

SEASONAL STUDIES ON PHYTOPLANKTON IN RELATION TO
SOME BIOLOGICAL AND PHYSICO-CHEMICAL FACTORS IN
LAKE HORA-KILOLE, ETHIOPIA



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Abstract

The temporal dynamics of plankton, benthic macroinvertebrates and physico-chemical variables were studied at a central station in Lake Hora-Kilole from August, 2007 to May, 2008. The lake remained small and shallow and consequently underwent complete mixing throughout the study period. Secchi depth ranged from 0.15 m to 0.78 m with high values coinciding with lower wind speed. Vertical extinction coefficient varied temporally (2.39-10.23 \ln units m^{-1}) with high values coinciding with relatively low algal biomass and high abiotic turbidity associated with wind-induced mixing. SRP and TP varied from 0.33 to 3.5 and 2.13 to 6.15 $\mu\text{g L}^{-1}$ respectively. The concentration of $\text{NO}_3 + \text{NO}_2\text{-N}$ (in $\mu\text{g L}^{-1}$) ranged from 17 to 303 while that of $\text{NH}_4^+ + \text{NH}_3\text{-N}$ varied from 1.7 to 49.09 $\mu\text{g L}^{-1}$. Molybdate reactive silica (in mg L^{-1}) ranged from 10.4 to 69.7. The phytoplankton community was composed primarily of green algae, euglenoids, diatoms, dinoflagellates and cyanobacteria with the overwhelming dominance of dinoflagellates and Cyanobacteria corresponding to the seasonal peaks of Chl *a* biomass of phytoplankton. The most dominant species of Dinoflagellates and Cyanobacteria were *Peridinium gatunense* and *Anabaena cf. agardhii* and *cylindrospermopsis curvispora* respectively. Zooplankton abundance peaked in February, 2008 coincident with the largest peaks of phytoplankton biomass and abundance and with *Thermocyclops decipiens*, *Brachionus sp.* and *Daphnia barbata* as the most important taxa. Among the macroinvertebrates, chironomids and *Lambriculidae-oligochaete* were dominant during the dry period. Total phytoplankton biomass showed seasonal variations (≈ 36 to $148 \mu\text{g L}^{-1}$) with large peaks in October, 2007 ($\approx 148 \mu\text{g L}^{-1}$) and February, 2008 ($\approx 147 \mu\text{g L}^{-1}$) and the seasonal minimum ($\approx 36 \mu\text{g L}^{-1}$) in January, 2008. Among the three size-groups of phytoplankton, the netplankton ($> 20 \mu\text{m}$ fraction) was the most important contributor to the total phytoplankton biomass with its biomass and percentage contributions to total phytoplankton biomass ranging from 13.21 mg m^{-3} and 32 % to 132.06 mg m^{-3} and 95 %, respectively. The percentage contributions of nanoplankton and picoplankton varied from about 0 to 64% and from 4 to 28 %, respectively. Depth profiles of gross photosynthesis were of typical pattern for phytoplankton without surface photoinhibition during the major rainy period. Light-saturated rate of gross photosynthesis (A_{max}) varied from 370 to 3843 mg O_2 (≈ 111.5 – 1199 mg C) $\text{m}^{-3} \text{ h}^{-1}$ with the maximum value corresponding to the seasonal maximum of phytoplankton biomass. Biomass-specific rate of gross photosynthesis at light-saturation varied from about 6 to 33 with positive and moderate correlation ($r=0.632$, $r^2=0.40$ at $p=0.0496$) with SRP. Hourly integral rate of gross photosynthesis, (ΣA), which was positively and strongly correlated with A_{max} ($r= 0.885$, $r^2=0.7895$ at $P = 0.0006$) and Z_{eu} ($r=0.7849$, $r^2=0.616$ at $p=0.0072$), ranged from 0.21 to 6 g O_2 (≈ 0.065 - 1.87 g C) $\text{m}^{-2} \text{ h}^{-1}$. The marked temporal variations in phytoplankton parameters are discussed in relation to physico-chemical and biological variables.

and the general knowledge of some biological characteristics of the species (Garcia *et al.*, 1989).

Limnology in the tropics has only recently developed past the stage of exploration, but the need of limnological knowledge is, as pressing at tropical latitudes as in the temperate (Melack, 1996; Talling and Lemoalle, 1998, Lewis, 2000). Despite the perturbation by humans, vast number of lakes of varied size and shape are found in most tropical regions. They are often inhabited by densely populated biota and have been the subject of some of the most scientifically informative studies of tropical aquatic ecosystems (Talling, 2001).

In Africa, the first assessment of phytoplankton seasonality stemmed from collections made in 1899 by the Fullenborn expedition to Lake Nyassa, and later to Lake Malawi (Talling, 1986). Extensive efforts were made after 1950, especially in East and Central Africa (Talling, 1986). Despite their tropical location, African lakes exhibit considerable seasonality related to alternations of warm, wet, cooler and dry seasons. Although numerous studies have been made on the species composition and photosynthetic production of phytoplankton in various East African lakes (Talling and Lemoalle, 1998), relatively little has been done on this aspect in Ethiopian lakes.

Ethiopia is rich in both natural water bodies such as rivers and lakes and man-made lakes (reservoirs) compared to other east African countries. Ethiopia also possesses many great crater lakes (Prosser *et al.*, 1968), among these are the Bishoftu crater lakes, which form an extensive series of volcanic explosion craters in the vicinity of the city of Bishoftu (Debrezeit). The Bishoftu crater lakes are grouped among the most scientifically known lakes of Ethiopia until recently (Zinabu Gebre-Mariam, 1994). Volcanic crater lakes include lakes located in craters formed after eruption and they have small surface area and steep crater wall (Hutchinson, 1957).

We have some scientific information on the Bishoftu crater lakes dating as far back as the early 1930`s and 1940`s (Omer-Cooper, 1930; Vatova, 1940; Loffredo and Maldura, 1941; Cannicci and Almacia, 1947, cited in Prosser *et al.*, 1968). In the early 60`s, different aspects of these lakes were studied (Baxter *et al.*,1965; Baxter and wood, 1968; Prosser *et al.*, 1968; Talling *et al.*, 1973; Wood *et al.*, 1976, 1976, 1984; Wood and Talling, 1988). It is these investigations which tempted Zinabu Gebre-Mariam (1994) to describe the Bishoftu crater lakes as being among the most studied lakes of Ethiopia. There is, however, scanty scientific information on several aspects of these lakes, particularly on some biological aspects.

Lakes throughout the temperate and tropical latitude have been drastically altered as a result of the burden they carry when there is an increase in population density, economic growth, and change in land cover (Lewis, 2000). It is also known that climatic change especially rainfall, have a prominent effect on the limnology of a lake, resulting in changes in different parameters of a lake. Human interventions are the main cause of lake deterioration and it has various consequences. Human interferences are frequently reflected as changes in the trophic status of the lake, volume of the water, and consequent ecological changes. This is a phenomenon observed throughout the world, with some lakes changing from oligotrophic to eutrophic through mesotrophic or the reverse could happen. Increase or decrease in the biomass of plankton and level of nutrients and alteration in the underwater climate are some of the symptoms of eutrophication and/or oligotrophication. Thus, the trophic status of a lake can be determined from different physico-chemical and biological parameters. Euphotic depth, concentration of a limiting nutrient, phytoplankton biomass, primary productivity, and phytoplankton abundance are some of the basic and direct indicators of the trophic status of Lake. One can also look at the abundance and biomass of consumers (Zooplankton and fishes) to predict trophic status. These, the same parameters can be used to determine long term changes of lakes, and for comparison of two or more lakes

(Brook Lemma, 2002). The assessment of these physico-chemical and biological parameters is, therefore, crucial to evaluate the ecological health of aquatic ecosystems, optimize their exploitation, manage and conserve their resources.

Most of the Ethiopian lakes including the Bishoftu crater lakes, which are in the vicinity of a fast-growing town surrounded by agricultural lands, are subjected to shoreline modification, waste disposal, and other practices associated with population growth (Zinabu Gebre-Mariam, 1998; Zinabu Gebre-Maraim, *et al.*, 2002). Furthermore, many water bodies (predominantly rivers and lakes) in Ethiopia have been physically degraded or altered seriously by human manipulation (e.g. L. Hora-Kilole) and habitats have consequently been lost (e.g. L Haramaya) (Brook Lemma, 2002). Human-induced changes of lakes in Ethiopia are exemplified by the eutrophication of Lake Hayk (Elizabeth Kebede *et al.*, 1992), shrinkage of Lake Alemaya (Brook Lemma, 1994; 2002) and drastic changes in the water chemistry and species composition and productivity of phytoplankton in Lake Hora-Kilole (Brook Lemma, 1994; 2002).

Lake Hayk has changed greatly in its phytoplankton biomass and transparency (Elizabeth Kebede *et al.*, 1992). This was possible because of the introduction of planktivorous fish which freed the phytoplankton from grazers' control. The lake was stocked with tilapia species from a crater lake, probably Lake Hora in 1978 by the Fisheries Department, Ministry of Agriculture, to provide food, and harvest by a newly established fish gillnet. The commercial fishery of the lake increased to 200 tones per year (84Kg per hectare) (Elizabeth Kebede *et al.*, 1992). Lake Alemaya has been used for irrigation, animal watering and household consumption and consequently dramatic changes occurred in its volume has occurred (Brook Lemma, 1994; 2002). Lake Hora-Kilole was once grouped among the unique saline lakes of Africa, such as Arenguade, Chitu, Abijata and Shalla in Ethiopia and Nakuru in Kenya (Prosser *et al.*, 1968; Talling *et al.*, 1973; Vareschi, 1982; Wood *et al.*, 1984; Elizabeth Kebede *et al.*,

1986; Wood and Talling 1988; Green 1986; 1993; Tudorancea *et al.*, 1999). This lake was also known for its superabundance of *Spirulina spp.* assemblage and avifauna. In 1989, the Ministry of Agriculture (MOA), Addis Ababa, in an attempt to use the lake as a reservoir to gravitationally irrigate the southern and eastern low-lying plains, diverted River Mojo into Hora-Kilole resulting in the complete transformation of the lake ecology (Brook Lemma, 1994; 2002). After the diversion of the river, few investigations have tried to show ecological changes in the Lake (Brook lemma, 1994; 2002, Zinabu Gebre-Mariam, 1994; Zinabu Gebre-Mariam *et al.*, 2002). Diversion of R. Mojo into Hora-Kilole has caused substantial changes in the morphometric, biological and physico-chemical characteristics of the lake. So the aim of this study is to complement and update the physico-chemical and biological data generated for the lake in previous studies, which may help us show the seasonal and long-term changes that have occurred in the lake.

2. OBJECTIVES

2.1. General objective

* To generate scientific limnological knowledge on lake Hora-Kilole this together with existing knowledge, could be useful for rational utilization and conservation of the lake in particular and after aquatic resource in general.

2.2. Specific objectives.

* To asses temporal variations in the physico-chemical conditions of the lake and to compare with previous data in the literature.

* To investigate the temporal variations in species composition, biomass and primary production of phytoplankton and compare these with results reported previously.

- * To generate data on the composition of zooplankton and benthic fauna of the lake.
- * To identify what environmental factors are potentially limiting the growth of phytoplankton.
- * To estimate fish production from phytoplankton production.

3. REVIEW LITERATURE

A number of factors limit phytoplankton growth in lakes and reservoirs. Factors such as water level, meteorological factors like solar radiation, photoperiod, rainfall, wind velocity, etc., and hydrological conditions (inflows and outflows) have great influence on the rate of primary production in lacustrine and flowing waters (Gupta 1982; Verma and Datta Munshi, 1989, cited in Ahmed *et al.*, 2005). The following sections will attempt to give a bird's eye view of the factors that affect the composition, biomass and production of phytoplankton.

3.1 Light in aquatic ecosystems

Light is an important variable that controls phytoplankton growth and biomass. The quality of the underwater light rapidly changes with depth because of the spectral selectivity of water transparency (Tilzer *et al.*, 1995; Jassby *et al.*, 1999). The optical property of aquatic habitats strongly depends on the optical properties of water molecules as well as substances dissolved or suspended in it (Kishino *et al.*, 1984; Kirk, 1983). Moreover, absorption and utilization of light by phototrophic organism is highly selective with respect to the

wavelength of available light (Atlas and Banister, 1980; Kirk, 1983; Kishino, *et al.*, 1984). Some times, as a consequence of the high optical density of the water, in conjunction with the high spectral selectivity of particulate matter, dissolved substances and the photosynthetic pigments, the energy supply for photosynthesis is in short supply (Jerlov, 1976; Morel and Prieur, 1977). The energy shortage is furthermore amplified in vertically mixing water columns (Tilzer, 1990). Especially, due to the suspended particles, the underwater light field is highly diffuse.

The quality and quantity of light which can be seen emerging from water surface, carries important information not only on the optical properties of the water but also on factors controlling primary production (Lewis, 1992). The fraction of light which is intercepted by phytoplankton decreases with an increase in non-algal (abiogenic) turbidity (Tilzer, 1983). Furthermore, Falkowski and Grobbelaar (1981; 1984, cited in Tilzer *et al.*, 1995) found that the specific activity and light utilization index increased under such condition and concluded that the phytoplankton were shade-adapted.

Total suspended solid attenuate light and reduce transparency, whether the source is algal, algal detritus or inorganic sediment. Streams may also have high concentrations of light-absorbing dissolved compounds (e.g., black water streams). The concentration of total suspended solids can be determined directly as an effect on light transmission or scattering.

3.2 Chemical factors in aquatic ecosystems

Dissolved inorganic carbon, alkalinity and pH

Dissolved inorganic carbon (DIC) exists in aquatic systems as unionized carbon dioxide, present as H_2CO_3 and free CO_2 , and ionized species, HCO_3^- and CO_3^{2-} .

DIC is the greatest “active” carbon reservoir at the earth’s surface (Hedges, 1992). It has a mass equivalent to almost eight times the total comprised by other carbon reservoirs like atmospheric CO₂, land plants, seawater dissolved organic carbon, soil humus, soil carbonate and surface main sediment organic carbon (Hedges, 1992).

In aquatic ecosystems, physico-chemical and biological processes influence the inorganic carbon concentration (Pedrosa and Rezende, 2000, cited in Hedges, 1992). Atmospheric carbon dioxide, wind speed, pH, salinity, carbonates, depth, temperature, alkalinity, respiration and photosynthesis are factors that typically affect DIC concentration (Hedges, 1992).

Most lakes worldwide are supersaturated with CO₂, with a partial pressure that is on average three times that of the atmosphere (Cole *et al.*, 1994). It is also clear that inorganic carbon depletion episodes occur in productive water bodies (Maberly, 1996), limiting the rates of photosynthesis of phytoplankton and submerged macrophytes (Kalf, 2002). The dissociation of H₂CO₃ declines with decreasing ion concentration (ion strength) and pH. In calcareous drainage basins, about half of the HCO₃⁻ released is derived from weathering and dissolution of the substrate, whereas in systems with substrata that are very low in carbonates (e.g. igneous rock) or basins lined with peat (peat bogs), almost all of the HCO₃⁻ produced is the result of respiratory CO₂ production (Kalf, 2002).

Under extreme carbon depletion, the HCO₃⁻ declines in part by conversion to CO₃²⁻. Most freshwater systems have a pH between six and eight, and it is evident that inorganic buffering against rapid pH change in such waters is almost entirely provided by the HCO₃⁻ component, which dominates in this pH range. Only at a very high pH (9-10.5) recorded in highly productive water bodies and more than a minor fraction of the buffering is provided by CO₃²⁻. In low-pH lakes (<5-7) a high proportion of DIC is present as free CO₂ (Kalf, 2002).

Alkalinity is defined as the equivalent concentration of titratable base present. Higher alkalinity means a smaller change in pH in response to the addition of a particular acid or base, and thus the water is more buffered. The pH of both fresh and saline inland waters is predictable from alkalinity (Kalf, 2002).

Nutrients in aquatic ecosystems

The primary sources of new nutrients to lakes are terrestrial runoff and atmospheric input (Guildford and Hecky, 2000). Net nutrient uptake and regeneration generally follow approximately Redfield proportions (Redfield *et al.*, 1963 and Hecky *et al.* 1993; cited in Guildford and Hecky, 2000). Various combinations of dissolution, concentration, sedimentation, fixation, and biological transformation result in the variation of N:P mass ratios (Downing and McCauley, 1992). A relative abundance of N and P in lake water has been suggested to have both quantitative and qualitative effect on phytoplankton community (Downing and McCauley, 1992). The basic substrate factors limiting the development of phytoplankton biomass in nature are phosphorus (P), nitrogen (N) and silica (Si), the latter contained in golden algae (Redfield *et al.*, 1963). The molar ratio between nitrogen, silicon and phosphorus in marine phytoplankton and in deep oceanic waters is generally constant (N:Si:P = 16:15:1) and it is known as Redfield ratio (Redfield *et al.*, 1963). At this same ratio, phytoplankton consume nutrients from sea water, and bacteria mineralize organic nutrients to inorganic forms (Dafner *et al.*, 2001).

In aquatic systems, phytoplankton abundance is influenced by nutrient availability. For temperate zone lakes, it has been clearly shown that the variation among lakes in phytoplankton chlorophyll a concentration (*Chl-a*) is strongly correlated with total phosphorus (TP) level (Dillon and Rigler, 1974; McCauley, 1989; Prairie *et al.*, 1989, Cited in Champion and Currie, 1990).

Shindler (1977), in his whole-lake experiments, showed that phosphorus often limited the growth of phytoplankton. Nitrogen limitation of phytoplankton happens to be very common in tropical lakes (Lewis, 1996; Talling and Lemoalle, 1998).

In lakes, during the season of most active microbial and algal growth, both inorganic N and P often become immeasurable by standard methods (Guildford and Hecky, 2000). This happens because lakes are usually surrounded by productive terrestrial and urban ecosystems that release nutrients to lakes predominantly in fixed organic forms, either in solution or as particulates (Hecky *et al.*, 1993; Meybeck, 1993, Cited in Guildford and Hecky, 2000).

Dissolved oxygen

The dissolved oxygen (DO) levels in aquatic systems reveal about their metabolism probably more than any other single measurements. DO concentration reflects the momentary balance between oxygen supply from the atmospheric and photosynthetic source on one hand and the metabolic processes that consume oxygen on the other (Kalff, 2002). DO level not only affects the distribution and the growth of organisms but also has a major influence on the solubility of phosphorus and other inorganic nutrients including toxic metals through its influence on redox potentials (Kalff, 2002). The solubility of DO in fresh water is primarily determined by water temperature and the partial pressure which is actually determined by altitude and salinity (Kalff, 2002).

3.3. Catchment area and Sedimentation

The size of the catchment area modifies the N:P ratio with respect to the direct atmospheric precipitation. The runoff from lands usually exports high amount of N and P. The littoral zone is a locus of interaction between lakes and humans. Increasing nutrient loading and siltation are commonly recognized effect of lake-shore development (Kratz *et al.*, 1997).

Lake and wetland sediments are usually overwhelmingly derived via inflowing rivers from drainage basins (Kalff, 2002). The soils, the vegetation cover and the catchment slope determine not only the particle supply rate but also the extent to which the supply to aquatic systems is composed of inorganic particles rather than organic matter (Kalff, 2002). An important fraction of catchment-derived phosphorus, iron, manganese, and inorganic nitrogen exported to aquatic system as NH_4^+ travels adsorbed to inorganic and organic particles (Likens, 1984).

Small, relatively low-density particles in shallow water are readily resuspended by turbulence and transported by current in all aquatic system, but are particularly abundant in the water column of shallow lowlands. In Lakes at mid or low-latitude, a high proportion or all of bottom sediments are subject to wind- induced turbulence and resuspension (Kalff, 2002). The current velocities required to resuspend and transport particles in lake is primarily determined by lake size (fetch) and wind speed. In deep lakes, particles ultimately settle in the deepest water and there is little chance for their resuspension (Kalff, 2002).

3.4. Biological factors

Zooplankton

The plankton communities of freshwaters include animals as well as plants. Many of the animals are herbivores zooplankton, feeding directly upon phytoplankton and bacteria inhabiting the water in which they live. Inevitably their activities deplete the standing stock of phytoplankton and, hence may have a significant effect on the ecology of phytoplankton population dynamics (Reynolds, 1984). Each of the major groups represented in the freshwater zooplankton: protozoa, rotifers and crustacean include species which are believed to feed, partly or wholly, upon planktonic algae.

The zooplankton density depends on biotic and abiotic factors summarized in the top-down versus bottom-up regulation (Mc Queen *et al.*, 1986). Most zooplankters are phytoplankton consumers and thus contribute, along with other factors, to the reduction of phytoplankton numbers (Elbert and Shanz, 1989). If its density is high, the zooplankton can to have a great influence on the phytoplankton community. Since each species of grazer has its own preference for particular food organisms, selection preference has an effect on the composition of the phytoplankton community. Those species which are not preferred as food by the zooplankton are able to rapidly become dominant (Wetzel, 1983). Macroinvertebrates vary in grazing efficiency and algae differ in their susceptibility to ingestion based on growth form or on their position within vertically stratified biofilms (Steinman, 1996). Algal biomass and species composition may in turn strongly influence distribution of macroinvertebrates and behavior.

Benthic Macroinvertebrates

Benthic macroinvertebrates are important in the acceleration of the decomposition of detritus from (Pearson, 2001). They play several important roles in the aquatic community: they are involved in the mineralization and recycling of organic matter produced in the open water above or brought in from external source, and they are important as the second and third links in the trophic sequence of aquatic communities (Lind, 1979). The larvae of chironomidae are often the most abundant macroinvertebrates associated with detritus from litter and aquatic macrophytes (Pearson, 2001). Nematodes are ubiquitous and numerically the most important animal group in benthic aquatic habitats (Platt and Warwick, 1980; Heip *et al.*, 1985).

Changes in the above physicochemical and biological conditions of a body of water result in the seasonality of phytoplankton which determines their community structure, standing crop (biomass) and primary production directly or indirectly.

Seasonality of Phytoplankton

There are numerous descriptions of the seasonal periodicity of phytoplankton communities and the possible factors controlling their periodic changes in fresh water lakes. The habitats of phytoplankton, the open waters of lakes, rivers and sea, are characterized by persistent variability (Reynolds, 1990). Mostly, this is brought about by external factors like solar energy, either directly through variation in its distribution with time of day, season and latitude or indirectly through changes in atmospheric pressure, wind, evaporation and precipitation and geochemical movement of leachates and particulates emanating from catchments.

The aquatic life processes are able to respond to physical and chemical fluctuations which modify their growth and community structure. The species composition of phytoplankton communities and the relative abundance of component species undergo changes in varying scales. These range from frequent reorganization of existing community structure in response to advective mixing processes, to annually recurrent cycle of compositional change that accompany underlying cyclical fluctuations. The species composition of phytoplankton communities in temperate climate experiences seasonal variations (Wetzel, 1983). These variations are less pronounced in oligotrophic lakes than in eutrophic lakes (Elber and Shanz, 1989). However, in hypertrophic lakes with more or less permanently blue-green algal blooms, the biomass may be almost constant during summer and autumn (Moed and Hoogveld, 1982). In comparison to temperate lakes, tropical lakes are characterized by uniformly high solar radiation and temperature. Nevertheless, as stated by Hare and Carter (1984), the lack of marked seasonal variation in day length and temperature does not preclude the existence of distinct seasonal cycle in tropical waters, which may also exhibit simultaneously marked diurnal cycles, as demonstrated by Talling (1965) in east African waters and by Talling *et al.* (1973) and Wood *et al.* (1976) in Lake Arenguede, Ethiopia.

Phytoplankton Diversity

The diversity of a phytoplankton community can be used to characterize its structure. This structure is determined by the number of species present, their physiological properties and by the genetic potential of the organisms making up the community (Elber and Shanz, 1989). The chemical and physical environment, grazing and parasitism also play an important role in determining phytoplankton diversity. Diversity is dependent on the number of species present in the community and on the distribution of individuals

amongst those species (evenness) (Pielou, 1966, cited in Holzman, 1993). The term `stability` as applied to a natural ecosystem refers to the qualitative and quantitative constancy of composition of the ecosystem during a long period of time, and also to the ability of the system to return to its original state after the occurrence of change in the environment (Elber and Shanz, 1989). In lakes which react rapidly to environmental influence, an estimate of the stability can be made based on a relatively short period of investigation. Small lakes are especially suitable for such investigations due to the rapidity with which the structure of their phytoplankton community responds to environmental changes. High diversity or increases in diversity were found to be associated with the factors like, low and constant nutrient level and grazing pressure, which reduces or prevents the dominance of individual species. Low diversity were, however, found to be associated with conditions which are extremely favorable for a particular species of phytoplankton or low grazing pressure (Elber and Shanz, 1989).

