# DYNAMICS OF PHYTOPLANKTON IN RELATION TO PHYSICO-CHEMICAL FACTORS IN LAKE BISHOFTU, ETHIOPIA.

A Thesis Presented to the School of Graduate Studies of the Addis Ababa University in Partial Fulfilment of the Requirements for the Degree of Masters of Science in Biology.

By Tadesse Ogato

July, 2007
Addis Ababa, Ethiopia.

DECLARATION

This paper is my original work that all sources of materials used in it have been gratefully acknowledged.

Name Tadesse Ogato

Signature ---------  ---------

Date July, 2007.

This work has been presented with my approval as a supervisor

Name Demeke Kifle (ph.D)

Signature ----------

Date July, 2007.

Approved by the examiner board

| Name | Signature |
| --- | --- |
| Chairman, Department Graduate Committee | |
| External Examiner | |
| Internal Examiner | |
| Research Advisor | |

**Acknowledgement**

I would like to express my deepest gratitude to my advisor, Dr. Demeke Kifle for his consistent advice and support from the beginning up to the completion of this work. Really, this work would not have been completed without his kind support and follow up. I am also grateful to Dr. Seyoum Mengistu, stream advisor, for his help and always readiness to offer any support.

My thanks go to Girma Tilahun (graduate class PhD student) for his assistance in laboratory in developing standard curves for nutrient analysis and in identification of phytoplankton.

The School of Graduate Studies at Addis Ababa University and SIDA are acknowledged for financial support that I got through my advisor. I am impressed for the invaluable cooperation of the chairman and secretaries of the department of biology. I also thank National Ethiopian Meteorological Service Agency for providing meteorological data of the study period.

My heartfelt gratitude is due to the Ministry of Education for sponsoring me to pursue the graduate studies and my families for their motivation and encouragement.

I appreciate my field assistant for his good work, attitude and strength, and the people of Debre-Zeit town for wide range of supports.

Finally, I am grateful to all my friends and my colleagues in Fisheries and Aquatic Science Stream for their all-round encouragement.

## Table of Contents

## List of Tables

## List of Figures

## List of Appendices

***Abstract***

*The seasonal dynamics of phytoplankton in relation to some physico-chemical and biological parameters were studied at a near-shore and central stations in Lake Bishoftu from August, 2006 to May, 2007. Water transparency ($Z_{SD}$) ranged from 0.50 to 1,05 and from 0.46 to 1.0 m at the Central and Near Shore stations respectively, with high and low values corresponding to dry and rainy periods respectively. Mean vertical extinction coefficient varied temporally with higher values coincident with high algal biomass and abiogenic turbidity following rainy periods. The lake exhibited both superficial and deep-seated thermal stratifications, with ill-defined thermoclines on some occasions and never underwent complete mixing during the study period. Algal nutrients except nitrate-nitrogen showed temporal variations whose changes were inversely correlated with Chl a.The phytoplankton community of the lake, which consisted of five algal classess was dominated by cyanobacteria with Microcystis spp. as the most abundant and persistent taxa and with their contributions to the total abundance of the phytoplankton assemblage of the lake ranging from 58 to 99%. The zooplankton community was dominated by Calanoids and Rotifers with Lovenula africana and Brachionus spp.as the most numerically important taxa. Phytoplankton biomass measured as Chl a showed seasonal variations with maximum values during the rainy and post rainy months at both stations. Depth profile of photosynthesis showed a region of photoinhibition and condensed photosynthetic zone, a feature of some east African lakes. Light-saturated rates of gross photosynthesis ($A_{max}$) at the central station varied from a minimum of 410 to a maximum of 1630 mg $O_2$ $m^{-3}$ $h^{-}$ and with fairly strong and positive correlations with Chl a ($R^2$=0.38, p=0.08), Soluble Reactive Phosphate, SRP ($R^2$=0.46, p=0.07) and Light utilization efficiency, Φ ($R^2$=0.61, p=0.02). Biomass specific rate at light-saturation exhibited unusually high values (29-91) and was positively and significantly correlated with SRP ($R^2$=0.59, p=0.02), Areal rates varied from 0.89 to 3.88 g $O_2$ $m^{-2}$ $h^{-1}$ in association with biomass and $A_{max}$. The possible causes for the observed saptio-temporal variations in physico-chemical and biological features of the lake are discussed and suitable conservation strategies recommended.*

