and is the first of its kind in the tropics. The wetlands with an innovative multi-cell multi-stage system is designed for multi-functional uses which include stormwater treatment, provision of habitat, passive recreation, aesthetics, public education and a wetland research centre (Khor, 1988). The wetland cells were planted with different macrophytes which colonised at different water depths. This helps to increase the efficiency of the cleansing mechanism. Three macrophyte zones adopted in the wetlands system were shallow marsh (water depth 0 - 0.3 m), marsh (water depth 0.3 - 0.6 m) and deep marsh (water depth 0.6 - 1.0 m). The macrophytes include *Eleocharis variegata, Saccharum spontaneum, Scleria sumatrana, Eleocharis dulcis, Scirpus grossus, Lepironia articulata, Phragmitis karka* etc (Putrajaya Corporation, 2000). Over 12 million plants of 52 different species were propagated, planted and established during the implementation stage (Beharrell, 2001).

The Putrajaya Lake covers an area of approximately 570 hectares which include 197 hectares of wetlands. The catchment area of the Phase IA Lake is approximately 34 km^2 and its storage capacity is about 3.4 million m^3 (Khor, 1988); consists of 197 hectares of wetlands and 100 hectares of water body (Norazmi and Chee, 2000). The six wetlands system consist of the Upper North, Upper West, Upper East, Lower East, Upper Bisa and Central Wetlands were constructed to act as buffer zone and filtration system for the surface runoff before discharge into the lake. The depth of Phase IA Lake range from 3 m to 7 m.

The ultimate purpose of the lake water is for primary contact. The Putrajaya Lake is divided into a few zones to cater for different types of activities at designated zones. Therefore, it is important to ensure the lake water quality meets the requirements of the Putrajaya Lake Water Quality Standard (Putrajaya Corporation, 1998b).

The objectives of the Putrajaya Lake are to create (Norazmi & Chee, 2000):

(a) A lake with water quality suitable for body contact activities;

(b) A self-sustaining and balanced lake and wetland ecosystem that is unique in the world;

(c) A natural ecosystem for conservation of wetland flora and fauna;

(d) An environment suitable for education and scientific research on wetlands; and

(e) An attractive and pleasant surroundings for residents and visitors of Putrajaya.

During construction stage, some of the human activities carried out on-site have polluted the inland water either directly or indirectly. The pollutants discharged into the lake could be either from point source or non-point sources. The point sources of pollutants identified were:

(a) Sewage - from the temporary toilets and overflowed from portable toilets at construction site discharged into the drainage system which eventually discharged into the lake.

(b) Oil and grease - spillage of diesel and hydraulic oil during the maintenance of vehicles and machinery.

(c) Organic wastes - wastewater from the process of cleaning and washing at canteen and leachate from organic wastes.

The non-point sources at the catchment area are mainly from the surrounding development area which involves land clearing and soil disturbance. The removal of vegetation has disrupted the mineral recycling process thus accelerating minerals being lost through surface runoff water. The minerals released from the soil and plants into the waterbody may affect the lake water quality. In addition, the maintenance of plants and turfed area by using agrochemicals and fertilisers was the major source of nutrient inputs into the lake.

2.9.1 Water quality

Baseline study on water quality of Putrajaya catchment area was conducted to assist the design of the lake and artificial wetland systems as part of the water quality control and management strategy (Putrajaya Holdings, 1996). A total of 54 water quality parameters were measured for the design of Putrajaya lake and wetlands. However, only relevant water quality of Sg. Bisa catchment area are summarised in the Table 1 below for comparison with the water of lower Bisa of Putrajaya.

Table 1. Baseline water quality parameters of Sg. Bisa Catchment Area

Parameters	Result
Temperature (°C)	25.4 - 27.3
pH	4.8 - 7.2
Conductivity (uS cm^{-1})	24 - 60
Dissolved oxygen (mg L^{-1})	5.6 - 7.6
PO_4 (mg L^{-1})	0.22 - 8.0
NH_3 (mg L^{-1})	0 - 9.04
SiO_2 (mg L^{-1})	4.7 - 97.6

(Source: Excerpt from Putrajaya Holdings, 1996)

2.10 Studies of phytoplankton in the lakes

Whitton (1975) commented that the studies of lotic algae are less advanced than studies on the phytoplankton of standing water. These were due to economic reasons, water chemistry and features of the habitat. In addition, changes in lotic environment are often more rapid and less predictable than a lentic one.