Phytoplankton Biomass and primary production

Ambient nutrients are believed to be an important factor in regulating the size structure of a phytoplankton community (Furuya and Marumo, 1983; Maita and Odate, 1980; Malone, 1980 and Parsons and Takahashi, 1973, cited in Shiomoto, 1997). Large sized phytoplankton dominate in eutrophic conditions and small-sized ones in oligotrophic conditions (Shiomoto, 1997). The contributions of small cells to the standing crops increase when the total chlorophyll a concentration decreases (Chisholm, 1992).

Chl-*a* concentration and production of large phytoplankton increase in the season of high nutrient supply (Shiomoto, 1997). The variability and distribution of the size-fractionated phytoplankton biomass and productivity

have important implications in the path of carbon produced in the euphotic zone, and the pelagic food chain structure (Ryther, 1969; Walsh, 1976).

Annual primary production, a close correlate of annual mean biomass, appears to be related to latitude (Lewis, 1992). Phytoplankton productivity follows essentially the same pattern in turbid as in clear waters (Grobelaar, 1985), except that the productivity profiles are compressed, due to the rapid attenuation of light (Grobelaar, 1985). Of importance to the overall algal productivity is also the "critical mixing depth" (Sverdrup, 1953), which determines the time fractions phytoplankton spend in the light and dark. The smaller the euphotic:aphotic zone ratio, the lower the overall productivity (Grobelaar, 1985). Primary production in warm tropical lakes is higher than that in temperate lakes (Melack, 1979; Lemoalle, 1981; Lewis, 1987). The reason is that maximum rate of photosynthesis per unit biomass and time (biomass-specific rates of photosynthesis at light saturation, photosynthetic capacity) is a function of temperature (Harris, 1978). Higher incident irradiance and enhanced vertical mixing are additional factors promoting primary production in tropical lakes (Lewis, 1987).

Fish Biomass Production and Phytoplankton

Fish biomass can be estimated using different empirical formulas from which phytoplankton biomass and primary productivity are prominent estimating parameters. Despite the proven relationships between primary production and fish yield, primary production is seldom measured by fish biologists. Fish yield, the catch of fish per unit surface area, is an economically important parameter (Lampert and Sommer, 1997). Empirical models that use phytoplankton primary production as the main controlling variables for predicting fish yield in lakes have resulted in more successful predictions than any other methods (Melack, 1976; Oglesby, 1977; Lowe-McConnell, 1987; Downing *et al.*, 1990;

Knosche and Bar-Thelmes, 1998, cited in, Hoker *et al.*, 2001). A good correlation between daily photosynthesis and production of fish in ponds and lakes has also been observed (Wolny and Grygierek, 1972, cited in, Hoker *et al.*, 2001).

The ratio of fish yield to primary production is expected to be higher in tropical than in temperate lakes (Hooker *et al.*, 2001). Melack (1976) also showed that the fish yield of lakes in Africa and India increased exponentially as primary production increased linearly. He hypothesized that herbivorous fish became increasingly numerous in more eutrophic waters. Hence, a shorter food-chain leads to higher efficiency in energy transfer along the food chain. However, changes in phytoplankton species composition to the less edible and less nutritious cyanobacteria (Ahlgren *et al.*, 1992) tend to counteract the effect.

The equation $FY = 0.0023 \times PP^{0.9}$ ($0.0021 \times PP^{0.92}$) predicts that the average fish yield is about 0.1- 0.2% of the primary production (Hakason and Boulion, 2001). The implication of this is that one can quite confidently predict that the fish catch will not exceed about 0.3% of the primary production. In fertilized ponds, the primary production is often between 300 and 3700 mg ww/m² yr⁻¹, and fish catches between 6 and 600 mg ww/m² yr⁻¹ (Hakason and Boulion, 2001).

4. DESCRIPTION OF STUDY AREA

Bishoftu crater lakes are extensive series of volcanic crater lakes, located in the vicinity of Bishoftu (Debrezeit), which is situated 47 km south east of Addis Ababa at an altitude of approximately 1900 m [fig. 1](#). Mohr (1961, cited in Prosser *et al.*, 1968) recognized thirteen craters and commented that the explosion craters are quite distinct from other volcanic craters being sunken basin-shaped depressions wholly below ground level except their rims. They

have steep sides and flat bottoms, have a diameter close to 1 Km and are not directly associated with lava flow. From eleven craters the two, one of which contains Lake Hora-Kilole lies east of the general alignment. Mohr (1961, cited in Prosser *et al.*, 1968) provided evidence which suggests that the craters were formed during Makalian wet phase (5000 B.C) as a result of the explosive expansion of subterranean super-heated steam derived from waters of originally extensive rift valley lake.

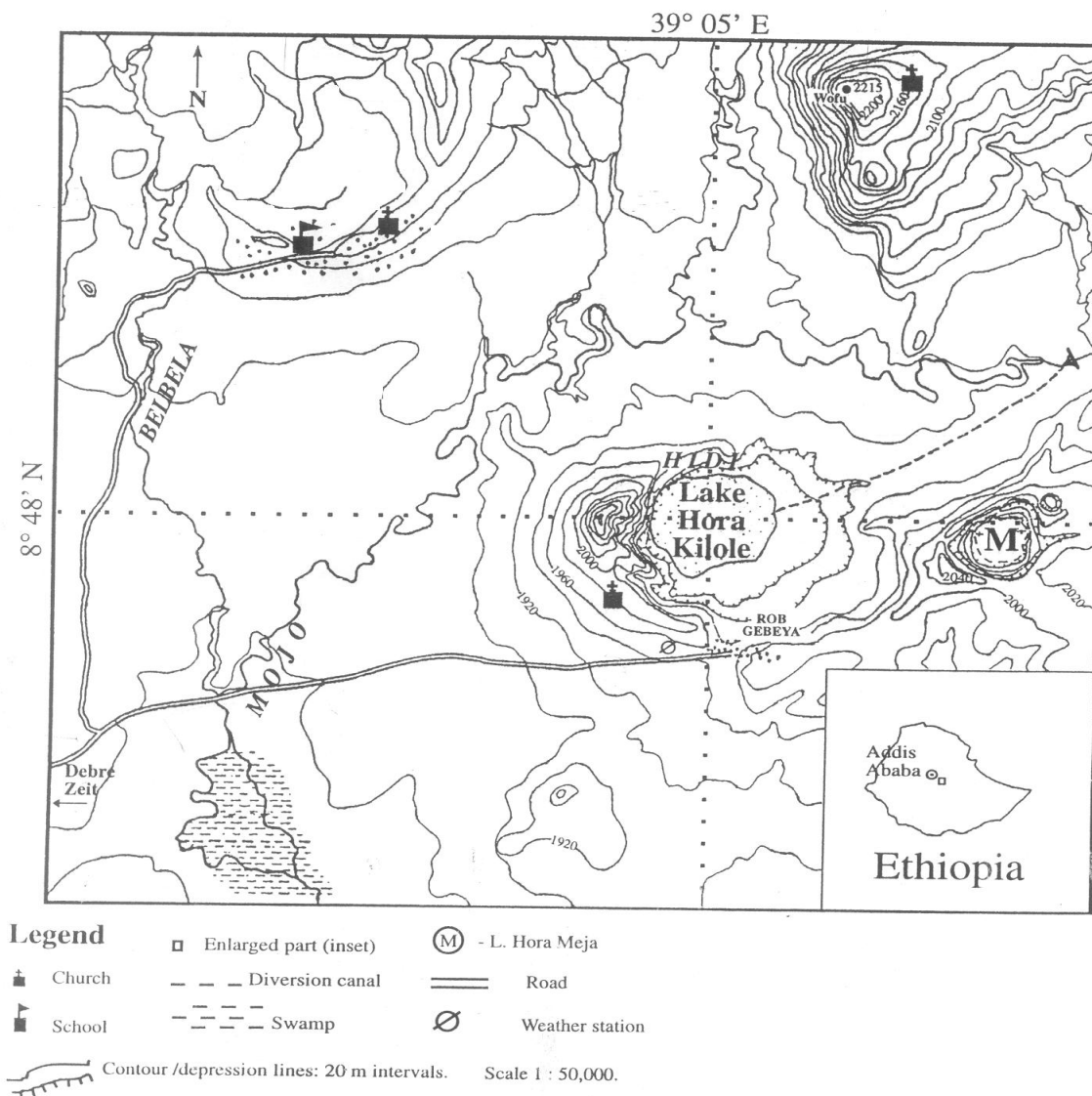


Fig.1. Location of the study lake, Lake Hora-Kilole, Mojo River and the western and south- western fields planned for irrigation (Brook Lemma, 1994).

Lake Hora-Kilole was given different names at different time by different researchers: Lake Hora-Kilole (Brook Lemma, 1994); Kilotes by Mohr (1961), Kiloti by Na office, Uk (1946) and Chilotes by Omer-Cooper (1930, cited in Prosser *et al.*, 1968). Lake Hora-Kilole is located 18 km east of the town of Bishoftu (Debrezeit) in a locality known as Hidi at 8°48` N and 39°5` E and at an altitude of 1980 m asl (Brook Lemma, 1994) .

The cater of lake Hora-Kilole is considerably eroded and slumped in north-south direction and becomes particularly conspicuous in the east-west direction (Wood *et al.*, 1976 and Elizabeth Kebede *et al.* (1986, cited in Brook Lemma, 1994). To the east, there is Mount Meja (2000m) which has at its peak a small crater lake (L. Hora Meja). This lake doesn't have any water-shed except its thin rim to the west of Hora-kilole, the crater rim rises to a peak of 2100m to north and adjacent to the lake, river Mojo, a tributary of R. Awash, flows in east-west direction between the crater rim of the lake and the northerly Mount Wofu (2215 m) (Brook Lemma, 1994). This river originally did not flow into Lake Hora-kilole [fig. 2](#) show channel by which the river mojo was diverted. There are no other streams or rivers flowing into the lake and out lets are apparently lacking (Talling *et al.*, 1973).

Fig. 2. Channel through which Mojar River was Diverted into the lake in December, 2008.

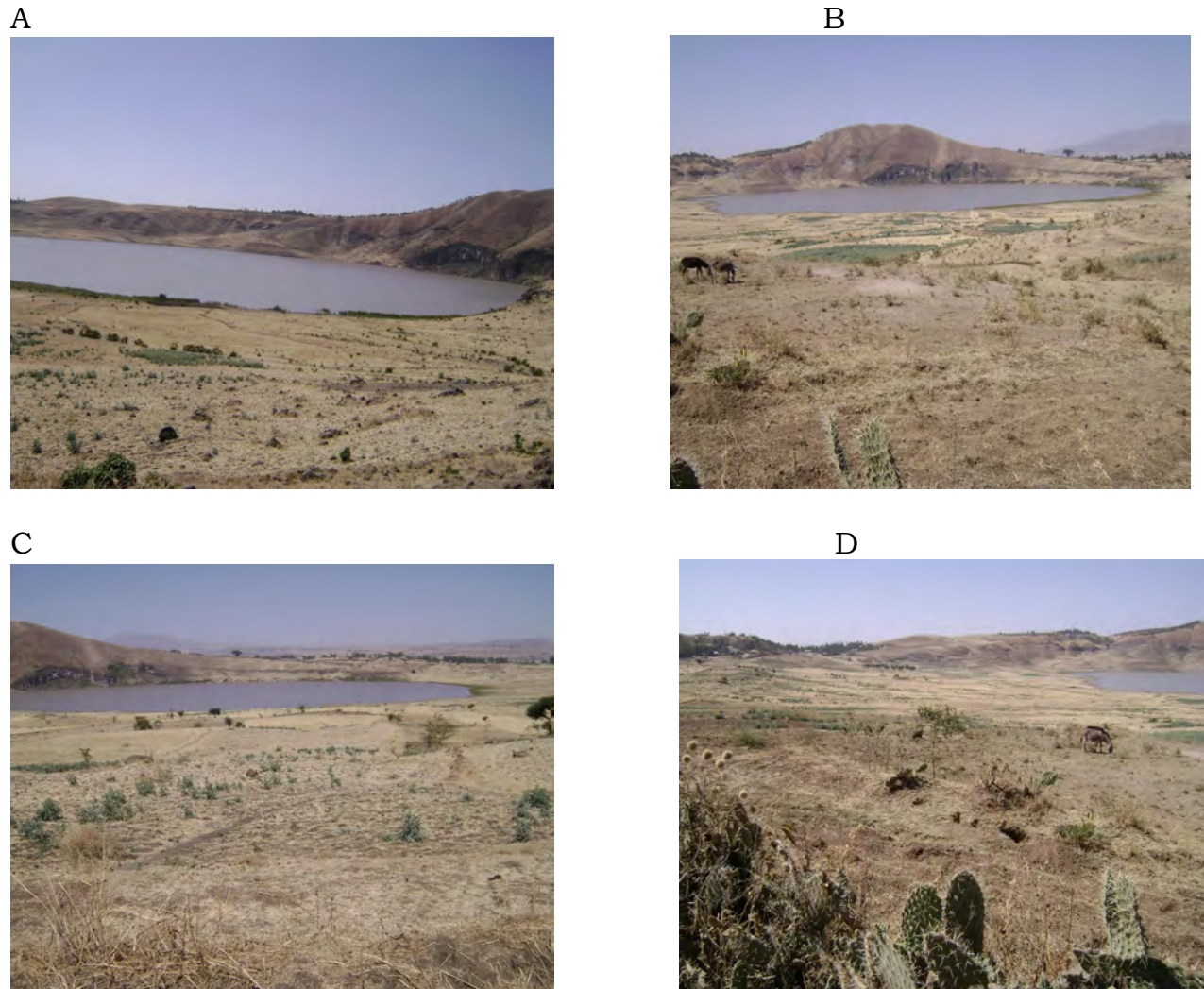


Lake Hora-Kilole occupies a small area of a very large area, and in the east and south it has ill-defined crater and consequently the exposure to wind is high. Diameter of Lake Hora-Kilole alone has a greatly exceeding the maximum of 1.6 Km suggested by Williams (1941, cited in Prosser *et al.*, 1968). The study lake is small, shallow, roughly circular, not totally enclosed by crater wall and well mixed (turbulent) (see Fig. 3. A-D). Comparative summary of the physico-chemical and biological characteristics of Lake Hora-Kilole before and after 1989 and at present are given in Appendix 11.

Almost 75% of the catchment area is used as agricultural land by people living in the vicinity. In the SE direction of the lake the river channel is located and the farmers continuously use the land as farm plot. When they face scarcity of water for their farms they open the channel. Overflowing water most probably joins the lake carrying organic and inorganic nutrients, silt and detritus encountered on its way in to the lake. The farmers grow onion, teff and tomato. In contrast to those farmers found on the SE side of the lake, farmers in the SW direction pump out the lake water using motor generators. The lake's region is characterized by moderate rainfall, high incident solar radiation and low relative humidity. The region has two rainy periods, the minor one extending roughly from February to April and the major one beginning in June and ending in September.

Before dilution, Lake Hora-Kilole was well exposed and shallow, hence showed no evidence of stratification except for slight reduction in oxygen concentration near the mud surface (Wood *et al.*, 1976). Primarily, the weathering of the predominantly basaltic rocks forming the crater coupled with concentration by evaporation and possible under-ground seepage, water containing minerals dissolved from more distant sources, has resulted in mineral-rich inflows and lake water rich in inorganic nutrients (Prosser *et al.*, 1968). Prosser *et al.* (1968) argued that Lake Hora-Kilole should be grouped with the more concentrated lakes on the basis of total concentration of electrolytes. Until 1989, the original

water of this Crater Lake was not potable for people or animals due to its high salinity (K_{20} , $6720 \mu\text{Scm}^{-1}$) (Talling and Talling, 1965; Wood and Talling, 1988). Although the purpose of diversion was to irrigate the southern and eastern low-lying plains of about 3000 hectares of farmland by gravitational flow, it did not reach the desired elevation for gravitational irrigation (Brook Lemma, 2002).



(By: rediat abate)

Fig. 3. A-D-General morphology of the study lake, the topography of the catchments in the vicinity of the lake and shoreline modification undertaken by farmers.

The phytoplankton dominant before diversion of Mojo river (*Chroococcus minutus* and *Spirulina*) were replaced by *Peridinium*, *Cosmarium*, *Staurastrum*, and *Nitzschia* spp. in the same order of dominance (Brook Lemma, 1994, 2002). Phytoplankton density depth profile also showed seasonality (Brook Lemma, 1994, 2002). The dominant macrophyte is found on the sides of the lake where agricultural activities are intensive.

The original dominant zooplankton in Lake Hora-Kilole were *Lovenulla africana* DADY and *Afrocylops gibsoni* BRADY (Green, 1986; La Barbari and Kilham, 1994). Later Green and Seyoum Mengistou (1991) reported the presence of the rotifers *Anuraeopsis coelata*, *Ascomorpha salfans*, *Asplanchna brightwelli*, *Brachionus caudate* and *Filinia* sp.

Oreochromis niloticus and *Barbus* sp are founding the lake; with *Barbus* sp dominating the fish catch (Brook Lemma, 1994, 2002). Some times very small-sized dead *Barbus* sp. were seen on the surface of the lake, which was most probably imported from the river through the channel (personal observation and communication with villagers). There are about (10-15) bird species dwelling around the lake system as their permanent or temporary habitat.

There are few fishermen (around 4) using the lake as fish source for both household consumption and commercial purposes. The lake might have not been exploited up to its optimum potential considering the size of the net used, the method of fishing and the number of fishermen operating there.

4.1. Meteorological Data

Temporal variations in total monthly rainfall mean minimum and maximum air temperature and wind speed are shown in Figure 5.

The monthly mean minimum air temperature ranged from 9.37 °C of October, 2007 to 13.7 °C of August, 2007 and January, 2008, while the mean maximum air temperature varied from 23.6 of September, 2007 to 29.2 of May, 2008. The relatively low maximum air temperature levels occurred during the months with the present large peaks of precipitation, August and September, 2007. The relatively low mean minimum air temperature levels were, however, observed during the dry period indicating that the period extending from November to January is not the driest but the coldest period of the year in this lake region.

Total monthly rainfall over the study period ranged from 3.4 mm of November, 2007 to 203.3 mm of August, 2007. The monthly rainfall decreased almost consistently from the seasonal maximum in August, 2007 to the seasonal minimum in November, 2007 before it exhibited small but consistent increases from November to February, 2008. Although the region was described by Baxter *et al.* (1965) as having two rainy periods, the minor one extending roughly from February to April and the major one beginning in June and ending in September, substantial quantities of rainfall were recorded only during August-September, 2007. Rippey and Wood (1985) also documented that this lake area has moderate rainfall, varying around about 850 mm per annum.

The present meteorological data for Lake Hora-Kilole show a 10-month period rainfall of about 420 mm. The annual rainfall for the year 2008 is not expected to be significantly different from that estimated by Rippey and Wood (1985) considering the present very small contribution of the period extending from February to March to the annual rainfall of the region.

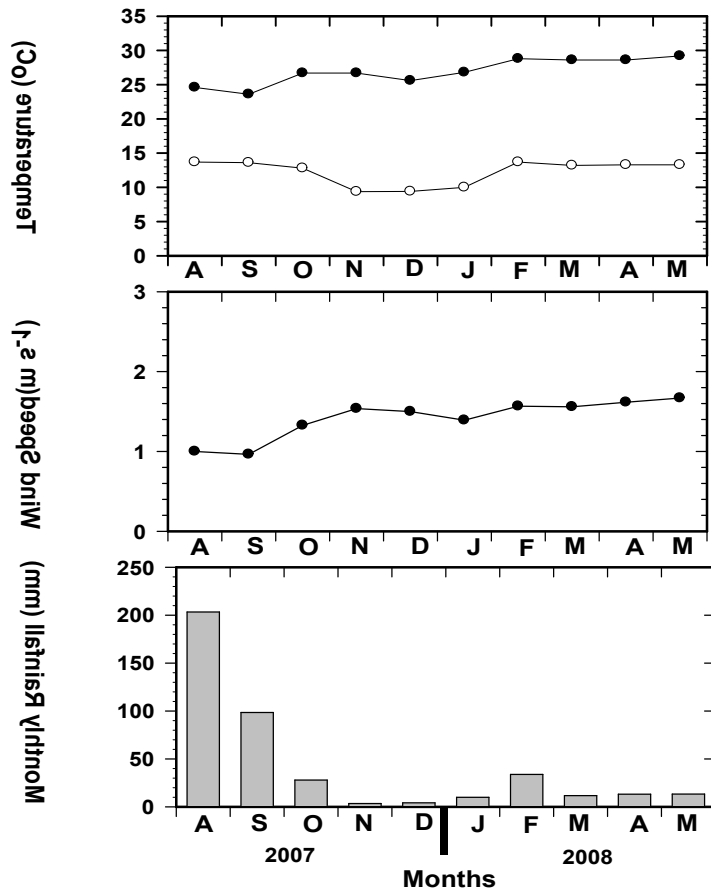


Fig. 4. Meteorological data of Lake Hora-Kilole: mean maximum (closed circle) and minimum (open circle) air temperature, wind speed and monthly rainfall. (Source: National Ethiopian Meteorology service Agency)

Monthly mean wind speed (in m s^{-1}) ranged from about 0.96 in September, 2007 to nearly 1.7 in May, 2008, with most values slightly greater than 1.5 m s^{-1} . Wind speed varied temporally in a pattern roughly similar to that of mean maximum air temperature. Wind speed was low during the major rainy period and gradually increased to a peak in November, 2007 before it declined to a lower value in January and then consistently but gradually increased until May, 2008.

5. MATERIALS AND METHODS

5.1 Sampling protocol

In view of the fact that there are intensive human activities around the lake one sampling site at 6 m depth, is optimum owing to the complete wind-induced mixing and small size of the lake, at the centre of the lake was selected for regular sampling. Water sample collection and field measurements were made at this station at about monthly intervals. Sampling station was tracked by using GPS and the location was 37P0509194; UTM 0973908 NE direction.

Specie identification and estimation of biomass, abundance and primary production of phytoplankton were made using composite samples. For the determination of alkalinity, pH and analysis of inorganic nutrient, composite samples were used. Composite samples were prepared using samples collected by a bottle sampler (Kemmerer) from different depths distributed up to 2 meter beyond the euphotic zone (total of 4 meter depth) and mixed in equal proportion in a large bucket. Preparation of composite samples was required to make analyses manageable as the analysis of samples collected from different depths for biomass; primary production and inorganic nutrients requires a lot of time and resources. For species identification and estimation of abundance of zooplankton, zooplankton net of mesh size 55 μm was used. For species identification and estimation of abundance of benthic macroinvertebrates, a benthic sampler (Ekman grab) was used. Water samples were also collected one time from Mojo River and from the point at which the river entered the lake during the dry season when the farmers diverted the river.

5.2. Measurement of physico-chemical parameters

Different physical and chemical parameters were measured *in situ* or analyzed in the laboratory using appropriate methods. The various equations used in the estimation of different parameters are shown in Appendix 12.

5.2.1 *In-situ* measurements and calculation of secondary data

Vertical distribution (Depth profiles) of temperature and oxygen were determined at the selected station using an oxygen meter connected to Oxygen-Temperature combination probe (Model HI 9143). The Winkler method for oxygen determination was also used for the determination of Oxygen-depth profiles. pH was measured on composite samples by a digital pH meter (Hanna 9024). All the meters were calibrated every time measurements were made.

Water transparency (vertical visibility) of the lake was estimated with a standard Secchi disc of 20 cm diameter. Down-welling irradiance (PAR) was measured *in situ* using LI-COR underwater quantum sensor (LI-102 SB) connected to LI-185 B photometer. From the underwater irradiance measurements, the mean extinction coefficient of down welling irradiance (K_d) was calculated. Using the calculated values of K_d , euphotic depth (Z_{eu}), the depth at which the down-welling irradiance was only 1% of the surface irradiance and light attenuation due to chlorophyll a in algae (K_s) were estimated as a fraction of K_d . The reported values of experimental estimates for the attenuation of PAR by *Chl-a* in algae ranges from 0.006 to 0.018 (Kirk, 1975; Dubinsky and Berman, 1981). The intermediate value of 0.016, Dubinsky and Berman (1976), was used for the calculation of K_s in this study.