phytoplankton was based on short-term observations, which were not systematic. Wood and Talling (1988) have compiled the sporadic information on the dominant or most common species of phytoplankton reported in various limnological papers. The systematic and detailed taxonomic studies conducted on phytoplankton to date are those of Tsegaye Mihrete-Ab (1988), Elizabeth Kebede and Amha Belay (1994), Elizabeth Kebede (1996) and Elizabeth Kebede and Willén (1998). Also several studies (Talling *et al*., 1973; Amha Belay and Wood, 1984; Girma Tilahun, 1988; Brook Lemma, 1994; Taylor and Zinabu Gebre-Mariam 1989; Demeke Kifle and Amha Belay, 1990 and Eyasu Shumbulo, 2004; Girma Tilahun, 2006) have investigated the dynamics of phytoplankton in relation to some limnological aspects in Ethiopian lakes.

Although the Bishoftu crater lakes have been subjects of many limnological investigations, some dating as far back to the early 1930's (Prosser *et al*., 1968), information on the temporal dynamics of the community structure and photosynthetic production of phytoplankton in relation to physico-chemical factors in Lake Bishoftu is non-existent. The early short-term comparative studies made on the Bishoftu lakes focused mainly on the assessment of general trends in physico-chemical limnological features. Even the few published reports on the phytoplankton biomass (Zinabu Gebre-Mariam, 1994; Wood and Talling,1988) and photosynthetic production (Talling *et al.*, 1973) in the Bishoftu crater lakes were based on short-term observations although it was indicated that phytoplankton of tropical waters exhibit temporal changes in their species composition, biomass and primary production (Talling,1986).

In Lake Bishoftu, some-short term studies have been reported on bathymetry, stratification, some chemical and morphometric aspects by expeditionary limnologists such as Baxter *et al*. (1965), Baxter and Wood (1965), and Wood and Talling (1988). These short-term studies were based on occasional sampling for the purpose of comparison among crater and tropical Rift Valley lakes.

Comparative study with another soda lake, Lake Aranguade, on zooplankton structure and dynamics has been conducted by Afeworki Ghebrai (1992). Therefore, in comparison with other Debre-Zeit and Rift Valley lakes, someone can confidently talk of that Lake Bishoftu is not studied in phytoplankton aspect over extended periods.

Zinabu Gebre-Mariam (1994), Brook Lemma (2002) and Zinabu Gebre-Mariam *et al.* (2002) have noted that the Ethiopian Rift Valley and crater lakes have been undergoing changes in their limnological features during the last two decades or so because of increased human interventions. The present study lake is no exception. Lake Bishoftu is surrounded by a fast growing town, Debre Zeit, and its shores are used for washing clothes, watering livestock and recreation and the like. Shoreline modifications made on almost all sides of the lake for various purposes (e.g. for the construction of resort hotels and residences in the catchments) introduce enormous amounts of particulate wastes, which form suspensions in the water column thereby reducing light penetration at least in the near-shore regions of the lake. The lake has also been serving as a major dumping site for domestic wastes (solid and liquid wastes) originating from households, hotels and small industrial operations, including a privately-owned tannery. These activities could lead to changes in the physico-chemical limnological features of the lake resulting in the disruption of the lake ecosystem, with consequent changes in the species composition and photosynthetic production of phytoplankton, which determine the pelagic food web structure and fish production in the lake. It is also possible that degradation of this aquatic ecosystem may go on unnoticed for a long time and eventually result in unexpected disastrous effects. The assessment of qualitative and/or quantitative changes taking place in this lake, therefore, necessitates the generation of basic information on the physical, chemical and biological aspects of this water body over an extended period of time.

Thus, the purpose of this research project was to look into the temporal variation in the species composition, seasonal abundance and photosynthetic production of phytoplankton in relation to some physico-chemical variables in Lake Bishoftu.

### 1.2. Review of Relevant Literature

Fresh waters are important habitats as they are generally very productive at the primary (algae), secondary (zooplankton) and tertiary (fish and other aquatic vertebrates) levels. However, in industrial areas and urban centres there is pollution of these water bodies associated with high levels of domestic and indusrial wastes originating from human activities.