Since 1970, studies of algae in the lake have been started in Malaysia which included Taiping Lakes (Prowse and Ratnasabapathy, 1970) and Tasek Bera (Furtado & Mori, 1982).

Subsequently, more research had been conducted at various lakes in Malaysia. Dayang Lake (Yadav & Ratnasabapathy, 1974), University Malaya Lake (Li, 1979), Subang Lake (Aramugam, 1976) and Shah Alam Lakes (Hartina, 1999) due to deterioration of lake water quality.

2.10.1 Tasek Bera

Tasek Bera is the most well studied lake in Malaysia due to its being a "Wetlands of International Importance "under the Ramsar Convention in November 1994. The status of Tasek Bera as a Wetlands of International Importance is based on its ecological and socio-economic values (Lopez *et al.*, 2001). It was also selected as a typical and yet endangered natural ecosystem in Malaysia under the International Biological Programme (IBP), a joint effort between Malaysian and Japanese scientist in 1970 (Furtado & Mori, 1982). A checklist of algae was complied and utilised as one of the biotic parameters to evaluate the lake ecosystem.

More studies had been conducted to determine the state of environment by researchers. Phang and Murugadas (1997) reported that the algal cell density and chlorophyll-a concentration increased compared with the early studies, and this may be due to the increase of fertilisers, detergents and organic pollution from sewage. Tang (2001) reported that eutrophication in Tasek Bera were mainly due to the fertiliser runoff.

2.11 Putrajaya lake management

The purpose of lake management is to control the "cultural" man-made nutrient contribution in order to restore or maintain waterbodies at the desired trophic state (OEDE, 1982). The question of what is the desired trophic state of a waterbody is a management policy decision which would depend on the intended use of the water and the conditions and expectations in each country.

The Putrajaya Lake Management Guide was published in 1998 to provide the guide for lake management which comprise of planning, administration, monitoring, enforcement, research and development aspects. This guide has been used as a reference to minimise the negative impacts of the development projects implemented within Putrajaya. Therefore, Putrajaya Lake water quality depends on the catchment management and efficiency of wetlands system.

2.11.1 Catchment management and monitoring

The catchment management is important to ensure the landuse of the catchment areas are planned to avoid any development which can cause serious negative impacts to the lake water quality and to minimise the sources of pollution. There are internal and external catchment sources, the internal catchment sources of pollution within the Putrajaya are controlled through proper planning but the external sources of pollution (UPM, MARDI, TNB and IOI Palm Garden) are pre-treated with artificial wetlands before discharge to the lake (Khor, 1998). The point source pollution (e.g. sewage) and non-point source pollution (e.g. surface runoff from garden) are significantly increased due to the urbanisation of Putrajaya and its surroundings. Hence, preventive measures to minimise the pollutants into the lake water is essential to ensure the lake water quality meets the requirements of the Putrajaya Lake Water Quality Standard (Putrajaya Corporation, 1998b).

Monitoring programmes are conducted to determine and assess the activities within the sub-catchment areas, source of pollutants and the negative impacts to the lake water quality.

2.11.2 Wetlands management and monitoring

The efficiency of the wetlands is directly dependent on retention times, pollutant loading rates, hydrology, sedimentation process, morphometry and biological processes (Putrajaya Holdings, 1996). The wetlands are appropriately managed to ensure the system is not overloaded; to provide the diverse habitats for aquatic fish, to ensure a balance of phytoplankton and macrophyte communities, to prevent invasive weeds and excessive sedimentation and to control mosquito outbreaks.

A comprehensive monitoring programme was implemented to monitor the water efficiency of pollutant removal, aquatic fish structure, dominance of primary production, weed encroachment and mosquito abundance.