5.2.2. Chemical analyses

Determination and analysis of total dry mass

For total dry mass (weight), the dried filter paper was first weighed on a sensitive balance (Sartorius sensitive balance) and its dry mass registered, and appropriate volumes (150-200 ml) of composite samples were gently filtered through 47 mm diameter glass fiber filter papers (Whatman, grade GF/F, 0.6-0.7 μm pore size) with the aid of electrically-operated suction pump (Model SPEEDIVAC 2). The material retained on the pre-weighed filter was dried in an oven at 105 °C overnight and weighed on a sensitive balance and the results were recorded. The filter was then placed in a preheated muffle furnace ignited to 500 °C for 2 hours and organic-free dry mass was determined (Lind, 1979; Wetzel and Likens, 2000). Calculations for total, organic and inorganic (Ash) dry mass were made according to the equations in Appendix 12.

Determination of Alkalinity and Inorganic Carbon Concentration

Total and phenolphthalein alkalinity were determined by titration of the sample with 0.01N HCl to a pH of 4.5 using phenolphthalein and bromocresol green-methyl red indicator solutions within a few hours after sample collection according to Wetzel and Likens (2000) and expressed in meq L^{-1} .

Total dissolved inorganic carbon was calculated using software (CTDA.EXE) which gives the value of total inorganic carbon, HCO_3^{1-} , CO_3^{2-} and CO_2 in meq/L . Mean temperature, Total alkalinity and pH are fed into the program and the program gives the concentration of the inorganic carbon forms.

Analysis of inorganic nutrients in the laboratory

Inorganic nutrients were analyzed using standard methods (Nelson *et al.*, 1954; Lind, 1979; APHA *et al.*, 1999; Wetzel and Likens, 2000). Composite samples were filtered with glass fiber filter paper on the sampling day and inorganic nutrients were analyzed on the same day. The absorbance of reagent-treated colored samples was measured with a visible spectrophotometer (Model PYE UNICAM SP6-350). The regression equations of the standard curves produced by plotting absorbance against concentration of standard solutions were used to determine the concentration of each nutrient in the water sample (Appendix 12.7).

Nitrate+ Nitrite- Nitrogen ($\text{NO}_3+\text{NO}_2\text{-N}$) concentration was determined using the Zinc Reduction method (Nelson *et al.*, 1954). NH_4+ $\text{NH}_3\text{-N}$ was analyzed by the Phenate Method (Lind, 1979; Wetzel and Likens, 2000). Dissolved SiO_2 (Molybdate Reactive Silica) was determined using the Molybdosilicate method (APHA *et al.*, 1999). Soluble Reactive Phosphate-P (SRP) and Total Phosphorus (TP) were determined by the Ascorbic Acid Method (APHA *et al.*, 1999). TP was determined by the Ascorbic Acid Method after digestion of the sample with Persulfate. Molar concentration of total nitrogen was calculated from $\text{NO}_3+\text{NO}_2\text{-N}$ and NH_4+ $\text{NH}_3\text{-N}$ compounds or the estimation of Redfield ratio of TN:TP. Conversion to μmolL^{-1} was made by multiplying TN:TP by 2.21 (Downing and McCauley, 1992).

5.3. Measurement of Biological Parameters

5.3.1. Species composition and abundance of Plankton

Estimation of phytoplankton abundance was done using prepared composite samples. From these 100 ml aliquots were taken and placed in brown bottles (125 ml) and preserved with Lugol's iodine solution. These were transported

to the laboratory and transferred to a measuring cylinder of 100ml and stored in darkness for sedimentation. After a period of 48 hours the upper 80 ml of the sample was siphoned off and the remaining 20 ml was mixed to make it homogenous. Assemblage of 1 ml as pipetted into Sedgwick-Rafter cell and cells within 80-100 grids were counted randomly under an inverted microscope (Nikon) at a magnification of 150x. The cell number (cells ml⁻¹) of the lake water was calculated according to Hotzel and Croome (1999) and Wetzel and Likens (2000) (see Appendix 12.8.A). The cell counts of major phytoplankton species were added together to give total abundance of phytoplankton. All possible, species were counted separately; the number of individual per species was counted for each strip, summed up, and the Shannon-weaver diversity index calculated to show the diversity (see Appendix 12. 8. B).

Both preserved and fresh samples were used for identification of phytoplankton taxa using identification keys of Whitford and Schumacher (1973), Gasse (1986), Komareck and Kling (1991) and Cronberg *et al.* (2000).

Zooplankton samples were collected by towing upward from 2 m meter depth using a tow net (55 µm) and preserved with 5% formaldehyde solution in dark glass bottles of 125 ml capacity. Two meter depth was selected to relate zooplankton abundance to phytoplankton abundance and biomass of the euphotic zone. In the laboratory, each sample was homogenized and sub-sample of 25 ml was taken with a wide-mouthed pipette and placed in a grided Petri dish and counted. The calculation was done using the formula in Lind (1979) and Wetzel and likens (2000). Zooplankters were identified using of key of Fernando (2002).

5.3.2. Identification and enumeration of benthic Macroinvertebrates

Samples were taken with 429 cm² Ekman grab, at the central station. After the sample was pulled up, it was immediately transferred in to plastic bag. All processes for separation of organisms from the sediment were done in the laboratory by screening through different-sized sieves that remove the sediment (Lind, 1979; Wetzel and Likens, 2000). For the present work, the samples were sieved on a Canadian standard Sieve Series with 1.5, 1 and 0.5 mm mesh opening to separate the sediments and other constituents from the macrofauna of the substrate. In the laboratory, the contents of the sieves were collected in a white pan and Petridishes and transferred into one collection bottle. For counting and identification of benthic animals, the whole sample was poured into grided Petridises and dissecting microscope (20-40X) was used. For identification, identification keys of fresh water macroinvertebrates collected from internet and Fernando (2002) were used.

Fig.5. Laboratory works on benthic sample of Lake Hora-kilole.



5.3.3. Estimation of phytoplankton biomass and its size-fractionation

Phytoplankton biomass was size-fractionated using composite samples collected from the central station. Chlorophyll a (*Chl-a*) concentrations (uncorrected for phaeopigments) were determined by measuring the absorbance of pigment extracts. Appropriate volumes of composite samples of the lake water were taken and filtered sequentially through a filtration cascade of 20, 2, and 0.22 μm pore size membrane filter papers (Nucleopore). For the first size-class ($> 20 \mu\text{m}$) 100-150 ml of composite sample was filtered using membrane filter papers of 20 μm pore size. For the second size-class (2- 20 μm), 50-60 ml of the sample that passed through 20 μm filter papers was filtered with a filter paper of 2 μm pore size. For last size-class ($< 2 \mu\text{m}$), 40 ml of the sample that passed through 2 μm filter paper was filtered onto 0.22 μm pore size filter paper. The filtration process was aided by electrically-operated suction pump (Model SPEEDIVAC 2). The filters were manually ground gently in a test tube with a glass rod in a small volume (5-8 ml) of 90% acetone and centrifuged at 3000 rpm for 10 minutes in a parafilm-covered centrifuge tubes. The extract was then decanted to a 10 ml volumetric flask and made up to the mark with 90% acetone. The optical density of the sample extract (Absorbance) was then measured against a blank at 665 nm and 750 nm with a spectrophotometer (Model PYE UNICAM SP6-350 visible spectrophotometer) following the procedures outlined in Wetzel and Likens (2000). Finally *Chl-a* concentration was estimated using the equation of Talling and Driver (1963) (see Appendix 12.10) and the euphotic zone chlorophyll a (ΣB) was estimated by multiplying phytoplankton biomass per unit volume (B) with Z_{eu} (Eriksson *et al.*, 1991).

5.3.4. Measurement of Phytoplankton Photosynthetic production

In-situ photosynthetic rates of phytoplankton were estimated by the light and dark bottle technique and the Winkler method of dissolved oxygen determination (Lind, 1979; Wetzel and Likens, 2000). Composite samples of the lake water were transferred to transparent (light) and opaque (dark) bottles (273 ml capacity), and duplicate light bottles were suspended *in-situ* at different depths within the euphotic zone (0.00, 0.25, 0.75, 1.25, 1.5, 2. and 2.5 meters), while only two dark bottles were suspended, one near the surface and the other near the lower end of the incubation line for periods of 3 to 3.5 hours during 12 A.M to 4 PM. A pair of bottles was fixed with Winkler reagents immediately after incubation of the light and dark bottles to serve as initial bottles. At the end of the incubation period, bottles were taken out and fixed with Winkler reagents and transported to the laboratory in light-proof boxes.

The concentration of oxygen (in mg O₂ L⁻¹) in each bottle (initial, dark and light bottles) was determined by titration with standard sodium thiosulfate solution (0.0125N) using starch as an indicator (Lind (1979)). Using the concentration of O₂ determined for initial, dark and light bottles, net and gross photosynthetic rates and respiration were estimated (see Appendix 12. 11) and the concentration of O₂ was converted to carbon to calculate photosynthetic efficiency on caloric basis. Conversion of the amount of oxygen evolved to the amount of carbon assimilated was made assuming a photosynthetic quotient of 1.2 (Wetzel and Likens 2000). Different photosynthetic parameters were also estimated. The volumetric rates of gross photosynthesis were converted to areal rates of gross photosynthesis using Grid enumeration technique (Olson, 1960). Areal photosynthesis is the area enclosed by the curve formed when rates of gross photosynthesis are plotted against depth of incubation. The hourly rates of gross photosynthesis were converted to daily rates of gross photosynthesis

by multiplying with the commonly used factors, 10 and 0.9 derived for tropical waters by Talling (1965). 10 is the number of hours of sunshine and 0.9 is a factor for the effective day length. Biomass-specific rates of gross photosynthesis were determined by dividing volumetric rates of gross photosynthesis by phytoplankton biomass (See appendix 12.11E).

5.3.5. Estimation fish biomass production

Primary production and biomass of phytoplankton can be good estimators of fish biomass production. Different empirical formulae were used to determine fish yield and the mean value was taken as the fish yield of Lake Hora-Kilole.

5.4. Statistical Analyses

Different computer programs such as Sigma plot 10 and Microsoft Excel were used for statistical analysis. Results of the statistical analyses of the relationship among different physico-chemical and biological parameters measured in this study are given in Appendix 10.

5.5. Description of symbols used in the text

Z_{sd}	Secchi depth (m)
Z_{eu}	Depth of euphotic zone (m)
K_d	Mean vertical extinction coefficient (ln units m^{-1})
Chl a	Chlorophyll a, in $mg\ m^{-3}$ or $\mu g\ L^{-1}$
B	phytoplankton biomass ($mg\ Chl\ a\ m^{-3}$)
GP	Gross photosynthesis per unit volume ($mg\ O_2\ m^{-3}\ h^{-1}$)
NP	Rate of net photosynthesis per unit water volume, ($mg\ O_2\ m^{-3}\ h^{-1}$)
A	Rate of gross photosynthesis per unit water volume. in $mg\ O_2\ m^{-3}\ h^{-1}$

A_{\max}	Light- saturated rate of gross photosynthesis, in mg $O_2 m^{-3} h^{-1}$
P	(A/B) Specific rate of gross photosynthesis per unit biomass, in mg $O_2 (mg\ Chl\ a)^{-1} h^{-1}$
$P_{\max}(A_{\max}/B)$	Specific rate of gross photosynthesis per unit biomass at light-saturation, Photosynthetic capacity or Assimilation number [mg $O_2 (mg\ Chl\ a)^{-1} h^{-1}$]
ΣA	Hourly rate of gross photosynthesis per unit area (mg $O_2 m^{-2} h^{-1}$)
$\Sigma \Sigma A$	Daily rate of gross photosynthesis per unit area (g $O_2 m^{-2} d^{-1}$)
I_0	Photosynthetically Available Radiation (PAR) just below the surface ($\mu mol\ photon\ or\ micro-einsteins\ m^{-2} s^{-1}$)
I_z	PAR at depth, Z ($\mu mol\ photon\ m^{-2} s^{-1}$)
DM.....	Dry mass of particulate matter (mg/L)
ADM.....	Ash Dry Mass of particulate matter (mg/L)
DIC	Dissolved Inorganic Carbon (mg L^{-1})
PA	Phenolphthalein alkalinity (meq L^{-1})
TA	Total alkalinity (meq L^{-1})

6. RESULTS AND DISCUSSION

6.1. Physicochemical Parameters

6.1.1. Lake water volume and maximum depth

The volume of the lake has remarkably changed since the maximum depth (Z_m) decreased dramatically from about 24 m of a large monomictic lake that prevailed from 1991 to 2001 (Brook Lemma, 1994; 2002) to the present small polymictic lake with a maximum depth of only 7.8 m. Observations made on the position of the surface water of the lake in reference to a post (water level indicator) located in the littoral zone of the lake showed that the lake shrunk by 7-8 m during March and May, 2008, which suggests that an incredibly large volume of water that entered the lake through precipitation and the diversion of channel is lost through abstraction (consumption), evapo-transpiration and probably seepage.

Measurement of Z_m was taken during the major rainy season of the region and was found to be 7.8 m, which is about three times less than the Z_m recorded by Brook Lemma (1994) after the dilution of the lake in 1991 and is greater by only about 1.4 m than the depth recorded before dilution (Wood and Talling 1988). This decrease in Z_m was most probably caused by underground seepage of the lake water (Brook Lemma, Pers. Comm.) although household consumption, irrigation and evapo-transpiration obviously have some contribution.

Water level decline during dry periods of the year is an expected phenomenon in such lake regions where rainy events are strongly seasonal and occur in irregular precipitation regimes and has been recorded for other lakes of the Bishoftu group although the extent of decline is different (Yeshiemebet Major, 2006; Abebaw Wondie, 2007; Tadesse Ogato, 2007; Zelalem Desalegn, 2007).

Seasonal water level fluctuations, which are associated with water input-output (precipitation, evaporation, abstraction), influence the physical, chemical and biological features of a water body (Talling, 1986; Wetzel, 2001). As it will be presented later the increase in the ambient concentrations of nutrients, particularly nitrate, during the dry period in Lake Hora-Kilole seems to corroborate this.

6.1.2. Optical Characteristics

The variations in time of the optical parameters estimated for Lake Hora-Kilole in relation to dry weight of particulate matter and phytoplankton biomass estimated as areal chlorophyll *a* concentration are shown in Fig. 6 (see also Appendix 2). The temporal variations in environmental variables which are believed to have a bearing on the underwater light climate of a body of water, dry weight of particulate matter (both organic and inorganic fractions) and euphotic zone phytoplankton biomass estimated as chlorophyll *a* concentration, ΣB , are illustrated in Fig. 6C.

Lake's transparency (vertical visibility), measured as Secchi depth (Z_{SD}), varied (mean=0.35) varied between 0.15 m in December, 2007 and 0.78 m in August, 2007. Secchi depth increased continuously from August to its seasonal maximum in October, 2007 before it declined consistently to its seasonal minimum in December, 2007 and then increased steadily to the end of March, 2008. The temporal variations in Secchi depth were inversely related to those of the dry weight of suspended particulate matter. The variations in Secchi depth, however, exhibited a seasonal pattern which was more or less similar to that of phytoplankton biomass in the euphotic zone during the major rainy season and the dry period. Although Secchi depth in Lake Hora-Kilole is a function of both biogenic and abiogenic turbidity, the latter seems to be much more important than the former considering the pattern of co-variations of dry weight of inorganic and organic particulate matter and Secchi depth and the

calculated chlorophyll a-specific extinction coefficients K_s of down-welling irradiance (see Appendix 2). Lake's transparency, however, showed a direct and strong relationship ($r= 0.8422$, $r^2=0.7091$ at $p=0.0022$) with euphotic zone *Chl a*. Although the present Secchi depth readings of Lake Hora-Kilole are broadly similar to those reported for another lake of similar maximum depth from the same region, Lake Koriftu (0.35- 0.6m; Zelalem Desalegn, 2007), they are much lower than those reported for the same lake by Brook Lemma (1994; 2002) after dilution (see Appendix 11) and for Lake Babogaya (1.48 to 4.46 m; Yeshiemebet Major, 2006).

The very low Secchi depth reading reported by Green (1986) for the same lake and which was similar to the seasonal minimum recorded in the present study (0.15 m) was attributed to self-shading associated with the dominance of the cyanobacterium *Chroococcus minutus*.

Mean vertical extinction coefficients of downwelling irradiance (K_d , in \ln units m^{-1}) varied (mean= 5.44) from 2.39 in October, 2007 to 10.23 in December, 2007. The lowest value of K_d coincided with the seasonal maximum value of ΣB while the peaks of K_d of the dry season corresponded to very low ΣB values. K_d was negatively and moderately correlated with areal *Chl a* ($r=0.64$ at $P= 0.05$), with the variations in areal *Chl a* accounting for nearly 40 % of the variations in K_d ($r^2 = 0.4091$ at $P= 0.05$).

High vertical extinction coefficient values are typical of lakes with dense algal crops or with suspended silt associated with wind-induced mixing and produce shallow euphotic zone (Talling, 1973). Similarly, roughness of the water and cloud cover influence the transfer of light into the water (Melack, 1979).

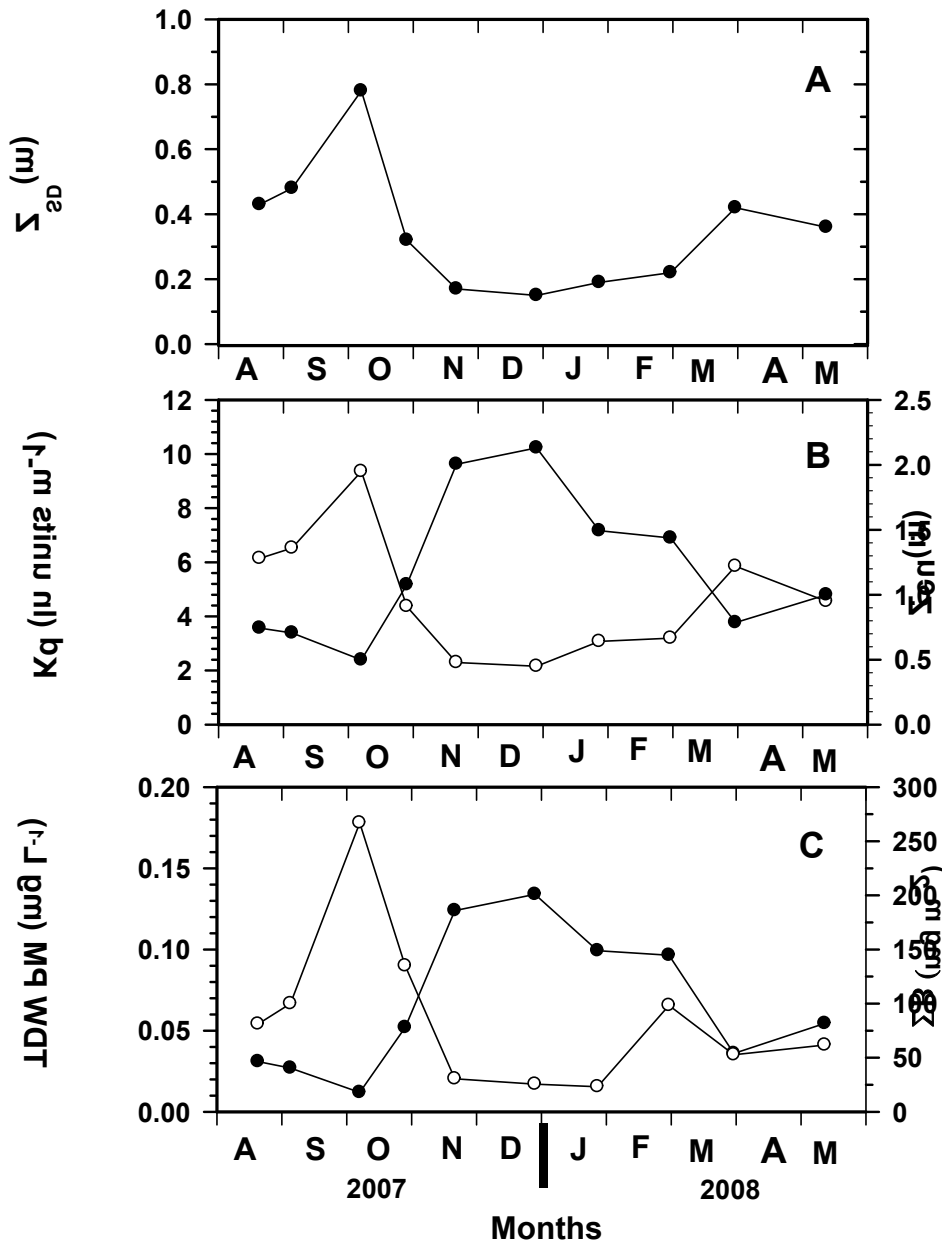


Fig. 6. Temporal variations in (A). Secchi depth (Z_{SD}), (B). Euphotic Depth (Z_{eu} , open circle) and Mean vertical extinction coefficient (K_d , closed circle) in relation to (C). Euphotic zone $Chl a$ (ΣB , open circle) and total dry weight of particulate matter (TDWPM, closed circle) in Lake Hora-Kilole during the study period.

K_d of Lake Hora-Kilole was positively but poorly correlated with monthly mean wind speed ($r = 0.3583$, $r^2 = 0.1283$ at $P = 0.3094$). K_d values of most natural lake waters range from nearly 0.2 m^{-1} in such clear lakes as Crater lake and Tahoe in USA (Smith *et al.*, 1873) to about 4 m^{-1} in highly stained lakes with high biogenic turbidity (Wetzel, 2001). About half of the observed values of K_d for Lake Hora-Kilole are outside this range unlike those reported for the very deep crater Lake Bishoftu by Tadesse Ogato (2007) and for the similarly shallow Lake Koriftu by Zelalem Desalegne (2007).

The calculated biomass-specific light extinction coefficient (k_s), varied temporally with very low values ($< 2\%$ of K_d) during the dry season. The proportion of K_d constituted by k_s was positively and strongly correlated ($r = 0.95$, $r^2 = 0.91$ at $P < 0.0001$) with ΣB . The contribution of k_s to K_d , varied from $< 1\%$ in December to about 39% in October, 2007 while light extinction due to non-algal components (K_w) ranged from about 61 to 99% of K_d in October and December 2007 respectively (see Appendix 2). This implies that non-algal turbidity is of greater importance in determining the photic conditions in the water column of Lake Hora-Kilole. The association of large contribution of organic dry mass to the dry weight of particulate matter with the lowest K_d during the wet season at the time when phytoplankton biomass was at one of its seasonal peaks and the association of large contribution of organic dry mass with relatively low phytoplankton biomass during the dry season (see Appendix 2) also corroborate the greater importance of non-algal turbidity in Lake Hora-Kilole. High contribution of organic dry mass coincided with high phytoplankton biomass and high K_d only in February, 2008. Similarly high values of percentage light attenuation due to non-algal turbidity were found in Lake Bishoftu ($\approx 80-93$, Tadesse Ogato, 2007) and in four Ethiopian Rift Valley lakes, Lakes Langano ($94-98\%$), Shalla, Ziway and Abijata (78%) (Wood *et al.*, 1978). When suspended non-algal material is

small, extinction of light by phytoplankton becomes an important component of K_d in Lake Hora-Kilole.

Euphotic depth (Z_{eu} in m), which was estimated from K_d , ranged (mean= 0.94) from about 0.45 in December to 1.95 m in October, 2007 with mean value of 0.94. Z_{eu} was relatively shallow during the dry period. This may be due to wind-generated turbulence which might have resulted in the re-suspension of particulate matter in the water column of the lake. The diversion of Mojo River into the lake may have also introduced allochthonous particulate matter which led to reduced light penetration. Z_{eu} was positively and strongly correlated with Z_{SD} ($r= 0.9906$, $r^2= 0.98$, $p < 0.0001$). The negative correlation between Z_{eu} and dry weight of particulate matter was much stronger ($r=-0.9263$, $r^2= \approx 0.8580$, $p= 0.0001$) than that between Z_{eu} and ΣB ($r= 0.7978$, $r^2 = 0.6362$, $P=0.0057$) suggesting the overriding importance of non-algal particulate suspended matter, which is largely constituted by non-organic fractions (see Appendix 2) in determining the underwater light climate of Lake Hora-Kilole. This was further supported by the correlation between the inorganic fraction of dry weight of particulate matter and K_d , which was positive and strong ($r = 0.9824$ at $P < 0.0001$) with the former accounting for over 95% of the variations in the latter ($r^2 = 0.965$ at $P < 0.0001$).