The quality of water, unlike the very obvious physical changes that take place during the development of water resources, is an attribute that affects the biodiversity (flora and fauna) and productivity of aquatic systems. As water quality is an index of water pollution, assessing water quality parameters is a baseline for monitoring freshwater environments. The voluminous literature on water quality reflects the fact that these parameters clearly show the dynamics of a lake, its balance and trends (Margaleff, 1996; Chapman, 1997).

Phytoplankton form the base of the aquatic food chains and are important indicators of the productivity of aquatic environments. Their productivity and composition are influenced by the spatial and temporal dynamics of environmental factors. Nutrients, underwater light climate, temperature, pH, water clarity, dissolved oxygen, biological components and wind-induced mixing/thermal stratification of water columns are some of the major dynamic water quality parameters that bring about the dynamics of phytoplankton (Jones, 1977; Reynolds, 1984).

Phytoplankton productivity and composition are influenced by the spatial and temporal dynamics of environmental factors. Their periodicity in temperate areas follows a typical seasonal pattern (Sommer,1989; Reynolds, 1989) dominated by the solar energy cycle (Patterson and Wilson, 1995) but this pattern in the tropics is less apparent and is controlled mainly by weather and related changes. Melack (1996) indicated that in most tropical lakes, seasonal and interannual fluctuations of phytoplankton correspond to variations in rainfall and the consequent runoff or vertical mixing within the lake. In Africa, phytoplankton biomass, species composition and productivity vary widely because African lakes' hydroclimatic conditions cover a great span of variation (Lemoalle *et al*., 1981). Phytoplankton studies in some African lakes have shown dynamics that are the results of several years of cultural eutrophication (Ochumba, 1987; Hecky, 1993) and Talling (1986), who devoted more time in studying tropical waters, also indicated that phytoplankton seasonality in larger and deeper African lakes is influenced by external factors (e.g. biological) and periodic changes in the hydrographic structure of the water column, which is more influential in closed water bodies, like Lake Bishoftu.

The succession of different phytoplankton populations is dependent on the degree to which they can adapt to changes in the critical environmental factors such as nutrients, sedimentation, light and turbulance (Smayda, 1980). Margaleff (1996) suggested that turbulence is a major factor in determining the structure, organization and succession of phytoplankton communities. A number of observations have established that flagellate species tend to predominate in stratified waters while diatoms characterize waters that are more turbulent (Reynolds, 1984; Smayda, 1980). Such observations corroborated the general view that the thermal regime of water mass influences the species composition of phytoplankton (Talling and Lemoalle, 1998).

Photosynthetic production in aquatic environment can be measured by either $C^{14}$ or Oxygen methods depending on the sensitivity of the method with regard to the trophic status of the water. In eutrophic waters, the large phytoplankton biomass produces a measurable oxygen uptake over short periods so that assessment of net production is possible by the Winkler method of oxygen determination (Wetzel and Likens, 2000).

**Dissolved Oxygen and Temperature**

The concentration of oxygen in fresh water has implications for the presence and distribution of organisms, and anoxia can result in the death of aquatic animals.

Due to the important correlation between DO and temperature, it is important to analyze both parameters together. Oxygen in aquatic systems is measured in its dissolved form as dissolved oxygen (DO: mg $L^{-1}$) and normal DO levels in freshwater are between 8 and 10 mg/L (APHA, 1992). The level of DO in the water can correlate with the start of a sudden phytoplankton population increase.

The observed range of dissolved oxygen concentrations reported worldwide is 0 mg/L (anoxic conditions) and 19 mg/L (supersaturated conditions). Super-saturated conditions are caused by algal blooms; high amounts of algae produce more dissolved oxygen in the aquatic systems (Margaleff, 1996). Anoxic conditions, or periods of zero dissolved oxygen concentration in the water, leads to undesirable odours until oxic or aerobic conditions develop (Mays, 1996).

The rates of biological and chemical processes also depend on temperature. Aquatic organisms from microbes to fish are dependent on certain temperature ranges for optimal development (APHA, 1992). Temperature varies locally and over short time scales, including diel and seasonal cycles, in freshwater aquatic systems. If temperatures are outside optimal range for a prolonged period of time, organisms are stressed and can die (USEPA, 1991; Chapman, 1997).