Total dry weight ($g L^{-1}$) of particulate matter varied (mean= 0.067) from 0.012 in October to 0.134 in December, 2007 while its organic (mean=0.0231) and inorganic (mean=0.0424) fractions ranged from 0.01143 and 0.0005 (October) to 0.042 and 0.104 (December and November), respectively. The inorganic fractions were generally much more important than the organic ones in their contributions to total dry mass (weight) of particulate matter in Lake Hora-Kilole. The correlation between the organic fraction and *Chl a* was positive but poor ($r= 0.22$ at $P=0.5409$) with the latter accounting for only about 5% of the variations in the former ($r^2 = 0.0485$ at $P= 0.5409$).

Z_{eu} values recorded for Lake Hora-Kilole in the present study are much higher than those reported previously for the same lake (0.24-0.38 m) and Lake Arenguade (0.15-0.27m) by Talling *et al.* (1973) with the major cause of light attenuation in the last two cases being self-shading due to the superabundant phytoplankton communities dominated by the cyanobacterium *Spirulina platensis* (Talling *et al.*, 1973).

6.1.3. Temperature and Dissolved Oxygen

Figure 7 shows the depth profiles of water temperature and dissolved oxygen in Lake Hora-Kilole. The surface water temperature of the lake averaged 23.7 °C, and ranged from 17.5 °C in December, 2007 to 26 °C in May, 2008 varying directly with air temperature. Water temperature was lower during November, 2007- January, 2008 than the rest of the study period. Top-bottom temperature differences were small averaging 2.28 °C and ranging from 0.27 to 4.3 °C. The water temperature at the deepest part (6) ranged from 17.3 °C in November, 2007 to 23.3 °C in May, 2008. The present surface water temperature levels are slightly different from those reported previously for the same lake (18.5-21.1, Brook Lemma, 1994; 2003).

The decline in temperature per meter of a depth of over 1.5 °C with increasing depth was observed near the surface, probably associated with solar heating, in January and February, 2008 while such declines for other sampling months were less than 1 °C. Well-marked, deep-seated and prolonged thermal stratification was not, however, observed as the lake was frequently mixed owing to its shallowness and exposure to strong wind-action.

Seasonal thermal stratification of different magnitude may occur In Crater lakes of East Africa including those in Ethiopia (Wood *et al.*, 1976, 1984), Kenya (Melack, 1981) and Uganda (Melack, 1978), depending on the extent the

lakes are protected from wind, which is provided by their crater walls (Wood *et al.*, 1976, 1984). The Bishoftu crater lakes including Hora-Kilole are small (surface area =0.77 Km²) and have steep-sided basin and variation among these lakes in the extent of mixing seems to be related to the variation in their depth and degree of exposure to wind (Baxter *et al.*, 1965; Wood *et al.*, 1976, 1984). Frequent and complete mixing is to be expected in Lake Hora-Kilole in light of its shallowness and exposure to wind action. Baxter *et al.* (1965) also noted that complete mixing is normally frequent in African lakes with a maximum depth (Z_{\max}) of less than about 15-30 m and that thermal stratification is diurnal.

Dissolved oxygen (DO) concentration (in mg L⁻¹) showed both spatial and temporal variations (see Appendix 1). DO in the surface water of the study lake varied from 9.5 in December, 2007 to 13 mg L⁻¹ in May, 2008. The seasonal maximum concentration of DO (17 mg L⁻¹) was observed at 0.5 m in May, 2008, while the minimum (6.9 mg L⁻¹) was recorded at 5 and 6 m depth in Sep, 2007.

The maximum concentration of DO recorded for surface water in the present study was noticeably different from that reported in Brook Lemma (1994). The lowest and highest concentrations of DO at the surface recorded by Brook Lemma (1994) were 3.4 (in July, 1990) and 10.6 mg L⁻¹ (in January, 1991) respectively. The previous lower surface DO concentrations were probably associated with the stratified and hence oxygen-depleted large volume of water, which upon mixing, result in the reduction of oxygen concentration at the surface. Subsequent to flooding, the decay of the recently inundated vegetation undoubtedly resulted in anaerobic conditions in the deeper water layers. Hypolimnetic oxygen depletion was a major problem in 1990-91 despite the input of atmospheric oxygen by wind action and anaerobic conditions prevailed in the lake until complete mixing occurred during the rainy season (Brook Lemma, 1994; 2002).

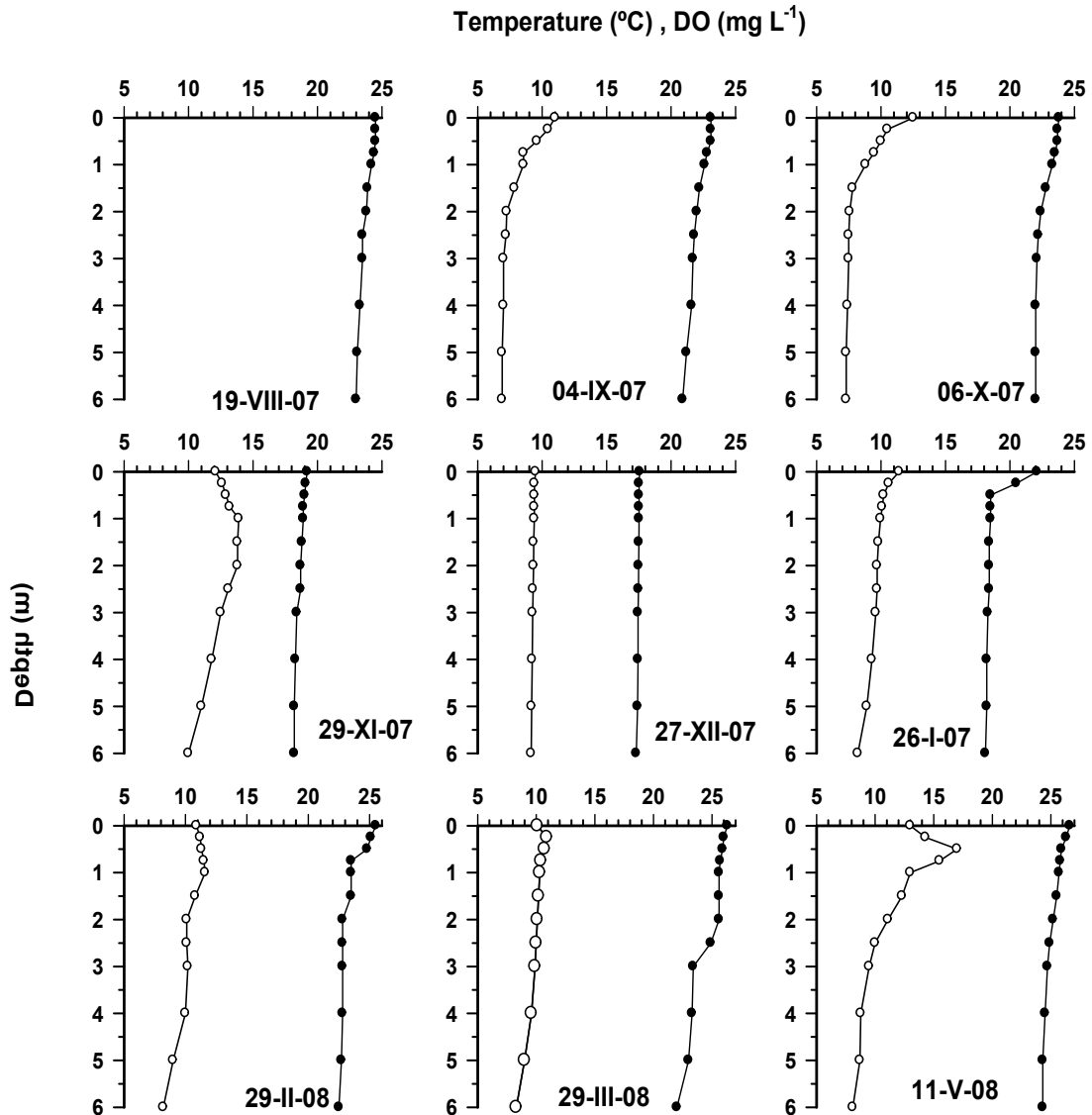


Fig. 7. Depth profiles of water temperature (closed circle) and concentration of dissolved oxygen (DO, open circle) at a central station in Lake Hora-Kilol

The observed higher levels of surface DO in the present study are attributable to greater input of atmospheric oxygen favored by a combination of shallowness of the lake and exposure to wind action. It is also possible that the present higher surface oxygen levels resulted from increased photosynthetic production.

The DO concentration difference between the surface and the deepest depth of measurement never exceeded 5.2 mg L^{-1} and the change in oxygen concentration with every 1 meter increase in depth was generally abrupt in 0-1 m layer and small in the deeper layers of the water column. This is to be expected in light of the greater influence of input from the atmosphere and photosynthetic production on the concentration of oxygen in the near-surface regions. The lower oxygen concentration at the surface observed on some sampling dates seems to be associated with the effect of high temperature on gas solubility and photoinhibition. The depth profiles of oxygen seem to corroborate the absence of deep-seated and marked thermal stratification which the present temperature data suggested.

6.1.4. Inorganic carbon species, Alkalinity, pH and conductivity

Fig. 8 show the temporal variations in the concentration of inorganic carbon species in relation to light-saturated rate of gross photosynthesis and *Chl a* biomass of phytoplankton. The concentration (in meq L^{-1}) of bicarbonate (HCO_3^-) averaged 4.4 and ranged from 3.28 in October, 2007 to 5.6 in May, 2008 while that of carbonate (CO_3^{2-}) averaged 0.243 with a maximum value of 0.445 in October, 2007 and a minimum value of 0.085 meq L^{-1} in August, 2007. CO_2 concentration (in meq L^{-1}) also showed considerable temporal variations varying from 0.003 in October, 2007 to 0.023 in August, 2007. The maximum concentration of CO_3^{2-} coincided with a high value of A_{max} and the lowest value of CO_2 concentration. Although the correlation between CO_2 and HCO_3^- was positive but weak ($r = 0.4317$, $r^2 = 0.1869$ at $p = 0.2129$), these two inorganic carbon species showed a more or less similar pattern of temporal variations, which was the inverse of CO_3^{2-} concentrations, at least during the major rainy season and the dry period. CO_2 declined to its seasonal minimum level in October, 2007 coincident with the seasonal minimum concentrations of HCO_3^-

and seasonal maxima of CO_3^{2-} , phytoplankton biomass and light-saturated rate of gross photosynthesis (A_{max}).

High CO_2 levels in Lake Hora-Kilole were generally associated with low levels of phytoplankton biomass and A_{max} because the correlations between CO_2 and biomass and A_{max} were negative but weak ($r = -0.5865$, $r^2 = 0.3439$ at $p = 0.0747$ and $r = -0.2557$, $r^2 = 0.0654$ at $p = 0.4757$ respectively).

pH of surface water varied (mean=8.92) from 8.5 in November to 9.5 in October, 2007. The seasonal maximum pH value coincided with the highest values of phytoplankton biomass and A_{max} . High pH values are generally associated with increased productivity and/or biomass (Talling and Lemoalle, 1998). According to Maberly (1996) high rates of primary production allow large daytime CO_2 and HCO_3^- withdrawal resulting in a large rise in pH and an increase in CO_3^{2-} , which cannot be used by the algae.

Talling *et al.*, (1973) have also shown for Ethiopian crater lakes including the pre-1989 Hora-Kilole that dense phytoplankton biomass and vigorous photosynthesis and respiration can shift pH upwards through more than one pH units. The present data on photosynthetic activity and biomass of phytoplankton in relation to CO_2 concentration imply considerable removal of carbon dioxide by photosynthesis. Hence, higher photosynthetic consumption of CO_2 probably led to the observed abrupt decline in the available free carbon dioxide and the consequent rise in pH in October, 2007. pH is negatively but moderately correlated with the concentration of CO_2 ($r = -0.5010$, $r^2 = 0.2514$ $p = 0.0080$).

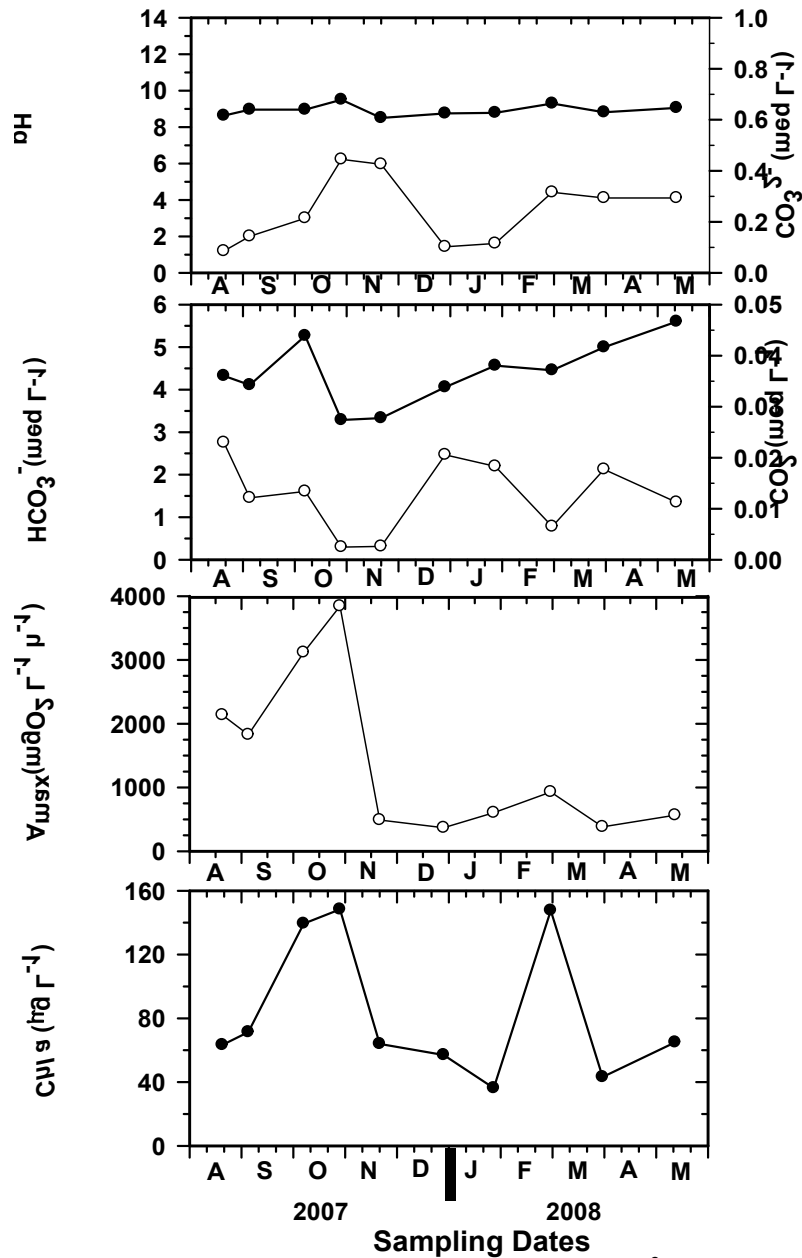


Fig. 8. Temporal variations in the concentrations of CO₃²⁻ (open circle), HCO₃⁻ (closed circle) and CO₂ (open circle) in relation to pH (closed circle), Chl a biomass and light-saturated rate of gross photosynthesis (A_{max}) of phytoplankton at a central station in Hora-Kilole.

Most pH values in the present study lie between those reported by Prosser *et al.* (1968; 9.6) and Brook Lemma (1994; 7.4 - 9.2). The pH of Mojo river (pH= 8) was closer to the pH measured in Dec, 2007, but still less than the mean pH value of the lake water.

Total alkalinity (TA) of the present study varied between 4.2 in October, 2007 and 6.2 in May, 2008. The present TA, values of Lake Hora-Kilole are more than twice higher than the value reported for the post-dilution period (2.4 meq L⁻¹; Zinabu Gebre-Mariam, 1994). The TA values of Lake Hora-Kilole are, however, much lower than those reported for other crater lakes of the same area including Lakes Bishoftu (13.7 to 16.8 meq L⁻¹, Tadesse Ogato, 2007), Babogaya (6.4-12.1; Yeshiemebet Major, 2006) and Hora (13.5- 26; Abebaw Wondie, 2006) although they are still higher than those of the shallow crater lake Kuriftu (2.3-3.1; Zelalem Desalegne, 2007).

The decline in alkalinity from 63.4 meq/L of the pre-dilution period (Talling et al., 1973) to 2.4 meq/L of the early 1990`s in Lake Hora-Kilole (Brook Lemma, 1994; 2003) was obviously related to the dilution of the lake water by Mojo river (Brook Lemma, 1994; 2002; Zinabu Gebre-Mariam, 1994). Alkalinity did not, however, change very much after the studies made by Brook Lemma (1994; 2003) although there does not seem to be a big difference in the volume of the lake between the pre-1989 period and the present time.

The high positive correlation between pH and alkalinity reported for many Ethiopian lakes (Wood and Talling, 1988; Yeshiemebet Major; 2006; Tadesse Ogato, 2007; Zelalem Desalegne, 2007) and saline lakes worldwide (Hammer, 1986) was not observed for Lake Hora-Kilole ($r=0.58$, $p = 0.008$), a situation which was also reported for a large Rift Valley lake, Chamo (Eyasu Shumbulo, 2004).

Conductivity (K_{25} , in $\mu\text{S cm}^{-1}$) measured in composite samples averaged 506 and varied from 476 $\mu\text{S cm}^{-1}$ in August, 2007 to 589 $\mu\text{S cm}^{-1}$ in May, 2008. The present K_{25} values are much lower than that reported for the pre-dilution period (6720 $\mu\text{S cm}^{-1}$) although they are still higher than those recorded by Brook Lemma (1994). Conductivity was positively but moderately correlated

with bicarbonate ($r=0.5553$, $r^2=0.3083$ at $p=0.0957$) and total alkalinity ($r = 0.6476$, $r^2=0.4194$ at $p= 0.0420$).

6.1.5. Inorganic Nutrients

The temporal variations in algal macronutrients in Lake Hora-Kilole are shown in Fig. 9. Nitrate + nitrite-nitrogen concentration ($\mu\text{g/L}$) ranged from a minimum of 17 in October, 2007 to a maximum of 303 in January, 2008 with a mean value of 130.3. The present $\text{NO}_3 + \text{NO}_2\text{-N}$ concentrations of Lake Hora-Kilole are over 5 and 15 times higher than those reported for samples collected after dilution in 1991 and 1992 respectively, (Zinabu Gebre-Mariam, 1994), and about 7-9 times higher than the concentrations recorded before dilution (Wood *et al.*, 1984, Wood and Talling, 1988).

The low $\text{NO}_3 + \text{NO}_2\text{-N}$ concentration of 1991 and 1992 may be related to the relatively low concentrations of $\text{NO}_3 + \text{NO}_2\text{-N}$ in the catchments area, which were again most probably associated with the then low agricultural activities.

The concentration of $\text{NO}_3 + \text{NO}_2\text{-N}$ was low during the major rainy period and increased consistently from its seasonal minimum in October, 2007 to its largest peak in January. The low levels of $\text{NO}_3 + \text{NO}_2\text{-N}$ during the major rainy period seem to have resulted from the phytoplankton biomass which increased continuously towards its seasonal maximum in late October, 2007 leading to rapid uptake and consequent diminution of the concentration of the nutrient. Thereafter, $\text{NO}_3 + \text{NO}_2\text{-N}$ increased continuously to its seasonal maximum value in January, 2008 while phytoplankton biomass declined from its highest peak of October, 2007 to its seasonal minimum in January, 2008. The high $\text{NO}_3 + \text{NO}_2\text{-N}$ levels of the dry period are probably the result of internal loading associated with the frequent and strong wind-induced mixing of this shallow and exposed lake.

It is also possible that the high levels of $\text{NO}_3 + \text{NO}_2\text{-N}$ in the dry season resulted from the diversion of the Mojo river in November–December, 2007, which possibly dumped all the nitrogen it accumulated while flushing the farm lands of the lake's catchments area on its way to the lake. The $\text{NO}_3 + \text{NO}_2\text{-N}$ concentration declined again in February, 2008 coincident with another large peak of phytoplankton biomass. Despite the very high algal biomass accumulated in February, the change in the concentration of $\text{NO}_3 + \text{NO}_2\text{-N}$ was relatively small, which may be related to further input of $\text{NO}_3 + \text{NO}_2\text{-N}$ associated with the small precipitation and the consequent runoff.

Phytoplankton biomass and $\text{NO}_3 + \text{NO}_2\text{-N}$ were negatively and weakly correlated ($r = -0.3208$, $r^2 = 0.1029$ at $p = 0.3662$) while the correlation between $\text{NO}_3 + \text{NO}_2\text{-N}$ and A_{max} was negative but moderate ($r = -0.6831$, $r^2 = 0.4642$ at $p = 0.0301$). The present levels of $\text{NO}_3 + \text{NO}_2\text{-N}$ are quite high considering the fact that $\text{NO}_3\text{-N}$ in Bishoftu crater lakes was rarely detectable (Wood *et al.*, 1984). Concentrations of $\text{NO}_3 + \text{NO}_2\text{-N}$ of the present study are probably indicative of the human-induced environmental degradation to which the lake ecosystem is subjected.

It is well established that nitrogen can become important in waters receiving agricultural runoff, wastewater through runoff, failing on-site septic systems, runoff from animal manure storage areas, and industrial discharges that contain corrosion inhibitors (USEPA, 1991; Welch, 1992).

Ammonium + ammonia-nitrogen ($\text{NH}_4^+ + \text{NH}_3\text{-N}$) concentration varied from 1.7 (October, 2007) to 49.09 $\mu\text{g L}^{-1}$ (March, 2008) respectively, with generally low levels during the dry and minor rainy periods. The highest value of $\text{NH}_4^+ + \text{NH}_3\text{-N}$ concentration corresponded to one of the peaks of phytoplankton biomass, which occurred during the major rainy period while the lowest coincided with the second lowest phytoplankton biomass observed in March, 2008. $\text{NH}_4^+ + \text{NH}_3\text{-N}$ was positively but moderately correlated with phytoplankton biomass ($r = 0.562$, $r^2 = 0.3156$ at $p = 0.0910$) and A_{max} ($r = 0.6565$, $r^2 = 0.4310$ at $p = 0.0392$).

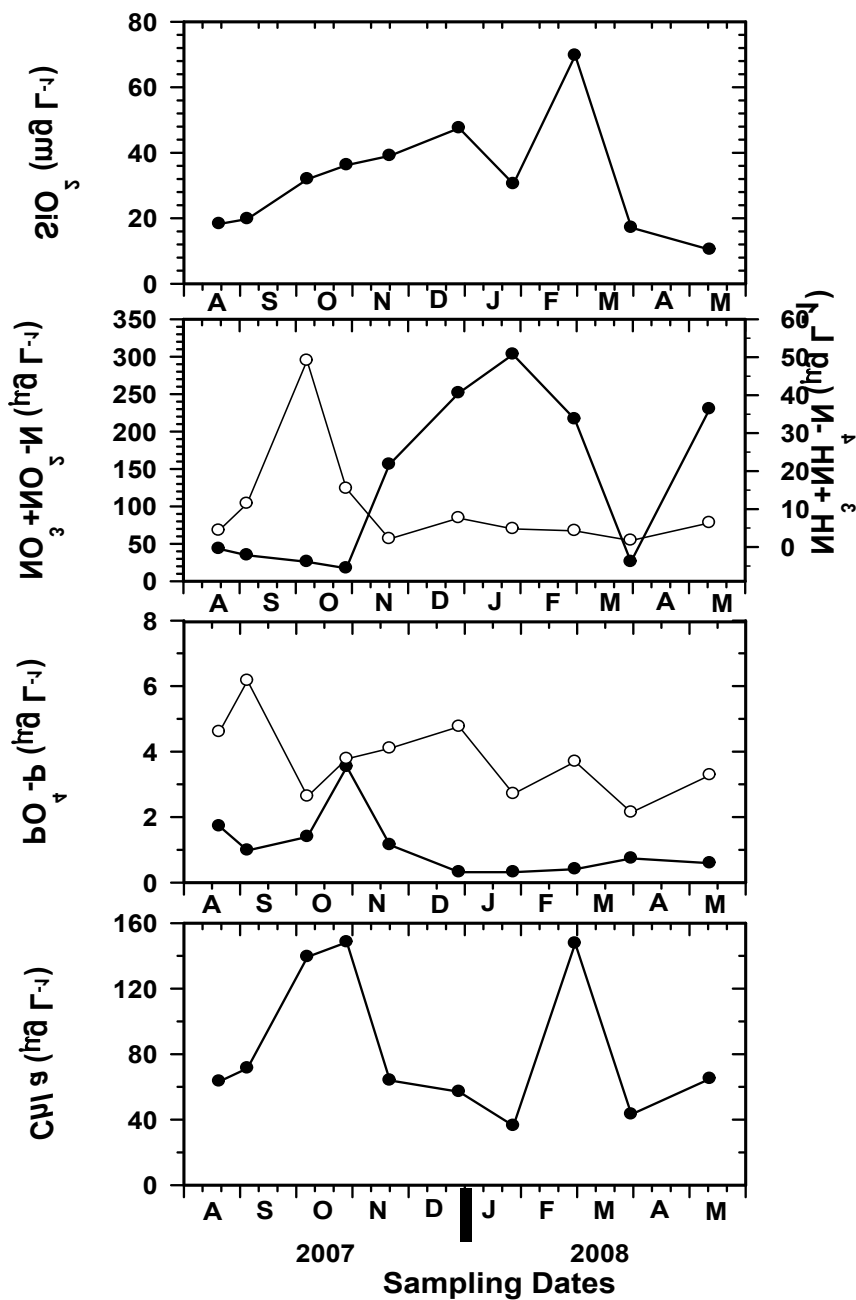


Fig. 9. Temporal variations in the concentrations of silica, nitrate + nitrite-nitrogen ($\text{NO}_3 + \text{NO}_2\text{-N}$, closed circle), ammonia + ammonium-nitrogen ($\text{NH}_3 + \text{NH}_4\text{-N}$, open circle) and, Soluble Reactive Phosphorus (SRP, closed circle) and Total Phosphorus (TP, open circle) in relation to phytoplankton biomass measured as *Chl a* at a central station in Hora-Kilole..

Soluble Reactive Phosphate-phosphorus (SRP-P, in $\mu\text{g L}^{-1}$) averaged $1.1 \mu\text{g L}^{-1}$ and varied between a minimum value of 0.33 in December, 2007 and January,

2008 to a maximum of $3.5 \mu\text{g L}^{-1}$ in October, 2007. The minimum SRP coincided with the lowest abundance of phytoplankton and low phytoplankton biomass in December, 2007. The seasonal maximum value of SRP corresponded to the largest peak of phytoplankton biomass and to one of the two large peaks of abundance of phytoplankton in late October, 2007. SRP-P of lake Hora-Kilole was positively and moderately correlated with phytoplankton biomass ($r = 0.521$, $r^2 = 0.2717$ at $p = 0.1223$).

The concentration of SRP measured in December, 2008 was higher in the river than in the Lake (0.493 and $0.329 \mu\text{g/L}$ respectively), whereas TP was higher in the lake than in the river (4.77 and $2.38 \mu\text{g/L}$ respectively). The smaller SRP in the lake may be the result of uptake by the presumably more concentrated phytoplankton in the lake water than in the river water and greater input of SRP into the river from the drainage basin.

The concentrations of SRP-P obtained in this study are much closer to the value recorded in 1991 than that measured in 1992 (4 and $27 \mu\text{g L}^{-1}$ respectively) by Zinabu Gebre-Mariam (1994). The concentrations of SRP reported by Wood *et al.* (1984) for Hora-Kilole of the pre-1989 period were high (4.8 - 5.5 mg L^{-1}). It can be seen that the level of phosphorus has generally been declining through time and may have been limiting the growth of phytoplankton in Lake Hora-Kilole. Because of its high reactivity, phosphorus may be lost out of the water column of Hora-Kilole through precipitation or adsorption onto inorganic particles which are continuously suspended as a result of deep-mixing. Phosphorus was identified as the primary nutrient limiting phytoplankton production in experimental lakes of the temperate region (Schindler, 1977) and concentration of phytoplankton biomass in Lake Sonachi, Kenya (Melack *et al.*, 1982; Kalff, 1983).

The present concentrations of SRP-P in Lake Hora-Kilole are much lower than those reported for the other Bishoftu crater lakes Like Lakes Bishoftu (17 - 45

$\mu\text{g L}^{-1}$, Taddese Ogato, 2007) and Babogaya ($18 \mu\text{g L}^{-1}$, Yeshiembet Major, 2006).

Like SRP, total phosphorus (TP) exhibited temporal variations with a mean value of $3.79 \mu\text{g L}^{-1}$. The seasonal maximum and minimum concentrations ($\mu\text{g L}^{-1}$) of TP were 6.15 and 2.13 recorded in September, 2007 and March, 2007 respectively. The maximum value was recorded during the major rainy season at the time of moderate algal phytoplankton biomass. The correlation between phytoplankton biomass and TP was negative and poor ($r = -0.0466$, $r^2 = 0.0022$ at $p = 0.8983$).

Lake Hora-Kilole generally exhibited high ratios (mean = 28.6:1) of $\text{NO}_3 + \text{NO}_2\text{-N}$ to $\text{NH}_4^+ + \text{NH}_3\text{-N}$. $\text{NH}_4^+ + \text{NH}_3\text{-N}$ concentrations are much lower than nitrate-nitrogen concentrations in most productive lakes after periods of circulation (Wetzel, 2001) with consequent high ratios. The high ratios of these inorganic nitrogen species in Lake Hora-Kilole seems to be related to the occurrence of deep-mixing in the lake that leads to the oxygenation of the entire water column and the subsequent oxidation of the reduced forms of nitrogen. According to Kalff (2002), the concentration of $\text{NH}_4^+ + \text{NH}_3\text{-N}$ in well oxygenated water is usually low relative to other forms of inorganic nitrogen due to its ability to be readily oxidized and the rapid and preferential uptake by phytoplankton (McCarthy, 1980). In studies on the uptake of nutrients by freshwater phytoplankton, Prochazkova *et al.* (1970) also observed phytoplankton preference for $\text{NH}_4^+\text{-N}$ over $\text{NO}_3\text{-N}$ even when the concentration of $\text{NO}_3\text{-N}$ exceeds that of $\text{NH}_4^+\text{-N}$ by six-fold.

The range of ambient or cellular N:P ratios have been used to define the transition between N and P limitation for algae (Sakamoto, 1966). If ambient N:P ratios (molar) are greater than 15-17:1, then P can be assumed to be in limiting supply. If the ambient N:P ratio is less than 9-10:1, then N can be assumed to be in limiting supply and in lakes with intermediate ratio, algal growth is nearly

balanced with both N and P, and the yield varies with an increase in either nutrient.

The ratio of TN to TP varied from 16:1 in October, 2007 to 251 $\mu\text{mol/L}$ in January, 2008 (See App 3). The ratio was in excess of 15-17:1 in all months except October, 2007. Generally the high TN:TP coincided with the low *Chl-a* concentrations probably indicating P limitation of algal growth in Lake Hora-Kilole. Nitrogen is generally regarded as the nutrient that plays the role of a limiting nutrient in the tropics (Talling and Lemoalle, 1998) due to its greater internal loss through denitrification, which is favored by the high lake bottom temperatures of the tropical region (Lewis, 1990). However, data that suggest the likelihood of both nitrogen-limitation (Talling and Talling, 1965; Lewis, 1996; Elizabeth Kebede and Willen, 1998; Talling and Lemoalle, 1998; Eyasu Shumbulo, 2004) and phosphorus-limitation (Kalf, 1983) of phytoplankton in East African lakes have been generated.

Unlike the combined inorganic nitrogen and phosphorus, molybdate reactive silica was found at concentrations above 10 mg l^{-1} throughout the study period as it is usually in East African lakes including those in Ethiopia (Talling and Talling, 1965; Wood and Talling, 1988; Talling and Lemoalle, 1998). Dissolved silica (Molybdate reactive silica, in mg L^{-1}) ranged from 10.4 in May, 2008 to 69.7 mg L^{-1} in February, 2008 with a mean concentration of 32 mg L^{-1} . The concentration of soluble reactive silica (SRSi) increased consistently from a relatively low value in August (18.27 mg L^{-1}) to a small peak in December (47.5 mg L^{-1}) before it declined in January, 2008 and then increased to its highest peak in February, 2008. The sharp drop in the concentration of SRSi which occurred in March, 2008 was followed by further decline to the seasonal minimum concentration in May 2008. The low levels of SRSi in January and May, 2008 coincided with peaks of contribution of diatoms to the total abundance of phytoplankton (see Fig.10).

SRSi showed positive but moderate correlation with phytoplankton biomass ($r=0.526$, $r^2=0.227$ at $p=0.01181$). Because of the moderate contribution of diatoms to the total abundance of phytoplankton relative to other groups of phytoplankton (blue-greens and dinoflagellates) during the present study period, internal loading associated with wind-induced mixing and external loading through runoff and Mojo River may be of overriding importance in determining the temporal variations in SRSi.

The mean level of silica concentration (32 mg L^{-1}) of the present study is the same to the value reported by Prosser *et al.* (1968) although it is much higher than the values recorded in 1991 and 1992 by Zinabu Gebre-Mariam (1994). The increase in SRSi from levels of 1991 and 1992 may have resulted from the weathering of silicate minerals in the catchments area and the subsequent transport of dissolved silica through runoff and Mojo River in addition to weathering of the bed rock. Silica values exceeding 100 mg L^{-1} have been observed in an Ethiopian alkaline saline crater lake, Lake Chitu (Wood and Talling, 1988; Elizabeth Kebede *et al.*, 1994). Measurements of silica concentration in samples collected in Dec, 2007 from both the lake water and Mojo River showed silica concentration of Mojo River which was nearly twice as much as that in the lake water, suggesting the possibly high contribution of the river water to elevated silica levels in the lake water.

6.2. Biological parameters

6.2.1. Seasonal dominance of algal groups and their Species composition.

The phytoplankton community of Lake Hora-Kilole exhibited temporal changes in both species composition and dominance of algal groups. The total abundance of phytoplankton peaked during the major and minor rainy periods when the largest peaks of *Chl a* biomass of phytoplankton were also observed. The relative contribution of phytoplankton taxa to the total abundance of

phytoplankton are given in Appendix 4 and 5 and their temporal changes shown in Fig. 10. List of major species of phytoplankton identified in samples collected during the study period is also given in Appendix 6.

Dinoflagellates (Dinophyceae) and blue-green algae (cyanobacteria, cyanophyceae) were the most important contributors to the total abundance of phytoplankton. Dinoflagellates dominated the phytoplankton community during the major rainy period (August-October, 2007) with contributions ranging from 62 to 90% of the total abundance of phytoplankton. The period of dominance of dinoflagellates coincided with large peaks of *Chl a* biomass of phytoplankton in October, 2007. The dinoflagellates remained at low levels of abundance during the dry period and increased to a small peak in May, 2008. The abundance of dinoflagellates was largely constituted by *Peridinium gatunense*.

The blue-green algae, which made relatively minor contributions to total phytoplankton abundance during the major rainy period, dominated the phytoplankton community during the period extending from January to March, 2008, with their peak of abundance coinciding with one of the two large peaks of *Chl a* biomass of phytoplankton in February, 2008. During the period of their dominance, the blue-green algae accounted for 50 to 83% of the total phytoplankton abundance. Among the blue-greens, *Cylindrospermopsis curvispora*, *Planktothrix cf. agardhii* and *Rhaphidiopsis curvata* were the most important in terms of percentage contribution to the total phytoplankton abundance.

The other algal groups which made considerable contributions to phytoplankton abundance were diatoms, euglenoids and green algae, with their peaks of abundance occurring during the dry period when the two major algal groups were less important and *Chl a* biomass of phytoplankton was relatively

low. Although green algae were less abundant, their representation in the phytoplankton community in terms of number of species was comparable to that of blue-green algae. In qualitative terms diatoms and euglenoids (represented solely by *Phacus longicauda*) were poorly represented in the phytoplankton community of Lake Hora-Kilole although their contribution to the total phytoplankton abundance was considerable during the dry period. The green algae were largely constituted by desmids of the genera *Pediastrum*, *Scenedesmus* and *Staurastrum*. The species diversity of phytoplankton in Lake Hora-Kilole was low, a situation which was also reported for other crater lakes of the same region including Lakes Babogaya (Yeshiemebet Major, 2006), Bishoftu (Tadesse Ogato, 2007) and Koriftu (Zelalem Desalegne, 2007).

The dominance of dinoflagellates during the major rainy period was probably associated with the prevalence of relatively calm water column conditions as dinoflagellates are inhibited by turbulence which impedes cell division and disrupts cells (Pollinger, 1988; Lewis and Hallett, 1997). Dominance of dinoflagellates is very common in freshwater lakes (Pollinger, 198) including Lake Babogaya (Yeshiemebet Major, 2006). The success of these organisms is attributed to such adaptive features as luxury consumption of phosphorus (Serruya and Berman, 1975) and nitrogen (Chapman and Pfiester, 1995), vertical migration which maximizes nutrient uptake from nutrient-deplete hypolimnetic waters (James *et al.*, 1992) and reduces sinking losses (Levandowsky and Kaneta, 1987). The sharp drop in dinoflagellate abundance in November-December and their replacement by cyanobacteria seems to be associated with increased wind-induced turbulence and depletion of available phosphorus.

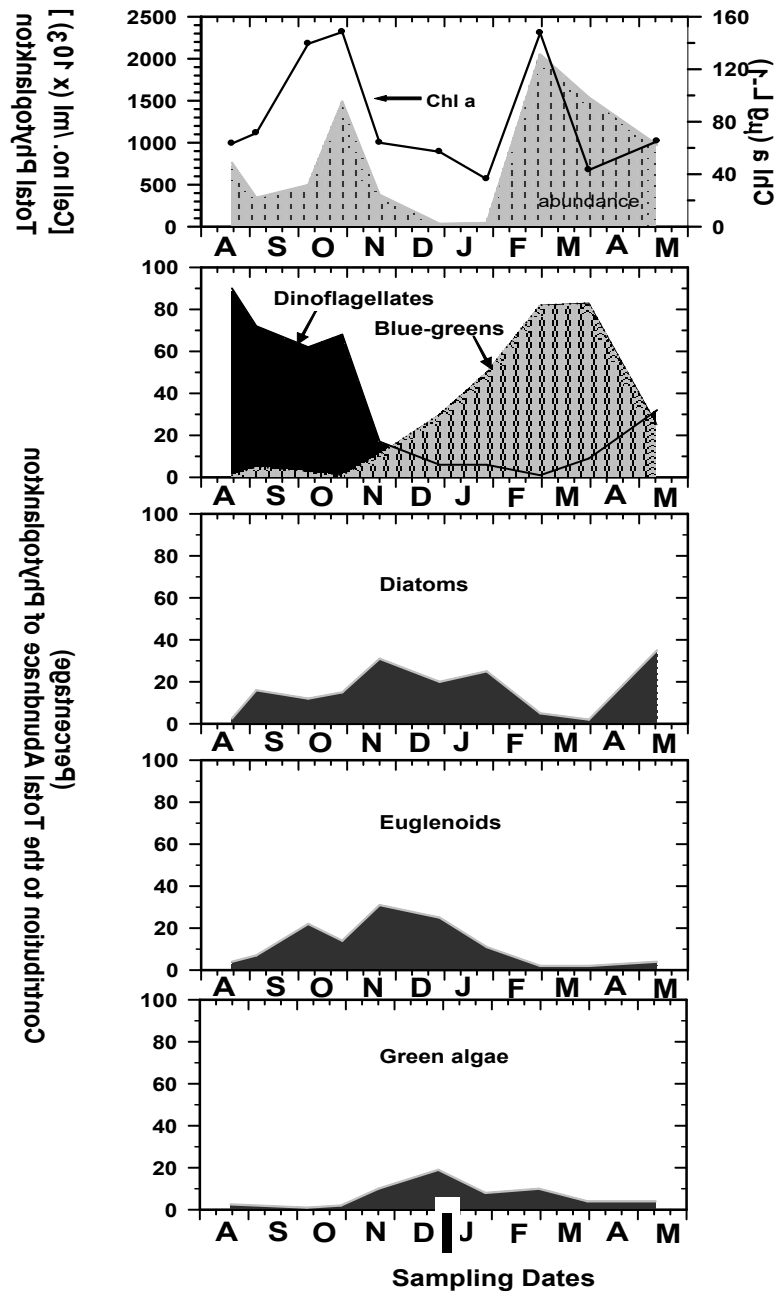


Fig. 10. Temporal variations in the contribution of different algal groups to the total abundance of phytoplankton in relation to total phytoplankton biomass measured as chlorophyll a.

The dominance of cyanobacteria during the dry period coincided with turbulent water column conditions and the consequent deterioration of the underwater light climate. Cyanobacterial dominance is a common phenomenon in lakes and reservoirs including those found in Ethiopia (see Adane Sirage, 2006; Hadgembes Tesfay, 2007; Tadesse Ogato, 2007). Although a number of water column conditions are known to lead to the dominance of cyanobacteria, low light (Smith, 1986), high temperature (Shapiro, 1990), phosphorus storing strategy (Peterson, *et al.*, 1993), ability to minimize grazing (Hanley, 1987), buoyancy (Reynolds, 1987) or low euphotic to mixing depth ratio (Jensen, *et al.*, 1994) seem to have relevance to the situation in Lake Kora-Kilole during the minor rainy period.

Deep mixing in Lake Hora-Kilole can affect the blue-green algae only temporarily since they can regain their vertical position quickly owing to their effective buoyancy mechanism associated with gas vacuoles (Reynolds, 1997).

Cyanobacteria built up their populations to a peak in February, 2008 despite the largest peak of abundance of zooplankton particularly rotifers and the fact that temporal dynamics of phytoplankton abundance and biomass are known to be controlled by loss processes including grazing by zooplankton. It is possible that the filamentous cyanobacteria of the present study lake were less susceptible to grazing due to adaptive features including size of algal units which were presumably not manageable by zooplankton. Carney and Elser (1990) have demonstrated the weak effect of grazers on large-sized, cyanobacteria-dominated algal assemblages in eutrophic lakes. Although rotifers particularly *Brachionus* species are known to have considerable effect on phytoplankton owing to their resistance to the toxicity of blue-greens (Gonzalez, 2000), the impact of zooplankton on phytoplankton did not seem to be significant in Lake Hora-Kilole at the time of cyanobacterial dominance.

The size-fractionation experiments conducted by Girum Tamire (2006) in Lake Kuriftu, in which colonial and filamentous cyanobacteria had quantitative importance, also seemed to indicate the lower contribution of grazers to the removal of phytoplankton. In eutrophic crater lakes like Hora-Kilole and Koriftu, colonial and filamentous blue-green algae can dominate and weaken the ability of crustacean zooplankton to graze on them. The rare occurrence of cladocerans and common occurrence of large-sized filamentous blue-green algae, which are less edible and sometimes toxic to cladocerans (De Bernardi and Guissani, 1990), in Lake Hora-Kilole may be one reason for the concurrence of seasonal maxima of abundance of phytoplankton (filamentous blue green algae), total zooplankton and rotifers in February, 2008.

Inspection of data generated at different times during the last five decades or so showed the prevalence of long-term changes in the species composition and dominance of algal groups. In the pre-1989 period, the phytoplankton community of Hora-Kilole was dominated by the cyanobacterial specie of the genera *Chroococcus* and *Spirulina*.

The study made by Brook Lemma (1994) showed a phytoplankton community characterized by increased diversity, less qualitative and quantitative importance of cyanobacteria and dominance by species of *Peridinium* and *Cosmarium*. The results of the present study, however, showed the dominance (in abundance) of dinoflagellates and cyanobacteria and the greater qualitative importance of diatoms and green algae.

Species Diversity of Phytoplankton

Appendix 5 shows seasonal changes in the species diversity of phytoplankton in Lake Hor-Kilole estimated by The Shannon-Weaver diversity index. The highest diversity was recorded in May, 2008 (3.1 bits/individual) and the lowest (1.3 bits/individual) was recorded in January, 2008. The entire water

column remained isothermal or nearly so in Lake Hora-Kilole throughout the study period (see Fig. 4). During the main rainy season, August-October, 2007, the Dinoflagellate *Peridinium* rapidly built up its population and became dominant during which the diversity was about 2.5 bits/individual. Diversity index increased to about three bits/individual in November, 2007 and then varied irregularly before it reached its lowest value (1.3 bits/individual) in March, 2008.

The seasonal variation in the number of species or richness was reflected on the diversity index. The diversity index for lake Hora-Kilole varied within a narrow range (1.3-3.11 bits/individual; mean= 2.25) and was generally higher than 1.3. A high value of the diversity index was found for November-December when diatoms and the species-rich green algae had quantitative importance while the low value of the index was associated with a low number of taxa. The leading cyanobacterium *Planktothrix cf. agardhii* accounted for about 77% of the total phytoplankton abundance when the diversity index was 1.3. On the other hand, diversity index was high (3.033 and 3.11 bits/individual) in November, 2007 and May, 2008 and was associated with relatively large number of taxa.

Lake Hora-Kilole has exhibited gradual increase in the diversity of phytoplankton with time. This may be attributed to an increase in the complexity of the water column. Fogg (1965) postulated a progressive increase in the number of niches available to phytoplankton as chemical complexity of the lake water increases. Secretion and excretion of organic substances by a succession of species are assumed to cause this presumed increase in chemical complexity (Moss, 1973). More importantly, as more organic compounds become available after rainy season, selection of participant species with increasingly complex nutrient requirements is presumed. Exact nutritional needs of almost all common phytoplankton species are not yet known, but the blue-green algae in general, though tending to grow in dry season, often have

purely inorganic nutritional needs (Moss, 1973). Egborge (1974) also reported, temperature appeared to be an important factor in the seasonal periodicity of phytoplankton communities which show greater diversity during the period of higher temperature.

6.2.2. Total and Size-fractionated Phytoplankton Biomass

The temporal variations in *Chl a* and percentage contributions of three size groups to the total phytoplankton biomass in relation to total abundance and biomass of phytoplankton and zooplankton abundance are shown in Fig. 11. Total phytoplankton biomass peaked in October, 2007 and February, 2008 coinciding with the highest peaks of total phytoplankton abundance. The first peak of *Chl a* coincided with the dominance of dinoflagellates and seasonal maximum concentration of soluble reactive phosphate, while the second one occurred at the time of cyanobacterial dominance and the highest peak of zooplankton abundance.

Phytoplankton biomass was positively but moderately correlated with the abundance of phytoplankton ($r=0.5373$, $r^2=0.2887$ at $p=0.1092$) and zooplankton ($r=0.5284$, $r^2=0.2792$ at $p=0.1364$). The poor correlation between phytoplankton biomass measured as *Chl a* and abundance of phytoplankton is attributable to differences among phytoplankton in cell size and chlorophyll a content per cell (Reynolds, 1984). Phytoplankton biomass was positively but moderately correlated with SRSi ($r=0.5263$, $r^2=0.227$ at $p=0.1181$), SRP ($r=0.5212$, $r^2=0.3439$ at $p=0.07473$) and ammonium+ ammonia-nitrogen ($r=0.5617$, $r^2=0.3156$ at $p=0.0910$). Phytoplankton biomass was also negatively and moderately correlated with CO₂ concentration ($r= -0.5865$, $r^2=0.3439$ at $p=0.0747$). (See Appendix 10).

The mean total phytoplankton biomass ($83.5 \mu\text{g L}^{-1}$) recorded in the present study is remarkably different from those recorded in 1991 ($35 \mu\text{g L}^{-1}$) and 1992 ($30 \mu\text{g L}^{-1}$) for the same lake by Zinabu Gebre-Mariam (1994). The observed increase in phytoplankton biomass seems to have resulted from the intensified human activities around the lake and the consequent increased input of algal nutrients. The mean phytoplankton biomass of Lake Hora-Kilole is considerably higher than biomass value reported for other lakes of the same region (Lake Bishoftu- $30 \mu\text{g L}^{-1}$, Taddese Ogato, 2007); Lake Hora- $25 \mu\text{g L}^{-1}$, Zinabu-Gebre Mariam, 1994: Lake Babogaya- $29\text{-}33 \mu\text{g L}^{-1}$, Yeshiemebet Major, 2006).

The *Chl a* values of the $> 20 \mu\text{m}$ (netplankton) and $2\text{-}20 \mu\text{m}$ (nanoplankton) fractions were much higher than those of the $< 2 \mu\text{m}$ fraction (picoplankton) as they usually are in eutrophic waters owing to their inability to capitalize on improved conditions that occur from time to time. The consistently lower biomass of the picoplankton is to be expected as the picoplanktons are commonly dominant in oligotrophic lakes (Stockner and Antia, 1986; Stockner, 1991). Among the three size- groups, the netplankton was the most important contributor to total phytoplankton biomass with its biomass and percentage contributions to total phytoplankton biomass ranging from 13.21 mg m^{-3} and 32 % to 132.06 mg m^{-3} and 95 % respectively.