**pH & alkalinity**

pH level is an important parameter to be measured since its level can correlate with the start of a sudden phytoplankton population increase (USEPA, 1991: Chapman, 1997)

pH outside the range 6.5 to 8 reduces the biodiversity in a lake because it stresses the physical system of most organisms and can reduce reproduction (USEPA, 1991). Low pH can also allow toxic elements and compounds to become mobile and "available" for uptake by aquatic plants and animals thereby producing conditions that are lethal to aquatic life, particularly to sensitive species (USEPA, 1991).

High alkalinity waters are often more biologically productive than low alkalinity waters (Chapman, 1997). Consequently, total alkalinity was once used as an indirect measure of a lake's productivity. In recent years, research has shown that water bodies with low alkalinity levels are more susceptible to the effects of acidic water inputs (acid rain) (Schardt and Ludlow, 2000).

**NUTRIENTS**

Nitrogen and phosphorus are the primary macro-nutrients that enrich freshwaters and cause nuisance levels of algae (algae blooms) that can frequently impact the aesthetic qualities of a lake.

Conditions that allow plankton biomass to accumulate (i.e., adequate light, sufficient water retention time, as well as low loss due to grazing) will not result in high biomass without sufficient nutrient supply. The availability of nutrients depends on the mixing of the water column. Nutrients, especially P, are frequently the key stimulus to high algal biomass. Phosphorus is the key nutrient controlling productivity and causing excess algal biomass in many freshwaters

worldwide (USEPA, 1991: APHA, 1992). However, nitrogen can also become important in waters receiving agricultural runoff and/or wastewater with a low N/P ratio and in waters with naturally phosphorus-rich bedrock (USEPA, 1991). The directly available forms of N and P are mainly inorganic ($NO_3^-$, $NH_4^+$ and $PO_4^{3}$). Because soluble inorganic fractions are directly available, soluble inorganic N, P, or both may be low during active growth periods when demand is high and, therefore, may not be good predictors of biomass (Schindler, 1977; USEPA, 1991). Total N and TP are often good predictors of algal biomass in lakes and reservoirs, to a large extent because much of the particulate fraction is live algal biomass. Together with phosphorus, nitrogen in excess amounts can accelerate eutrophication, causing dramatic increase in aquatic autotrophic growth and changes in types of plants and animals in the lake.

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; Foreberg *et al*., 1980). According to these authors, if ambient N: P ratios are greater than 15-17**:**1 by weight, 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.

Grazers – Phytoplankton Interactions

Chlorophyll a*,* which is an indicator of algal biomass in a lake or reservoir, is important because it decreases the beneficial recreational uses when present in excess (Camp Dresser & McKee, 1999).

Dense populations of algae-consuming grazers may lead to negligible algal biomass in spite of high levels of nutrients (Steinman, 1996). The existence of a “trophic cascade” (control of algal biomass by community composition of grazers and their predators) has been demonstrated for some freshwaters (e.g. Morris,

1980). At some point, however, productivity and biomass will cease to increase at all or the rate of increase per unit nutrient will be greatly reduced. One feature of highly enriched lakes and reservoirs is the switch to grazer-resistant filamentous/colonial blue-green algae, which reduces the efficiency of nutrient utilization and energy conversion to higher trophic levels (USEPA, 1991).

Mortality by grazing is one of the pressures on planktonic algae, and existing algal diversity has been shaped by selection for grazer avoidance (Leman, 1988) and the quantitative link between zooplankton and their phytoplankton food is generally expressed as a mortality rate. Grazers of phytoplankton include micro-zooplankton (ciliates, rotifers, tintinnids), meso- and macro-zooplankton including their certain developmental stages, meroplanktonic invertebrate larvae, benthic filter-feeders, fish larvae and adult fishes.

Grazing has been found to be the most important source of mortality for phytoplankton, which brings about seasonal changes in the abundance of phytoplankton (Reynolds, 1984). Zooplankton possess complex grazing behavior, and rates of particle capture may vary with size, shape, taste or surface charge of phytoplankton (Leman, 1988). Thus, grazing not only causes mortality but may also alter the size or species composition of the phytoplankton.

## 1.3. Description of the study area

Lake Bishoftu (Fig.1), is one of the Bishoftu crater lakes found in Bishoftu, a town situated 47km South East of Addis Ababa. Some morphometric, physico-chemical and biological features of the lake are given in Table 1.