Dominance of netplankton in biomass is not uncommon and has been reported for many water bodies including Lake Chamo (Girma Tilahun, 2006) and a tropical reservoir, Barra Bonita in Brazil (Calijuri and Dos Santos, 2001). The *Chl a* biomass of the nanoplankton varied from nearly 0 to 88.89 mg m^{-3} with its contributions to total phytoplankton biomass varying from almost 0 to 64%, while the picoplankton whose biomass varied between 2.78 and $11.57 \text{ mg Chl a m}^{-3}$ had percentage contributions that ranged from 4 to 28 %. Peaks of nanoplankton biomass coincided with relatively low biomass values of the netplankton and abundance of total phytoplankton suggesting that the

nanoplankton were largely constituted by diatoms and green algae, which are known to be good quality food for zooplankton (Ahlgren *et al.* 1990; Ahlgren, 1993).

The biomass of netplankton varied temporally exhibiting a seasonal pattern which was more or less similar to that of total *Chl a*, with seasonal peaks occurring in October, 2007 and February, 2008 coincident with those of total *Chl a* and phytoplankton abundance. The correlation between the netplankton biomass and total phytoplankton biomass was positive and strong ($r=0.8272$, $r^2=0.6842$ at $p=0.0031$) with the variations in the former accounting for nearly 68% of the variations in the latter. This indicates that the temporal variations in phytoplankton biomass in Lake Hora-Kilole are largely due to changes in factors that determine the biomass accumulations of the netplankton. The variation in time of nanoplankton biomass was peak nearly the inverse of the netplankton biomass. The biomass of the nanoplankton peaked when total phytoplankton biomass and netplankton biomass and abundance of zooplankton were relatively low. The decline in nanoplankton biomass in February, 2008 seems to have resulted from increased grazing pressure as the seasonal maximum of zooplankton abundance occurred in the same month. Furthermore, grazing often suppresses populations of nanoplankton leaving the netplankton largely unaffected (Reynolds, 1984).

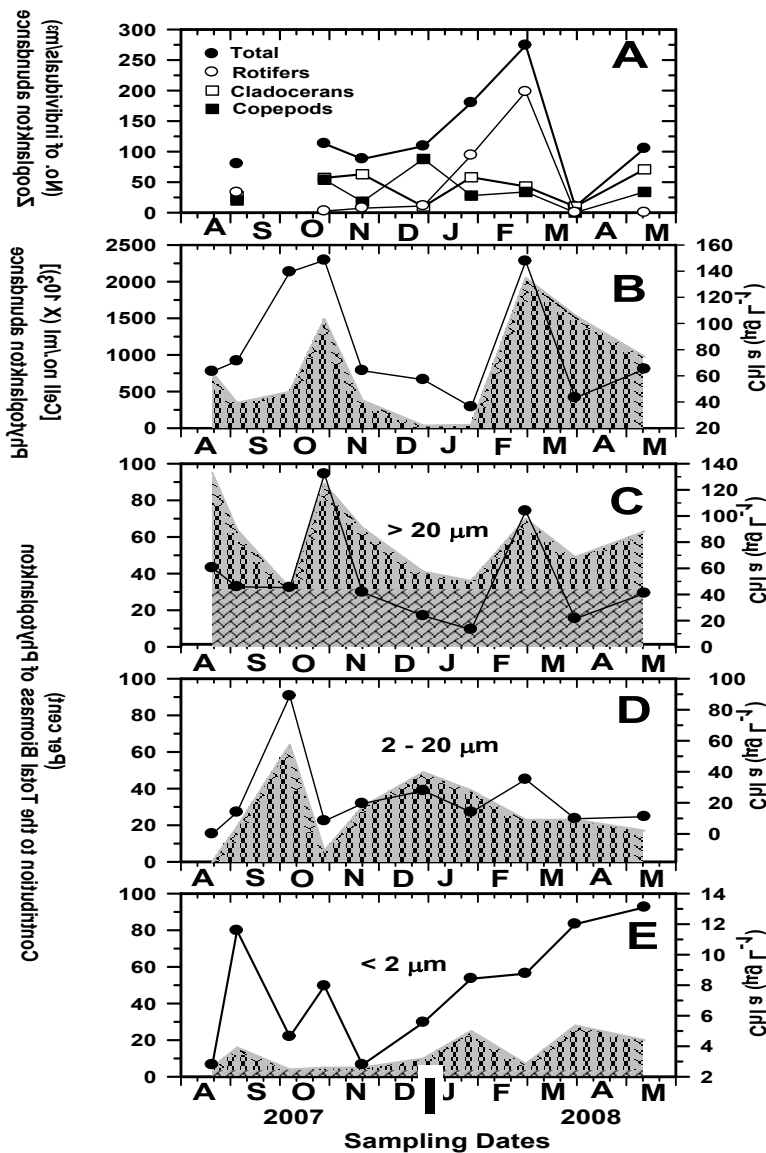


Fig. 11. Temporal variations in the biomass (line plot) and percentage contribution (area plot) of different size groups (C, D, E) to the total phytoplankton biomass measured as Chl *a* in relation to total abundance of phytoplankton (B, area plot) and total biomass (B, line plot) and zooplankton abundance (A) at a central station in Lake Hora-Kilole.

Temporal variations in the *Chl a* in Lake Hora-Kilole were observed in the present study. It is generally believed that tropical waters exhibit limited temporal variability in their biomass and primary productivity owing to the great reduction in variation imposed by marked seasonality in temperature and irradiance in the tropical regions (Lewis, 2000). Because the extent of the

seasonality in phytoplankton biomass in a lake can not be easily perceived from absolute values of *Chl a*, Melack (1979a) used coefficient of variation (CV, standard deviation/mean) as an index for determining extent of temporal variability in biomass and rates of production. Lake Hora-Kiloe, with a CV of 52.4 % for phytoplankton biomass, falls under Pattern A of Melack (1979a), with most tropical lakes including Lakes Chamo (Eyasu Shumbulo, 2004), the Kenyan freshwater Lakes Naivasha, Crater Lake and Oloidien (Melack, 1979b), Lake Chad in Chad (Lemoalle, 1975) and Victoria in Uganda-Kenya-Tanzania (Talling, 1965) in which biomass varied in relation to dry-wet seasons or vertical mixing/stratification or increased river discharge or a combination of two or more of these and the associated changes in turbidity and levels of nutrients (Melack, 1979a).

6.2.3. Photosynthetic productivity of phytoplankton

6.2.3.1. Depth-profiles of Gross Photosynthesis

Fig. 12. shows depth-profiles of gross photosynthetic production determined for all sampling periods. The depth distributions of rates of gross photosynthesis were of the typical pattern for phytoplankton with or without photo-inhibition at the surface. During the dry and minor rainy periods, the depth profiles were vertically compressed owing to increased turbidity associated with wind-induced vertical mixing of the lake, a depth-distribution pattern which is typical of turbid systems such as Lake Ziway (Girma Tilahun, 2006) and the man-made lakes in Ethiopia, Legedadi (Adane Sirage, 2006) and Koka (Hadjembes Tesfay, 2007) reservoirs in which resuspension of inorganic particles from the sediment by frequent mixing or loading from the catchments through runoff reduce light penetration (Dokulil, 1994)

Depressed photosynthetic rates at the lake's surface were generally observed during the dry and minor rainy periods. During the major rainy period and in the early part of the dry period, surface maxima of rates of gross photosynthesis were observed, which were probably associated with cloud cover, which is frequent during this period and tends to reduce the irradiance reaching the lake's surface. Maximum rates of gross photosynthesis below the surface, mostly at 0.25 m depth, were generally observed during the second half of the dry period (January-February) and the minor rainy period.

Reduced rate of gross photosynthesis of phytoplankton at a lake's surface is a common phenomenon in water bodies and has been reported for the other Bishoftu crater lakes (Abebaw Wondie, 2006; Yeshiemebet Major, 2006; Tadesse Ogato, 2007; Zelalem Desalegne, 2007). Photoinhibition is related to excess photons that become available when ambient light exceeds physiological saturation (Long *et al*, 1994; Falkowski and Raven, 1997). The decrease in photosynthetic rates results from photo-oxidative disruption of pigment systems (Amha Belay and Fogg, 1978; Falkowski and Raven, 1997), inactivation of photosynthetic enzymes (Steemann-Nielsen, 1962; Steemann-Nielsen and Jørgensen, 1962) and increased photorespiration (Harris and Lott, 1973; Osmond, 1981).

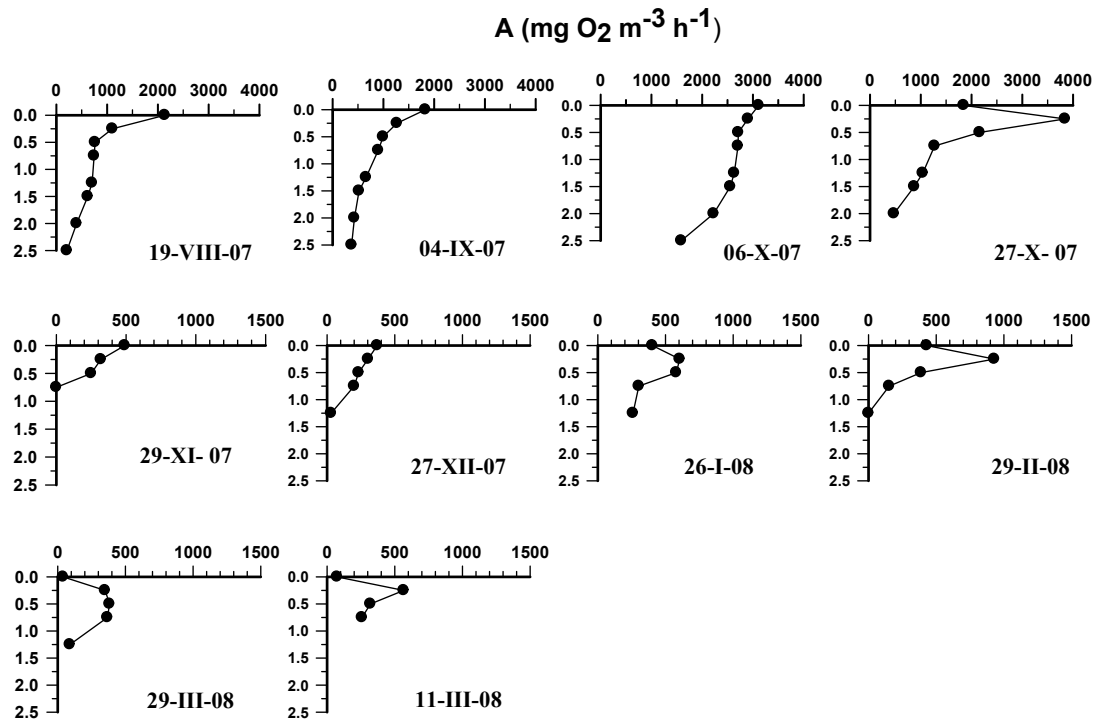


Fig. 12. Depth profiles of gross photosynthesis per unit water volume (mg O₂ m⁻³ h⁻¹) at a central station in Lake Hora-Kilole.

6.2.3.2. Photosynthetic parameters

The seasonal variation in light-saturated rate of photosynthesis (A_{max}), specific rates of gross photosynthesis at light-saturation [P_{max} , mg O₂ (mg Chl a)⁻¹ h⁻¹], and hourly rates of integral photosynthesis (ΣA , g O₂ m⁻²h⁻¹) in relation to phytoplankton biomass (B) are shown in Fig.13.

Temporal changes in light-saturated rates of photosynthesis (A_{max}) with a seasonal minimum value of 370 mg O₂ (~115.5 mg C) m⁻³ h⁻¹ in December, 2007 corresponding to one of the low biomass values and with a maximum value of 3843 mg O₂ (~1199 mg C) m⁻³ h⁻¹ in October, 2008, which coincided with the seasonal maximum *Chl a* concentration, were observed.

Most of the high values of A_{\max} were observed during the major rainy season, when photosynthetic capacity and phytoplankton biomass were also high. The congruence of seasonal changes of photosynthetic productivity with those of rainfall records has been regarded as being suggestive of a causal connection between rainfall and productivity (Khan and Ejike, 1984). Mellack (1979a) also attributed rapid phytoplankton growth and the consequent high photosynthetic rates in tropical waters to increased supply of nutrients as a result of rainfall. In Lake Hora-Kilole, ambient concentrations of nutrients (except ammonia + ammonium-nitrogen) were generally low during the major rainy period.

The present A_{\max} values for Lake Hora-Kilole are remarkably lower than that reported by Talling *et al.* (1973) for the same lake (11190 mg O₂ m⁻³ h⁻¹) although they are still much higher than that recorded by Brook Lemma (1994) after the diversion of Mojo River (115 mg O₂ m⁻³ h⁻¹). The high A_{\max} values (> 1800) recorded for Lake Hora-Kilole are within the ranges reported (in mg O₂ m⁻³ h⁻¹) for Lake Ziway in Ethiopia (1640-4670; Girma Tilahun, 1988), Lake George in Uganda (1900-600; Ganf, 1975) and Lake Simbi, in Kenya (1950-12900, Melack, 1979c). The lower values are, however, broadly similar to those reported for many Ethiopian Rift Valley and Crater lakes (Amha Belay and Wood, 1984; Demeke Kifle and Amha Belay, 1990; Eyasu Shumbulo, 2004; Tadesse Ogato, 2007).

A_{\max} of Lake Hora-Kilole was positively and moderately correlated with phytoplankton biomass ($r=0.6951$, $r^2=0.4832$ at $p=0.0256$) and photosynthetic capacity ($r=0.7742$, $r^2=9.5594$ at $p=0.0086$). Similarly high positive correlations between A_{\max} and phytoplankton biomass have also been reported for other lakes of the Bishoftu group (Yeshiemebet Major, 2006; Tadesse Ogato, 2007; Zelalem Desalegne, 2007). However, a phytoplankton biomass of about 139 mg *Chl a* m⁻³ was associated with an A_{\max} value of over 3000 mg O₂ m⁻³ h⁻¹ while a larger biomass (147 mg *Chl a* m⁻³) was associated with A_{\max} only about 900 mg

$O_2 \text{ m}^{-3} \text{ h}^{-1}$. This lack of correspondence between biomass and A_{max} was also reported for many other Ethiopian lakes including Lake Awassa (Demeke Kifle and Amha Belay, 1990), Lake Chamo (Eyasu Shumbulo, 2004), Lake Arenguade (Talling *et al.*, 1973) and Lake Babogaya (Yeshiemebet Major, 2007). According to Talling (1965) and Hammer (1981), high A_{max} values associated with low algal biomass are the result of high specific rates of gross photosynthesis. The fairly strong correlation between A_{max} and P_{max} ($r=0.7742$, $r^2=0.5594$ at $p=0.0086$) found in this study may provide an explanation for the association of high light-saturated rates with low algal biomass observed for Lake Hora-Kilole.

The correlation of A_{max} with phosphate was positive and strong ($r=0.8543$, $r^2=0.73$ at $p=0.0016$) and with ammonia + ammonium-nitrogen, it was positive but moderate ($r=0.6565$, $r^2=0.43$ at $p=0.0392$) while its correlation with nitrate + nitrite-nitrogen was negative but moderate ($r= -0.6813$, $r^2=0.464$ at $p=0.0301$). Talling and Lemoalle (1998) have shown for tropical lakes that the wide range of the saturation parameter per unit water volume, A_{max} , is a function of primarily variable biomass concentration, B (mg m^{-3}) and photosynthetic capacity, the light-saturated biomass-specific rate, P_{max} , $\text{mg O}_2 (\text{mg chl a})^{-1} \text{ h}^{-1}$. Although B and P_{max} are important in determining the temporal variations in A_{max} , nutrients may have a regulatory role as their present correlations with A_{max} seem to suggest. Smith (1979) has shown the presence of strong and positive correlation between A_{max} and inorganic nutrients (N and P).

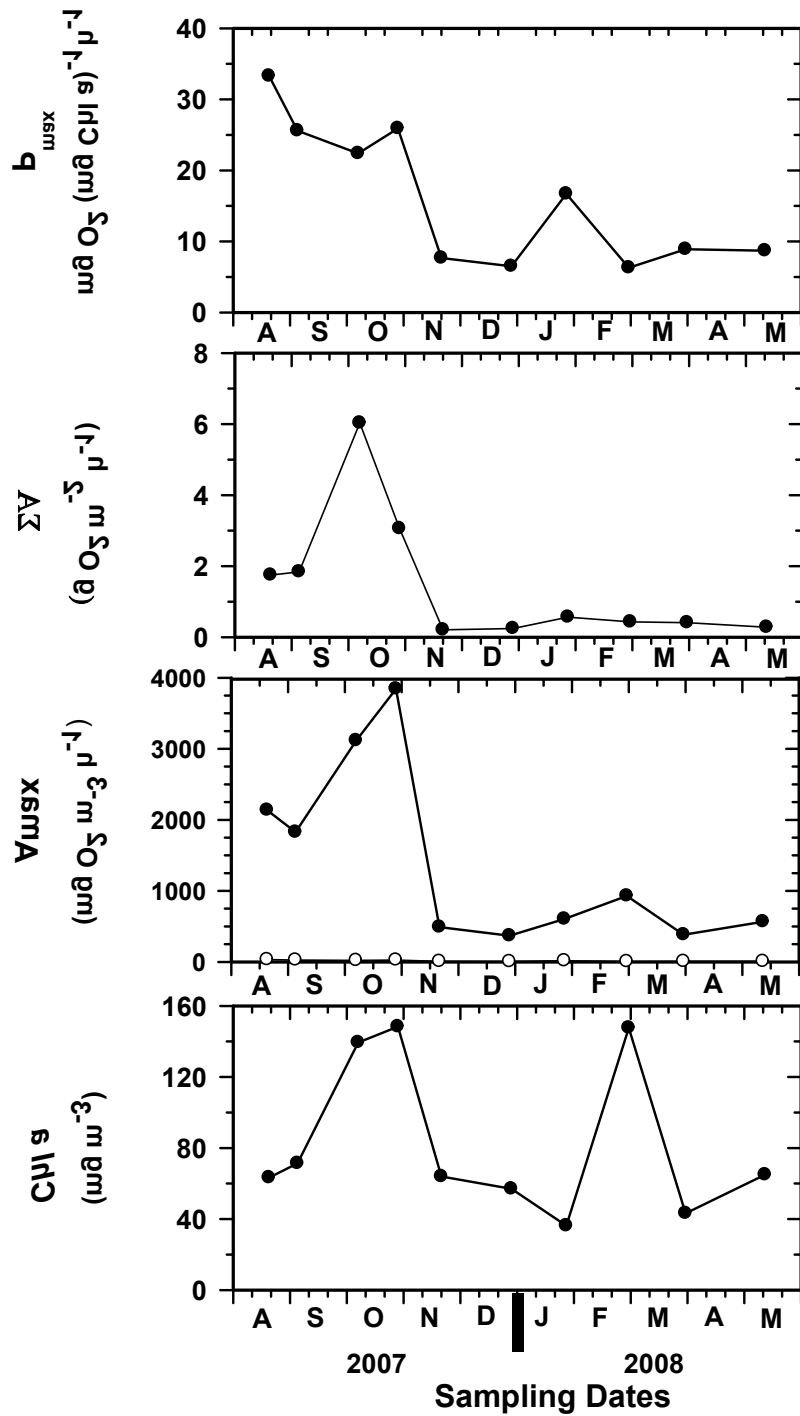


Fig. 13. Temporal variations in phytoplankton photosynthetic parameters in relation to biomass measured as Chl a in Lake Hora-Kilole.

After making a comparison of mean photosynthetic productivity in the trophogenic zone of tropical and temperate lakes, Lemoalle (1981) concluded that higher tropical rates originate from high photosynthetic capacity, which may be the result of the usual higher temperature in the tropics. The drop in photosynthetic capacity observed during the markedly cooler season in lakes MacIlwaine, Rhodesia (Robarts, 1979) and Chad in Chad (Lemoalle, 1983), also seems to support the same view. Tropical soda lakes including Lake Arenguade, Ethiopia (Talling *et al.*, (1973)and Lake Simbi, Kenya (Melack, 1979c), however, show a combination of high phytoplankton standing crop and above-average biomass-specific rates, partly due to the large reserve of CO₂ for localized photosynthetic activity in condensed photosynthetic zones (Talling *et al.*, 1973).

When comparing the photosynthetic capacity of phytoplankton communities, the magnitude of the light-saturated rate of photosynthesis per unit of chlorophyll a, specific rate of gross photosynthesis at light-saturation, [P_{\max} , mg O₂ (mg Chl a)⁻¹ h⁻¹], is commonly considered. Biomass-specific rates at light-saturation ranged from \approx 6 to 33 mg O₂ (mg Chl a)⁻¹ h⁻¹ with most values below 20. P_{\max} values of more or less similar magnitude were reported for Lake Chamo (10-34, Eyasu Shumbulo, 2004), Lake Hora-Kilole (16.3 - 33.7; Talling *et al.*, 1973) and an offshore station in Lake Victoria, Uganda (14 - 35; Talling, 1965). The upper values of the range of P_{\max} for Lake Hora-Kilole are considerably higher than those reported for another lake of the same region, Lake Aranguade (11-18; Talling *et al.*; 1973). The direct effect of temperature (Eppley, 1972), light (Beardall and Morris, 1976; Falkowski, 1981), nutrient regimes (Falkowski and Stone, 1975) and cell size (Malone, 1971) on photosynthetic capacity has been demonstrated. Temperature may not have played a regulatory role in the temporal variation of P_{\max} as water temperature was uniformly favorably high throughout the study period. Although irradiance data for the study period are unavailable, light was presumably relatively low

due to cloud cover during the main rainy season when all of the values of P_{\max} higher than 20 were observed. The P_{\max} values of the main rainy season are probably associated with high light utilization efficiency of photosynthesis under relatively low irradiance conditions (Kirk, 1994). Among the nutrients, SRP was positively but moderately correlated with P_{\max} ($r=0.632$, $r^2=0.40$ at $p=0.0496$) while nitrate and P_{\max} were negatively but moderately correlated ($r= -0.6244$, $r^2=0.3899$ at $p=0.0536$). It is, therefore, tempting to believe that light, algal type and nutrients like SRP and nitrate are of overriding importance in determining the magnitude of P_{\max} . Tadesse Ogato (2007) also reported a strong and positive correlation between P_{\max} and SRP and a strong but negative correlation between P_{\max} and PAR for phytoplankton of Lake Bishoftu.

A photosynthetic capacity of about 20 mg O₂ (mg Chl a)⁻¹h⁻¹ is considered as representative for many African lakes (Talling, 1965; Talling *et al.*, 1973) and an upper limit for lakes of the temperate regions (Bindloss, 1974).

The P_{\max} values for Lake Hora-Kilole are broadly similar to those reported for Lake Chamo Lake Koriftu (18.78 to 33; Zelalem Desalonegne, 2007) and Lake Babogaya (19-29; Yeshiemebet Major, 2006). Considerably lower biomass-specific rates of photosynthesis have been reported for Lake Arenguade (Talling *et al.*, 1973) and a number of lakes in the Ethiopian Rift Valley (Amha Belay and Wood, 1984; Girma Tilahun, 1988; Demeke Kifle and Amha Belay, 1990). Talling (1965) and Ganf (1975) also found maximum specific photosynthetic rates of up to 31 mg O₂ (mg Chl a)⁻¹ h⁻¹) from warm tropical lakes in Africa.

6.2.3.3. Production Rates per unit area

The hourly rate of photosynthesis per unit area (ΣA , mg O₂ m⁻² h⁻¹) estimated from depth profile of gross photosynthesis using the grid enumeration method (Osmon, 1960) and daily rates per unit area ($\Sigma \Sigma A$), which were obtained from hourly rates by multiplying with constants derived by Talling (1965), showed

seasonal variations in relation to some environmental factors. Hourly integral photosynthesis (ΣA) ranged from 0.21 to 6 g O₂ (\approx 0.065 - 1.87g C) m⁻² h⁻¹. The hourly integrals were higher during the main rainy season coincides with high as the *Chl a* biomass, A_{max} and P_{max} values. The positive and strong correlations between ΣA and A_{max} (r= 0.885, r²=0.7895 at P = 0.0006) and ΣA and Z_{eu} (r=0.7938, r²=0.6301 at p= 0.0061) seem to corroborate the assertion that gross photosynthesis per unit area is influenced by the light-saturated rate of photosynthesis and the vertical extent of photosynthetic activity.

Daily production rates per unit area ($\Sigma\Sigma A$, g O₂ m⁻² d⁻¹) were estimated from the hourly integral rates. The empirically derived factor of 0.9 was multiplied by the number of hours of sunlight (10 hr) and then the product was multiplied by the hourly rates per unit area for the estimation of daily rates of gross photosynthesis per unit area, The calculated daily rates of photosynthesis ($\Sigma\Sigma A$) ranged from 2.52 to 46.44 g O₂ (0.79-14.5 g C) m⁻² d⁻¹. The seasonal fluctuation of $\Sigma\Sigma A$ shows more or less the same pattern as ΣA . The highest daily rate of photosynthesis per unit area, 46.44 g O₂ (14.49 mg C) m⁻² d⁻¹ corresponds to an A_{max} of 3843 mg O₂ m⁻³ h⁻¹, which occurred in October, 2007. The unusually high maximum daily integral production value estimated for Lake Hora-Kilole is much higher than that of Lake Babogaya [(0.01 to 5.98 g O₂ (~0.32 to 1.87 g C) m⁻² d⁻¹] Yeshiemebet Major (2006).

Coefficient of variation calculated for primary production in Lake Hora-Kilole was 125.4%, which indicates that there was marked temporal variability in the photosynthetic production of phytoplankton in Lake Hora-Kilole.

6.2.4. Zooplankton Abundance

The seasonal pattern of zooplankton abundance observed during the study period is shown in Fig. 11 in relation to total phytoplankton abundance and biomass and biomass of different size groups of phytoplankton. List of zooplankton taxa identified during the study period is given in Table 2 while the seasonal abundance of zooplankton groups is presented in Appendix 9.

Copepods	Rotifers	Rotifers con..
		<i>F. Longiseta</i>
<i>Mesocyclops aequatorialis</i>	<i>Asplanchna sp.</i>	<i>Lecane (Mnostyla) bulla</i>
<i>Thermosyclops decipiens</i>	<i>Brachionus angularis</i>	<i>Kerratella cohlearis</i>
Cladocerans	<i>B. Caudatus</i>	
<i>Ceriodaphnia reticulate</i> Jurine	<i>B. falcatus</i>	
<i>Daphnia barbata</i>	<i>B. urceolaris</i>	
<i>Moina micrura dubai</i>	<i>Filinia opoliensis</i>	

Table 1. List of zooplankton taxa identified in samples collected from Lake Hora-Kilole

During the present study period, the zooplankton community was constituted by rotifers, cladocerans and copepods. Species of copepods were present throughout the study period with a peak of abundance ($88 \times 10^3 \text{ m}^{-3}$) during December. Total rotifers abundance was found to be very low in March and May and peaked ($198 \times 10^3 \text{ m}^{-3}$) in February, 2008.

Cladocerans showed a different seasonal pattern with a peak ($71 \times 10^3 \text{ m}^{-3}$) in May, 2008. Rotifers were the most abundant zooplankton in Lake Hora-Kilole as they were in Lakes Hora (Tamiru Gebre, 2006) and Koriftu (Girum Tamire, 2006). The mean value of rotifers density was $43 \times 10^3 \text{ m}^{-3}$, a value which is comparable to that recorded by Brook Lemma (1994). *Brachionus* and *Filinia* were the most commonly encountered rotifers during the study period in Lake Hora-Kilole. According to Fernando (1980), numerically, *Brachionus* typically

constitutes more than 50% of the total rotifer assemblage in tropical lakes, which may be partially attributed to their wide range of tolerance to alkalinity and salinity.

Cladocerans were the second numerically important zooplankton group in Lake Hora-Kilole. The mean value of cladocerans density was $42 \times 10^3 \text{ m}^{-3}$, a level of abundance which is also comparable to that reported by Brook Lemma (1994). The quantitative importance of cladocerans in Lake Hora-Kilole contrasts with the situation in Lake Hora in which cladocerans were rarely encountered in zooplankton samples (Tamiru Gebre, 2006). Copepods were the least abundant zooplankton group in Lake Hora-Kilole. The peak of abundance of total zooplankton and rotifers coincided with the peak of abundance and biomass of total phytoplankton.

The peak of cladocerans in December and the peak of copepods in January coincided with the decline of total phytoplankton biomass and abundance, which may indicate that the zooplankton are, at least partially, responsible for the decline of phytoplankton abundance and biomass during the part of the year when diatoms and green algae are of quantitative importance. The resulting increase in the zooplankton: phytoplankton biomass ratio would augment the relative grazing pressure on phytoplankton. The decline in *Chl a* : TP ratio at low TP concentrations coincides with an increase in the dry season (December and January, 2008) of mean zooplankton : phytoplankton abundance ratio, which may suggest enhanced top down control of phytoplankton biomass at low TP.

6.3.5. Benthic macroinvertebrates

The diversity of macrobenthic invertebrates was quit low with 4 species identified through out the study period (Table 3 and Fig.14). The benthic fauna was composed mainly of *Lambriculidae* worms, *Chironomidae* and *Monhystera spp.* An increase in the abundance of chironomids was observed during the main rainy season. A decrease in the abundance of Lambriculidae occurred during the main rainy season while the reverse was true during the dry season. The increase in the abundance of macroinvertebrates during the wet season may be attributed to the accumulation of allochthonous detritus. Williams (1980) showed that higher biomass and numbers of invertebrates are attained in treatments with more detritus, independent of substratum heterogeneity. The dominance of the benthic community by collector/gatherer Lambriculidae – Oligochaete worms and predator chironomid were documented in Kenyan reservoirs (Mwaura *et al.*, 2000).

Table 2. List of identified benthic macroinvertebrates and their abundance in the study lake Hora-Kilole.

Macroinvertbrates	Nov, 29/07	May, 11/08
<i>Chironomus tentas</i>	19	3
<i>Ablabesmyia spp.</i>	15	9
<i>Lambriculidae-Oligochaete</i>	-	20
<i>Monhystera spp.</i>	-	1

In November, 2007, the benthic macroinvertebrates were totally dominated by Chironomid larvae whereby *Ablabesmyia spp.* and *Chironomus tentas* accounted 44% and 64% of the macroinvertebrates respectively. During the minor rainy period (in May, 2008) more than half (60 %) of the community of macroinvertebrates was constituted by Lamburicudae-Oligochaete, 27 % by *Ablabesmyia spp.*, 10 % by *Chironomus tentas*, while the rest was contributed by *Monhystera spp.* Before diversion of the Mojo River, the benthic habitat in

Lake Hora-Kilole was inhabited by only two species, one from *Chironomidae* (*Kiefferulus disparilis*) and the other from *Nematoda* (*Mesodorylaimus macrospiculum*). The present increase in diversity most probably resulted from the change in Lake ecosystem due to dilution.

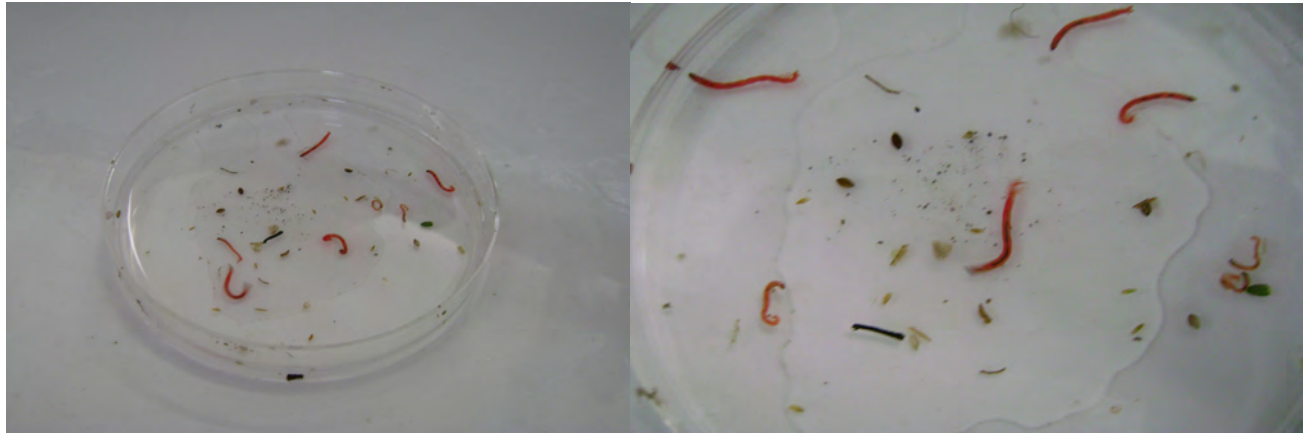


Fig. 14. Specimen of benthic macroinvertebrates. (By rediat abate)

The *Monhyстера spp.* are mostly common fresh water nematodes found especially in soft sediments of lentic systems (Traunspurger, 1996). These species are also found in two saline lakes of Ethiopia: Abijata and Shala and adjoining host springs (Traunspurger, 1996). Their high temperature-dependency, their capacity to withstand high osmotic stress conditions, and their occurrence in saline inland water bodies are well documented (Jacobs, 1978).

According to Eyualem Abebe (2000), the family *Monhysteriodae* comprises 27% of the nematode fauna of Rift Valley limnetic habitats and 26.1% of community outside the Rift Valley limnetic system. However, *Mesodorylaimus macrospiculum. sp. novo* was found to be a new species in Ethiopian soda lakes like Hora-Kilole, Abijata and Shala (Zullini, 1988). But in the present study no other specis of the family *Monhysteriodae* other than the species of

the genus *Monhyestera* was found, which may have resulted from the deterioration of the habitat. Harrison and Hynes (1986) have also indicated that benthic faunal communities are very sensitive to deterioration in rivers, caused by faulty agricultural practice and by pollution with domestic and industrial wastes.

6.3.6. Estimation of fish biomass production

A general rule of thumb states that 1/100 - 1% of the primary production of a body of water can go into fish flesh. The mean ratio of fish yield / ΣA is 0.35%. Considering community respiration, this figure should be multiplied by 0.25. Oglesby (1977) proposed two equations: (a) and (b) which estimate fish yield (Y_f g.d.w.m⁻² year⁻¹), based on summer chlorophyll (*Chl-a*) biomass or annual primary production (ΣA_y). Additional equations are given by Downing *et al.* 1999 (c), Knosche and Barthelmes (1998) (d) and Hakason, (2001).

$$\text{Log } Y_f(\text{d.w}) = -1.92 + 1.17 \text{ Log } Chl-a \dots\dots\dots(a)$$

$$\text{Log } Y_{fc}(\text{C}) = -6.00 + 2.00 \text{ Log } \Sigma A_y \dots\dots\dots(b)$$

$$\text{Log FP} = 0.6 + 0.575 \text{ X LOG } \Sigma A_y \dots\dots\dots(c)$$

$$Y = 14.24 + 0.056 \text{XPP} \dots\dots\dots(d)$$

$$\text{FY} = 0.0023 \text{XPP}^{0.9} (0.0021 \text{XPP}^{0.9}) \dots\dots\dots(e)$$

$$\text{Carbon} = \text{g O}_2 \times 0.375 \text{ (g) (Laevastu, 1957)}$$

$$\text{Organic matter} = \text{g O}_2 \times 0.69 \text{ (g) (Winberg, 1960)}$$

$$\text{Plankton biomass} = \text{g O}_2 \times 3.3 \text{ (g) (Winberg, 1960)}$$

$$\text{Energy production} = \text{g O}_2 \times 3.51 \text{ Kcal (Winberg, 1960)}$$

$$1 \text{ g of C} = 10 \text{ g of fish wet weight (Rodhe, 1958)}$$

$$1 \text{ g wet fish} = 1200 \text{ cal (Srenivasan, 1972)}$$

Most estimates are close to the rule of thumb, 1% of ΣA . An educated guess is thus the values of 47-65 Kg ha⁻¹ year⁻¹ are the most realistic. Table 3 shows different values of fish production calculated using different empirical formulas.

However, in order to use more accurate estimates of fish yield values for lake, food web losses must be taken in to consideration as discussed in Ahlgren *et al.* (2000).

Table 3. Estimated fish biomass production in Lake Hora-Kilole.

Fresh weight (Kg ha ⁻¹ year ⁻¹)	Conversion factor	references
647-64.7	1/100 - 1% of ΣA	Rule of thumb
647	1% of ΣA	Ryther, 1969
56.6	0.25 X 0.35% of ΣA	Melack, 1976
	Chl_s (Eq. a)	Oglesby, 1977
175.6	ΣA_y (Eq. b)	Oglesby, 1977
52.7	ΣA_y (Eq. c)	Downing <i>et al.</i> 1999
46.8	PP (Eq. d)	Knosche and Barthelmes, 1998
128	PP (Eq. e)	Hakason, 2001

Assumptions: 1 g C = 2 g d.w or 10 g fresh weight.

It has been found that the gross energy production (Kcal energy m⁻³ day⁻¹) by the primary producers was 28. Based on the conversion of gross carbon production into fish production, the annual yield of fish from the Lake Hora-Kilole was estimated to be 10.09 kg fish m⁻³year⁻¹. Based on the gross oxygen production the daily production of organic matter (g·m⁻³day⁻¹) and plankton biomass (g·m⁻³day⁻¹) in the Lake Hora-Kilole was estimated as 5.5 and 26.2 respectively.

7. General Discussion

Lake Hora-Kilole supports a phytoplankton community which exhibits temporal variations in its species composition, abundance, biomass and photosynthetic production in relation to changes in the physicochemical and biological conditions of its water column.

The phytoplankton community of Lake Hora-Kilole, in which five algal groups had qualitative and/or quantitative importance, was dominated by Dinoflagellates and Cyanobacteria whose abundance coincided with total phytoplankton biomass. The temporal variations revealed by comparing the present data with literature showed the exhibit both seasonal and long-term variations. The marked temporal variations in the biological parameters seem to be related to physical (e.g. turbidity), chemical (e.g. concentration of SRP) and biological (e.g. zooplankton grazing) factors, the relative importance of which can not be easily determined on the basis of the data generated in the present study.

The poor underwater climate in Lake Hora-Kilole is largely of abiogenic turbidity associated with such human activities as shore-line modification and diversion of Mojo River and wind-induced mixing favored by the lake's exposure to wind action and its shallowness which is partially the result of household and agricultural consumption of the lake water. Among the inorganic nutrients, phosphorus is likely to play the role of a limiting nutrient in light of its low ambient concentrations relative to those of inorganic nitrogen. Although grazing by zooplankton was obviously responsible for the removal of some phytoplankton biomass at least during the dry period when edible phytoplankton like diatoms and green algae were quantitatively important, it did not seem to have a significant impact on the large filamentous blue-green algae which were responsible for the largest seasonal peak of phytoplankton abundance and biomass during the minor rainy period.

Human activities are responsible for the changes in phytoplankton parameters through their impact on physico-chemical and biological conditions of the lake. If agricultural activities carried out in the catchment area of the lake continue to take place with the same place and intensity, the imminent environmental degradation of this aquatic ecosystem will lead to irreversible and undesirable changes. There is already a sign for the likelihood of the development of

nuisance and toxic algal blooms of cyanobacterial genera like *Cylindrospermopsis* whose abundance and persistence in the water column of lakes are favoured by turbid and nutrient-rich water column conditions which are being brought about by human activities related to agricultural practices.

8. CONCLUSION AND RECOMMENDATIONS

The results of the present study have shown that Lake Hora-Kilole is a very shallow, frequently mixing, turbid and eutrophic lake whose phytoplankton community exhibits marked temporal variations in species composition, abundance, biomass and photosynthetic production. Human activities taking place in the catchment area of the lake have resulted in seasonal and long-term changes in the physico-chemical and biological features of the lake. The phytoplankton community is dominated by dinoflagellates and cyanobacteria which seem to account for a major portion of the biomass of phytoplankton accumulated in the lake. The changes in phytoplankton parameters seem to be largely a function of physico-chemical conditions of the water column, which in turn are related to human activities.

Using data from previous studies the changes which took place in Lake Hora-Kilole can be summarized by the following generalized scheme,

Small, shallow, hypertrophic and polymictic- with light-limitation due

to self-shading and possibly nitrogen-limitation-----**Before 1989**



Large, deep, oligotrophic, monomictic, Nitrogen-and light-limited – **In early 1990`s**



Small, shallow, eutrophic, polymictic with possible phosphorus- and light-limitation of phytoplankton -----**At Present time**

On the basis of the results of the present study, the following recommendations are made:

- ❖ In order to update and complement the existing information on morphometric features of the lake, a new bathymetric map should be made as this is basic to understand the functioning of the aquatic ecosystem.
- ❖ A closer look at the impact of agricultural activities taking place along the lake's shore is required to have a better picture of the trends in the changes of the biological components of the system.
- ❖ There is a need for further study on the community structure, production and trophic interactions of zooplankton, macroinvertebrates and fish.
- ❖ To determine the importance of zooplankton grazing to temporal dynamics of phytoplankton, grazing experiments with possible fractionation should be done.

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10. APPENDICES

Appendix 1: Depth profiles of Temperature (° C) and Dissolved Oxygen (mg/L) at a central station in Lake Hora-Kilole.

Time	Aug, 19/07		Sep, 04/07		Oct, 06/07		Nov, 29/07		Dec, 27/07		Jan, 29/07		Feb, 26/07		Mar, 29/07		May, 11/07	
Depth (m)	D O	T (°c)	Do	T (°c)	Do	T (°c)	D o	T (°c)	Do	T (°c)	Do	T (°c)	Do	T (°c)	DO	T (°c)	DO	T (°c)
0.00	-	24.	11	23.1	12. 5	23. 8	12. 1	19. 2	9.5	17.5 7	11. 4	22. 1	10. 9	25.1	10.	26.	13	26.

		5												1	3		6	
0.25	-	24.5	10.46	23.1	10.5	23.7	12.6	19.1	9.4	17.52	10.6	20.5	11.2	24.8	10.9	26	14.3	26.3
0.5	-	24.5	9.6	23.1	10	23.7	12.9	19.0	9.4	17.52	10.2	18.5	11.3	25.5	10.7	25.9	17	25.9
0.75	-	24.4	8.56	22.8	9.47	23.5	13.2	18.9	9.39	17.52	10.1	18.5	11.5	23.5	10.4	25.7	15.5	25.8
1.0	-	24.2	8.1	22.6	8.81	23.3	13.9	18.9	9.39	17.52	9.96	18.5	11.6	23.5	10.3	25.6	13	25.7
1.5	-	23.9	7.86	22.2	7.8	22.8	13.8	18.8	9.35	17.51	9.8	18.4	10.8	23.5	10.2	25.6	12.3	25.5
2.0	-	23.8	7.26	22.0	7.58	22.4	13.8	18.7	9.34	17.49	9.7	18.4	10.1	22.8	10.1	25.6	11.1	25.2
2.5	-	23.5	7.2	21.8	7.5	22.2	13.1	18.7	9.3	17.47	9.7	18.4	10.1	22.8	10	24.9	10	24.9
3	-	23.5	7	21.7	7.5	22.1	12.5	18.4	9.27	17.44	9.6	18.3	10.2	22.8	9.9	23.4	9.5	24.7
4	-	23.3	7	21.6	7.4	22.0	11.8	18.3	9.23	17.44	9.3	18.2	10.0	22.8	9.6	23.3	8.78	24.5
5	-	23.1	6.9	21.2	7.3	22.0	11	18.2	9.19	17.41	8.9	18.2	9.0	22.7	9	23	8.7	24.3
6	-	23	6.9	20.9	7.3	22.0	10	18.2	9.15	17.3	8.2	18.1	8.2	22.5	8.3	22	8.1	24.3

Appendix 2: Optical parameters: Vertical Light Extinction Coefficient (K_d , m^{-1}), Secchi depths [Z_{SD} , m]], Euphotic [Z_{eu} m), Chl a-specific light extinction, K_s (%), light extinction by non-algal matter, K_w (%) in Lake Hora-Kilole.

Sampling Date	K_d	Z_{SD}	Z_{eu} (Kd/4.6)	g ODM/L	g AM/L	g DM/L	K_s (%)	K_w (%)	I_0
Aug, 19/07	3.57	0.43	1.28	0.021	0.01	0.031	7.95	92.05	928.5
Sep 04/07	3.39	0.48	1.36	0.0166	0.0106	0.0273	10.00	90.00	928.5
Oct, 06/07	2.39	0.78	1.915	0.01143	0.0005	0.012	39.04	60.96	1120
Oct, 27/07	5.17	0.32	0.91	0.0211	0.0313	0.05266	8.88	91.12	780

Nov, 29/07	9.62	0.17	0.478						660
Dec, 27/08	10.23	0.15	0.449	0.02	0.104	0.124	1.11	98.89	650
Jan, 26/08	7.17	0.19	0.641						816
Feb, 29/08	6.9	0.22	0.666	0.034	0.0653	0.0993	1.13	98.87	1225
Mar, 29/08	3.77	0.42	1.22	0.0293	0.06733	0.0966	4.96	95.04	1150
May,11/08	4.8	0.36	0.95	0.0135	0.0215	0.036	4.86	95.14	1112
				0.0225	0.022	0.0545	4.51	95.49	1112

Appendix 3: pH, Alkalinity (meq L⁻¹), free carbon dioxide (meq L⁻¹), carbonate and bicarbonate ions (meq L⁻¹) and conductivity of Lake Hora-Kilole.

Sampling date	pH	PA	TA	CO ₂ **	CO ₃ ²⁻ **	HCO ₃ ⁻ **	K ₂₅ (μS/cm)	
Aug. 19/07	8.63	0.40	4.5	0.023	0.085	4.325	476	
Sep. 4/07	8.96	0.50	4.4	0.012	0.143	4.108	463	
Oct. 06/07	8.96	2.50	5.7	0.013	0.214	5.265	469	
Oct,27/07	9.50	0.65	4.2	0.0025	0.445	3.287	483	
Nov. 27/07	8.50	0	4.8	0.0026	0.425	3.330	500	
Dec, 29/08	Lake	8.75	0.20	4.8	0.0206	0.102	4.059	470
	Entry of Mojo R.*	8.35	0.20	4.9				
	Mojo R.	8.00	0	4.9				
Jan,29/08	8.78	0.20	4.8	0.0183	0.115	4.566	532	
Feb,29/08	9.29	0.40	5.1	0.0065	0.316	4.455	528	
Mar,29/08	8.81	0.50	5.3	0.0177	0.293	4.998	556	
May,11/08	9.05	0.50	6.2	0.0112	0.293	5.602	589	

* Sample was collected at the point of entry of the river water into the lake.

** were calculated using a software and may show some deviation from total alkalinity.

Appendix 4: Ambient concentration of inorganic nutrients and ratio of total nitrogen to total phosphorus at a central station in Lake Hora-Kilole.

Sampling Date	NO ₃ +NO ₂ (μg/L)	NH ₄ ⁺ + NH ₃ (μg/L)	SiO ₂ (mg/L)	SRP (μg/L)	Total P(μg/L)	TN:TP (μmol/L)
Aug, 19/07	43.3	4.366	18.266	1.725969	4.6025	22:1
Sep, 04/07	34.65	11.39	19.769	0.9862	6.16418	16:1

Oct, 06/07		25.9	49.097	31.908	1.397	2.63	63:1
Oct, 27/07		17.33	15.396	36.217	3.53413	3.7807	19:1
Nov, 29/07		155.95	2.13	39.084	1.15065	4.1095	82:1
Dec, 27/08	Lake						
		251.25	7.6	47.5	0.3288	4.7669	120:1
	Entry			69	0.8219		
	Mojo			78.4	0.49313		
Jan,29/08		303	4.7926	30.48	0.3288	2.7122	251:1
Feb, 26/08		216.59	4.26	69.7	0.41095	3.6985	132:1
Mar, 29/08		25.99	1.7	17.1	0.7397	2.13691	27:1
May, 11/08		230	6.35	10.4	0.59	3.28	159:1

Appendix 5: Abundance of major phytoplankton taxa (X10³ cell count/ml) in Lake Hora-Kilole.

Phytoplankton Taxa	Aug, 19/07	Sep, 06/07	Oct, 06/07	Oct, 27/07	Nov, 29/07	Dec, 2708	Jan, 26/08	Feb, 29/08	Mar, 29/08	May, 11/08 208
<i>Phacus logicauda</i>	34	26	347	200	113	7	2	12	7	17
<i>Peridinium spp.</i>	450	247	228	968	63	1	2	18	138	307
<i>Raphidiopsis curvata</i>	21		2	42	11	6	12	96	17	20
<i>Cyclotella sp</i>	643	56	-	198	85	6	12			273
<i>Cylindrospermopsis spp.</i>	9	-	3	36	14	6	12	427	23	94
<i>Staurastrum spp.</i>		-	4	34	7	1	4	-	-	-
<i>Anabaena spp.</i>	24	-	-	3	6	3	9	28	23	-
<i>Anabaena cf. agardhi</i>	-	-	-	-	-	-	-	1199	1173	-
<i>Pediastrum spp</i>	-	-	-	-	3	-	-	103	-	-
<i>Spirulina sp.</i>		-	-	-		-	-	84	101	
Total	761	344	496	1490	380	34	45	2051	1537	974

Appendix 6. List of identified species of phytoplankton

Chlorophyceae	Cyanophyceae	Bacillariophyceae
<i>Pediastrum duplex</i>	<i>Anabaena bituri (spec nova).</i>	<i>Amphora lybica</i>
<i>Pediastrum simplex</i>	<i>Anabaena flos-aquae</i>	<i>Aulacoseria ambigna</i>
<i>Scenedesmus bijugatus</i>	<i>Anabaenopsis Elenkinii</i>	<i>Cyclotella glomerata</i>
<i>Scenedesmus latus</i>	<i>Coelosphaerium sp</i>	<i>Frostulia rhomiodes</i>
<i>Scenedesmus linearis</i>	<i>Chroococcus turgidus</i>	<i>Nitzschia spp.</i>
<i>Scenedesmus quadricauda</i>	<i>Cylindrospermopsis catemaco</i>	<i>Synedra ulna var. longissima</i>
<i>Scenedesmus platydiscus</i>	<i>Cylindrospermopsis cuvispora</i>	Crysophyceae
<i>Scenedesmus accumlate var. minor</i>	<i>Pseudoanabaena sp</i>	<i>Chrysoxys maior cf.</i>
<i>Schroederia setigra</i>	<i>Planktothrix agardhii</i>	Cryptophyceae
<i>Spinoclosterium sp</i>	<i>Raphidiopsis curvata</i>	<i>Cryptomonas marssonii</i>
<i>Staurastrum chaetoceras</i>	<i>Raphidiopsis medietrania</i>	<i>Cryptomonas obovata</i>
<i>Staurastrum juocemuelleri</i>	<i>Spirulina sp</i>	<i>Rhodomonas lacustris</i>
<i>Staurastrum punctulatum</i>	Dinophyceae	Euglenophyceae
<i>Closterium actum var. variable</i>	<i>Peridinium aciculiferum</i>	<i>Phacus longicauda</i>
<i>Closterium strigosum</i>	<i>Peridinium cinctum</i>	
<i>Cosmarim spp</i>	<i>Peridinium gatunense</i>	
<i>Monoraphidium contortatum</i>	<i>Peridinium volzii</i>	
<i>Monoraphidium mirabile</i>		

Appendix 7: Percentage contribution of major taxonomic groups and diversity index of phytoplankton in Lake Hora-Kilole.

Sampling date	Dinophyceae (dinoflagellate)	Cyano-phyceae (blue-greens)	Bacillario-phyceae (diatoms)	Eulenophyceae (euglenoids)	Chloro-phyceae (green algae)	Div. index
Aug, 19/07	90%	1%	2.5%	4%	2.5%	2.3
Sep 04/07	72%	5 %	16%	7%		2.354
Oct, 06/07	62%	3%	12%	22%	1%	2.504
Oct, 27/07	68%	1%	15%	14%	2%	2.34
Nov, 29/07	17%	11%	31%	31%	10%	3.034
Dec, 27/08	6%	30 %	20 %	25%	19%	2.861
Jan, 26/08	6%	50%	25%	11%	8%	1.277
Feb, 29/08	1%	82 %	5%	2%	10%	2.079
Mar, 29/08	9%	83 %	2%	2%	4%	1.38
May, 11/08	32%	25%	35%	4%	4%	3.11

Appendix 8. Chl a biomass and percentage contribution of three size-groups to the total biomass of Phytoplankton and total areal biomass of phytoplankton in Lake Hora-Kilole.

Sampling Date	B (mg Chl-a m⁻³)				contribution of size groups (%)			ΣB (mg Chl-a m⁻²)
	> 20 μ m	2 - 20 μ m	0.22 - 2μ m	Total (> 0.22 μ m)	> 20 μ m	2 - 20 μ m	0.22 - 2μ m	
Aug, 19/07	60.38	0	2.78	63.3	95	0	5	81.02
Sep, 04/07	45.85	13.9	11.57	71.32	64	19	16	96.99
Oct, 06/07	45.18	88.89	4.63	139.37	32	64	4	266.89
Oct, 27/07	132.05	8.34	7.94	148.33	89	6	5	134.98
Nov,29/07	41.7	19.46	2.78	63.94	65	30	5	30.56
Dec, 27/08	23.63	27.8	5.56	56.99	41	49	10	25.58
Jan, 26/08	13.21	13.9	8.42	36.22	36	39	25	23.2
Feb, 29/08	103.78	35.03	8.76	147.58	70	23	7	98.29
Mar, 29/08	21.5	9.7	12	43.2	49	23	28	52.7
May, 11/08	40.8	11.1	13.1	65	63	17	20	61.75

Appendix 9: Depth profiles of rates (in mg O₂ m⁻³ h⁻¹) of Gross Photosynthesis (GP) , Net Photosynthesis (NP) and respiration in lake Hora-kilole

Sampling date	Depth(m)	GP	NP	Respiration
AUG,19/07	0.00	2136	1472	665
	0.25	1105	440	
	0.50	765	100	
	0.75	745	80	
	1.25	704	40	
	1.5	0.6200	-	
	2.0	0.4000	-	
	2.5	0.2100	-	
Sep, 04/07	0.00	1827	1004	821
	0.25	1267	445	
	0.50	995	172	
	0.75	899	77	
	1.25	0.6600	-	

	1.5	0.5200	-	
	2.0	0.4300	-	
	2.5	0.3750	-	
Oct , 06/07	0.00	3116	1849	369
	0.25	2904	1697	
	0.50	2712	1560	
	0.75	2632	1503	
	1.250	2557	1457	
	1.500	2707	1271	
	2.00	2227	1214	
	2.5	1590	-	
Oct, 27/07	0.00	1847	1140	707
	0.25	3843	3137	
	0.5	2160	1453	
	0.75	1273	567	
	1.5	1040	333	
	2.0	873	167	
Nov, 29/07	0.0	490	170	320
	0.25	320	20	
	0.5	250	-	
	0.75	0.0	-	
Dec, 27/08	0.00	370	270	100
	0.25	303	203	
	0.50	233	133	
	0.75	200	100	
	1.25	30	-	
Jan, 26/08	0.00	403	150	253
	0.25	605	353	
	0.50	580	328	
	1.00	303	50	
	1.25		0.2600	
Feb, 29/08	0.00	430	360	71
	0.25	929	859	
	0.50	388	318	
	0.75	153	94	
	1.25	0.00	-	
Mar, 29/08	0.00	40	0.00	97
	0.25	350	133	
	0.50	383	167	
	1.00	367	47	
	1.50	90	22	
M ay, 11/08	0.00	74	0.00	212
	0.2500	566	354	
	0.5000	320	108	
	0.7500	258	46	

Appendix 10: Zooplankton abundance ($\times 10^3$ No/m³) in Lake Hora-Kilole.

Groups	Sep, 19/07	Oct, 27/07	Nov, 29/0 7	Dec, 27/08	Jan, 26/0 8	Feb, 29/08	Mar, 29/0 8	May, 11/08
Copepods	20	54	18	88	28	34	0.2	34
Cladoceran	27	57	63	10	58	43	10	71
Rotifers	33	2.6	7.3	11	94	198	0.07	0.2
Total	80	113	88	109	180	274	10	105

Appendix 11. Result of the statistical analyses of the relationship among different physicochemical and biological parameters.

Parameters/Variables		r	r ²	P
Predictor (Independent variable)	Response (Dependent variable)			
<i>Chl a</i>	DWOPM	-0.2203	0.0485	0.5409
ΣB	Z_{SD}	0.8422	0.7100	0.0002
ΣB	K_d	-0.6396	0.4091	0.0046
Wind Speed	K_d	0.3583	0.1283	0.3094
DWIPM	K_d	0.9824	0.9651	<0.0001
ΣB	K_s	0.9510	0.9100	0.0001
Z_{eu}	ΣB	0.7076	0.6362	0.0057
Z_{eu}	DWPM	-0.9263	0.8583	0.0001
HCO_3^-	CO_2	0.4317	0.1863	0.2129
<i>Chl a</i>	CO_2	-0.5865	0.3439	0.0747
A_{max}	CO_2	-0.2557	0.0654	0.4757
CO_2	pH	-0.5011	0.2514	0.0080
TA	pH	-0.0051	0.000026	0.9890
HCO_3^-	K_{25}	0.5553	0.3983	0.0957
TA	K_{25}	0.6476	0.4194	0.0420
B	$NO_3 + NO_2-N$	-0.3210	0.1020	0.3662
A_{max}	$NO_3 + NO_2-N$	-0.6830	0.4642	0.0301
B	$NH_4^++NH_3-N$	0.5620	0.3156	0.0910
A_{max}	$NH_4^++NH_3-N$	0.6565	0.4310	0.0392
B	SRP	0.5210	0.2717	0.1223
B	TP	-0.0466	0.0022	0.8983
B	Soluble Reactive Silica	0.5260	0.2270	0.0118
Phytoplankton abundance	B	0.5373	0.2887	0.1092
Zooplankton abundance	B	0.5284	0.2792	0.1364
Biomass of > 20 μm fraction	B	0.8272	0.6842	0.0031
B	A_{max}	0.6951	0.4832	0.0256
P_{max}	A_{max}	0.7742	9.5594	0.0086
SRP	A_{max}	0.8543	0.7300	0.0016
$NH_4^++NH_3-N$	A_{max}	0.6565	0.4300	0.0392
$NO_3 + NO_2-N$	A_{max}	-0.6813	0.4640	0.0301
SRP	P_{max}	0.6328	0.4005	0.0496
$NO_3 + NO_2-N$	P_{max}	-0.6244	0.3899	0.0536
A_{max}	ΣA	0.885	0.7895	0.0006
Z_{eu}	ΣA	0.7938	0.6301	0.0061

Appendix 12: Comparative summary of the physico-chemical and biological parameters recorded for Lake Hora-Kilole before and after 1989 and in the present study. Sources: ((1) Elizabeth Kebede *et al.* (1986), (2) Green (1986), (3) Green and Seyoum Mengistou (1991), (4) Melack *et al.* (1984), (5) Omer-Cooper (1930), (6) Prosser *et al.*, (1968), (7) Talling *et al.* (1973), (8) Wood *et al.* (1976), (9) Wood *et al.* (1984), (10) Wood and Talling (1988), (11) Brook Lemma (1994); (13), Mulugeta Assefa (cited in Brook Lemma, 1994)) and (12) Zinabu-Gebre-Mariam (1994).

Parameters	Before dilution in 1989	After dilution) In early 1990`s	Present study
Altitude (m asl)	2000 (3,7,10)	1920 (11)	1886
Surface Area (km ²)	0.77 (11)	1.18 (11)	-
Maximum depth (m)	6.4 (11)	29 (11)	7.8
Mean depth (m)	2.6 (11)	1.69 (11)	-
Volume (Km ³)	0.002 (11)	0.023 (11)	-
Conductivity (K ₂₀ , μS cm ⁻¹) ^a	5930 (11)	239-339 (11)	463-589
Dissolved oxygen (mgO ₂ /L)	1-6 (11)	3.4-10.6 (11)	6-17
pH	9.6 (11)	7.4-9.20 (11)	8.9
Water temperature (°C)	19-23 (11)	19.3-24 (11)	17.3- 26
Secchi depth (m)	0.15 (11)	0.37-1.8 (11)	0.15 -.78
Salinity (mg/L)	5.731 (6,10)	-	-
	6.76, 5	-	-
Σ _{an} (meq/L)	81.6 (10)	-	-
Na ⁺ (meq/L)	70.5 (6)	2.39 (13)	-
	71 (10)	-	-
Ca ²⁺ (meq/L)	0.7 (6)	0.956 (13)	-
Mg ²⁺ (meq/L)	<0.6 (6)	0.478 (13)	-
Alkalinity (CO ₃ ²⁻) (meq/L)	66.6 (10)	0.42 (13)	0.585
Σ _{cat} (meq/L)	75.7 (6)	-	-
HCO ₃ ⁻ +CO ₃ ²⁻ (meq/L)	63.4 (6,9)	2.15 (13)	4.95
	66.6 (10)	-	-
Cl ⁻	13.6 (6)	0.564 (13)	-
	11.5 (10)	-	-
SO ₂	Undetectable (9)	-	-
SO ₄ ²⁻	0.4 (4)	-	-
SiO ₂ (mg/L)	32 (4)	9.1, 2.8 (12)	28.5
NH ₃ -N (μg/L)	Undetectable (9)	-	10.7
PO ₄ ³⁻ P (μg/L)	4800-5500 (6,9)	0.004, 0.0027 (12)	1.12
	7000 (9)	-	-
(Ca+Mg)/(Na+Mg)	0.016 (6)	0.5 (13)	-
Alk/Cl	5.79 (6,9)	3.81 (13)	-
NO ₃ ²⁻ +NO ₂ -N (μg/L)	3-33 (9,10)	0.00 8, 0.017 (12)	130.4
Chlorophyll a (μg/L)	100-112 (7,10)	35 and 30 (12)	36-148
	535 (10)	-	-
Gross Photosynthesis (mg O ₂ m ⁻³ h ⁻¹)	4000-1000 (4,7)	21-225 (11)	370-3843

Appendix 13: Equations used in estimating different parameters

12.1.
$$K_d = \frac{\ln I_0 - \ln I_z}{Z}$$
 (Kirk, 1983)

where, K_d , mean vertical extinction coefficient; I_0 , surface irradiance; I_z , irradiance at depth Z ,

12.2.
$$Z_{eu} = 4.6 / K_d$$
 (Kalff, 2002)

12.3.
$$F_c = \frac{K_c \times [Chl\ a]}{K_d\ PAR} = \frac{K_c \times [Chl\ a]}{K_c \times [Chl\ a] + K_w}$$
 (Kirk, 1983)

where extinction coefficient of Chl a (K_c) = 0.016, K_w = the attenuation coefficient for non-chlorophyll components of the water, $K_d\ PAR$ = mean extinction coefficient.

12.4. DMSPM (mg L⁻¹) =

$$\frac{\text{Dry weight (mg) of SPM- weight of dried filter paper (in mg)}}{\text{Volume of sample Filtered (in liters)}}$$

SPM= Suspended Particulate Matter

DMSPM = Dry Mass (Weight) of Suspended Particulate Matter

Ash-free (organic) dry mass (ODM) = DM - AM

Organic-free Dry Mass= ADM (Ash Dry Mass)

12.5. Alkalinity (meq L⁻¹) =

$$\frac{(N_{\text{of acid}} \times 1000) \times V_{\text{acid}}}{V_{\text{of sample titrated}}} \quad (\text{Wetzel and Likens, 2000})$$

Where N = Normality

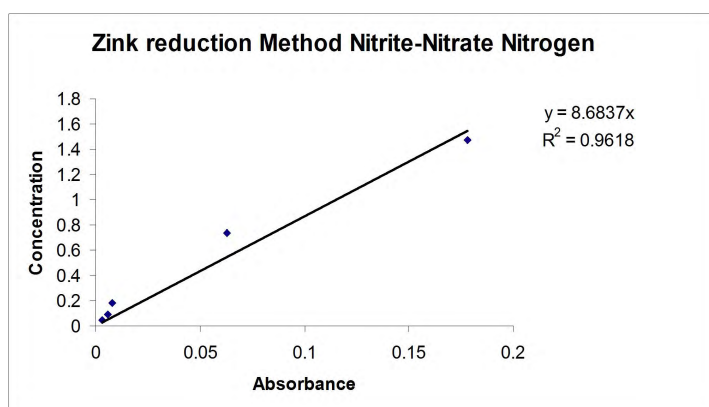
V = volume

12.6. Free CO₂ (mg /L) = 1.589 x 10⁶ [H] x mg/L alkalinity as HCO₃
(Rainwater and Thatcher, 1960).

12.7. Determination of concentration of Inorganic Nutrients

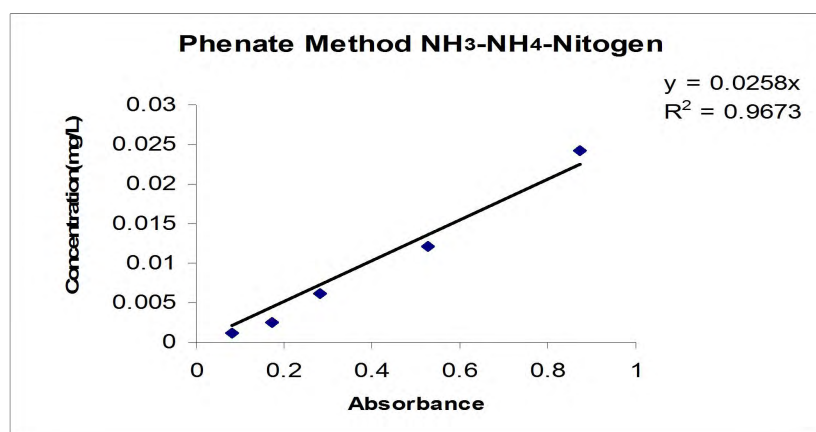
(A). NO₃-N (Zinc Réduction Method, Nelson *et al.*, 1954)

$$\text{Conc. (mg L}^{-1}\text{)} = 8.66 \times \text{Absorbance} + 0$$



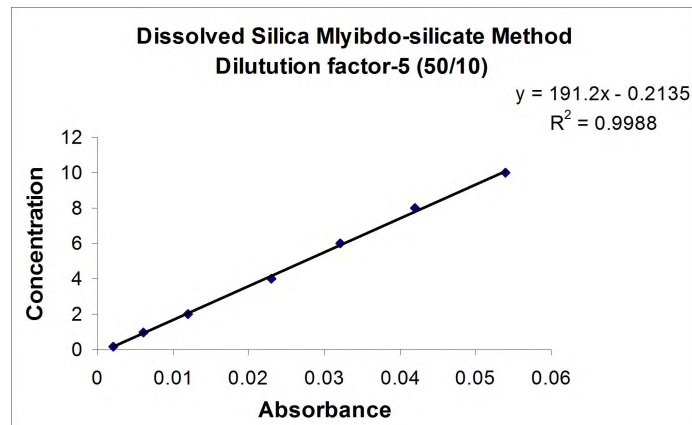
(B). NH₄⁺ -N (Phenate Method, APHA *et al.* 1999)

$$\text{Conc. (mg L}^{-1}\text{)} = 0.02580 \times \text{Absorbance} + 0$$



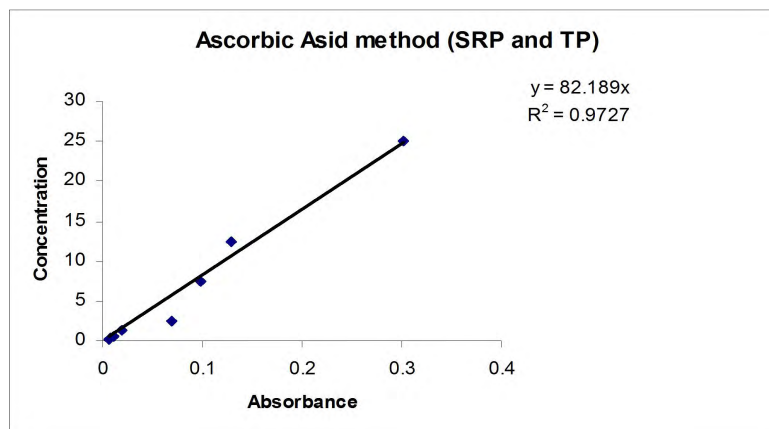
(C). Dissolved Silica (Molybdate reactive silica) –Molybdosilicate Method
(APHA *et al.*, 1999)

$$\text{Conc. (mg L}^{-1}\text{)} = 191.2 \times \text{Absorbance} - 0.214$$



(D). PO₄-P (SRP) and TP

$$\text{Conc. (mg L}^{-1}\text{)} = 0.821 \times \text{Absorbance} + 0$$



12.8 Phytoplankton abundance (Hotzel and Croome, 1999; Wetzel and Likens, 2000).

$$\mathbf{A)} \quad \text{Abundance (cells ml}^{-1}\text{)} = \frac{N \times 10^3 \text{ mm}^3}{A \times D \times F}$$

Where, N = number of cells or units counted

A = area of field (1mm²)

D = depth of field (Sedgwick-Rafter chamber depth- 1mm)

F= number of fields counted

$$\mathbf{B)} \quad H' = - \sum_{i=1}^S P_i \log_2 P_i \quad (\text{Shannon and weaver, 1949})$$

Where, H' = no. of bits per individual

S = no. of species

$P_i = N_i/N$ (N_i = no. of individual of species i, N= total no. of individuals).

12.9. Zooplankton relative abundance: (Edmondson and Winberg, 1971; Green, 1986)

$$V_{\text{net}} \text{ (m}^3\text{)} = \pi r^2 d$$

$$\text{No. /m}^3 = \frac{C \times \text{TG} \times F}{\text{CG} \times V_{\text{net}}}$$

Where, C= count of zooplankton, TG= total grid (15), F= factor of sub-sample, CG= counted grids, V_{net} = Volume of net (0.3 m³), r= radius of the net, d = the length of the course of the net through the water column (depth of sampling), $\pi = 3.14$.

12.10. Phytoplankton biomass estimation

$$\mathbf{(A).} \quad \text{Chl a (}\mu\text{g L}^{-1}\text{)} = \frac{13.9 (E_{665} - E_{750}) V_e}{V_s \times Z} \quad (\text{Talling and Driver, 1963})$$

where, E665 = extinction at 665 nm

E750 = extinction at 750 nm

V_e = volume of extract (in ml)

V_s = volume of sample filtered (in Litres)

Z = path length of the cuvette (Spectrophotometric cell) (in cm).

(B). Euphotic zone chlorophyll a, $\Sigma B = B_{chl\ a} \times Z_{eu}$ (Erikson *et al.*, 1991)

12.11. Primary production (Wetzel and Likens, 2000; APHA, 1999; Lind, 1979)

(A). Determination of oxygen concentration (Winkler Method)

$$\text{mg O}_2 \text{ L}^{-1} = \frac{(\text{ml titrant}) (\text{N of thiosulfate}) (8000)}{(\text{ml sample}) \left(\frac{\text{ml bottle} - 2}{\text{ml of bottle}} \right)}$$

(B). Gross photosynthesis, GP (mg C/m³/h)

$$\text{GP (mg C/m}^3\text{/h)} = \frac{[(\text{O}_2, \text{LB}) - (\text{O}_2, \text{DB})] (1000) (0.375)}{(\text{PQ}) (t)}$$

OR

$$\text{GP (mg O}_2\text{/m}^3\text{/h)} = \frac{[(\text{O}_2, \text{LB}) - (\text{O}_2, \text{DB})] (1000)}{(t)}$$

Where, t = hours of incubation, O_2 = Oxygen in mg/L, LB = light bottle, DB = dark bottle, 1000 = conversion factor of L to m³, 0.375 = the ratio of moles of carbon to moles of oxygen (12mgC/32mgO₂), PQ = photosynthetic quotient, assumed to be 1.2.

(C). Net photosynthesis, NP (mg C/m³/h)

$$\text{NP (mg C/m}^3\text{/h)} = \frac{[(\text{O}_2, \text{LB}) - (\text{O}_2, \text{IB})] (1000) (0.375)}{(\text{PQ}) (t)}$$

Or

$$\text{NP (mg O}_2\text{/m}^3\text{/h)} = \frac{[(\text{O}_2, \text{LB}) - (\text{O}_2, \text{IB})] (1000)}{(t)}$$

Where IB = Initial bottle

(D). Respiration (mg C/m³/h) = $\frac{[(\text{O}_2, \text{IB}) - (\text{O}_2, \text{DB})] (\text{RQ})(1000) (0.375)}{(t)}$

Or: R (mg O₂/m³/h) = $\frac{[(\text{O}_2, \text{IB}) - (\text{O}_2, \text{DB})] (1000)}{(t)}$

Where, RQ= Respiratory Quotient, assumed to be 1.

Daily Integral Photosynthesis, $\Sigma\Sigma A$ (mg O₂ m⁻² d⁻¹) = $\Sigma A \times 10 \times 0.9$

(Talling, 1965)

(E). Biomass-Specific hourly rate of gross photosynthesis, P

$$p \text{ (mg O}_2 \text{ (mg Chl a)}^{-1}\text{h}^{-1}) = \frac{A \text{ (mg O}_2 \text{ m}^{-3} \text{ h}^{-1})}{\text{mg Chl a m}^{-3}}$$