Some limnological studies made on Lake Bishoftu described bathymetry (Prosser *et al*., 1968), water chemistry (Prosser *et al*., 1968; Wood *et al.,* 1984; Zinabu Gebre-Mariam, 1994), physical and chemical stratification (Baxter *et al*., 1965),

chemical and algal relationships (Wood and Talling, 1988; Zinabu Gebre-Mariam, 1994), and zooplankton associations (Green, 1986, Afeworki Gebrai, 1992).

Lake Bishoftu is a crater lake with a small surface area (0.93 $km^2$), roughly circular and the deepest (87 m) of all Bishoftu crater lakes, found at an altitude of 1870 m and at about $9^0$N and $39^0$E latitude (Prosser *et al*., 1968). It is a closed system, surrounded by very steep sided and rocky crater walls, which function as a wind breakage by reducing or eliminating complete mixing (Baxter *et al*., 1965).

The lake's region is characterized by moderate rainfall, varying around about 850 mm per annum, which is the major source of water (Rippey and Wood, 1985), 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. The temperature of its surface water was frequently found to be about $22^0$C, with a maximum of 24.5 and a minimum of $19.2^0$C, while the bottom temperature was almost constant ($19.2^0$C-$19.4^0$C) (Wood, *et al.*, 1976).

The lake is fed primarily by precipitation falling directly on its surface, underground inflow and run-off from its small catchment area (Prosser *et al*., 1968), which was formed from volcanic rocks of basalt, rhyolite and tuff (Mohr, 1961). The weathering of the predominately basaltic rocks forming the craters, together with evaporative concentration of the lake water and possible underground seepage-in of water containing minerals dissolved from more distant sources, has resulted in mineral-rich inflows and lake waters rich in inorganic nutrients (Prosser *et al*., 1968). In this closed lake basin, without obvious surface outflow and where evaporation loss balances inflow and direct precipitation, underground outflow accounts for its saline nature (Wood and Talling, 1988).

Table1. Some morphometric and physico-chemical features of Lake Bishoftu (Source: [a] Wood and Talling, 1988 and, others fromZinabu Gebre-Mariam, 1994).

| Parameters | Values |
|---|---|
| Altitude (m) [a] | 1870 |
| Surface Area ($km^2$) [a] | 0.93 |
| Maximum depth (m) [a] | 87 |
| Mean depth (m) [a] | 55 |
| Volume ($Km^3$) [a] | 0.052 |
| Salinity (g/L) [a] | 1.92 |
| Conductivity ($K_{20}$, µS $cm^{-1}$) [a] | 1830 |
| Alkalinity (meq $l^{-1}$) [a] | 20 |
| Chl a (µg/L) | 60 |
| pH | 9.20 |
| $NO_3$-N (µg/L) | 25 |
| $PO_4$-P (µg/L) | 280 |
| $SO_4$ (mg/L) | 0.018 |
| Si as $SiO_2$ (mg/L) | 15 |
| Na (mg/ L) | 33 |
| Mg (mg/L) | 4.22 |
| K (mg/L) | 1.82 |
| Ca (mg/L) | 1.00 |
| Cl (Mg/ L) | 4.34 |
| Total cations (mg/L) | 40.04 |
| Total anions (mg/L) | 40.04 |

The lake is grouped with some East African lakes including Lakes Muntanda and Bunyoni in Uganda, Pawlo (Babogaya) and Awassa in Ethiopia, which are characterized by a pronounced and deep-seated thermal stratification (Baxter *et al.,* 1965; Wood *et al.*, 1976). The lake is also known by infrequent complete mixing (Oligomictic), which is also the feature of other East African lakes such as Lakes Bunyoni, Ndalaga and Luhondo in highlands of Uganda and Lake Pawlo in Ethiopia (Baxter *et al.,* 1965).

The lake has oxygen depth-maximum in the uppermost 0 to 5 m layer (Baxter *et al*., 1965) and shows decline of oxygen concentration near the surface due to the influence of rising temperature. Depletion of DO in the lake is connected with the barrier of thermal gradient formed in the upper 0 to 20 m zone (Baxter *et al*., 1965) and the superficial diurnal stratification merges with deeper and more persistent stratification.

Depth profiles of chemical stratification with regard to phosphate-phosphorus and ammonia-nitrogen, and presence of hydrogen sulphide under stratified conditions are common features of Bishoftu and Pawlo among Ethiopian crater lakes (Baxter *et al*., 1965).

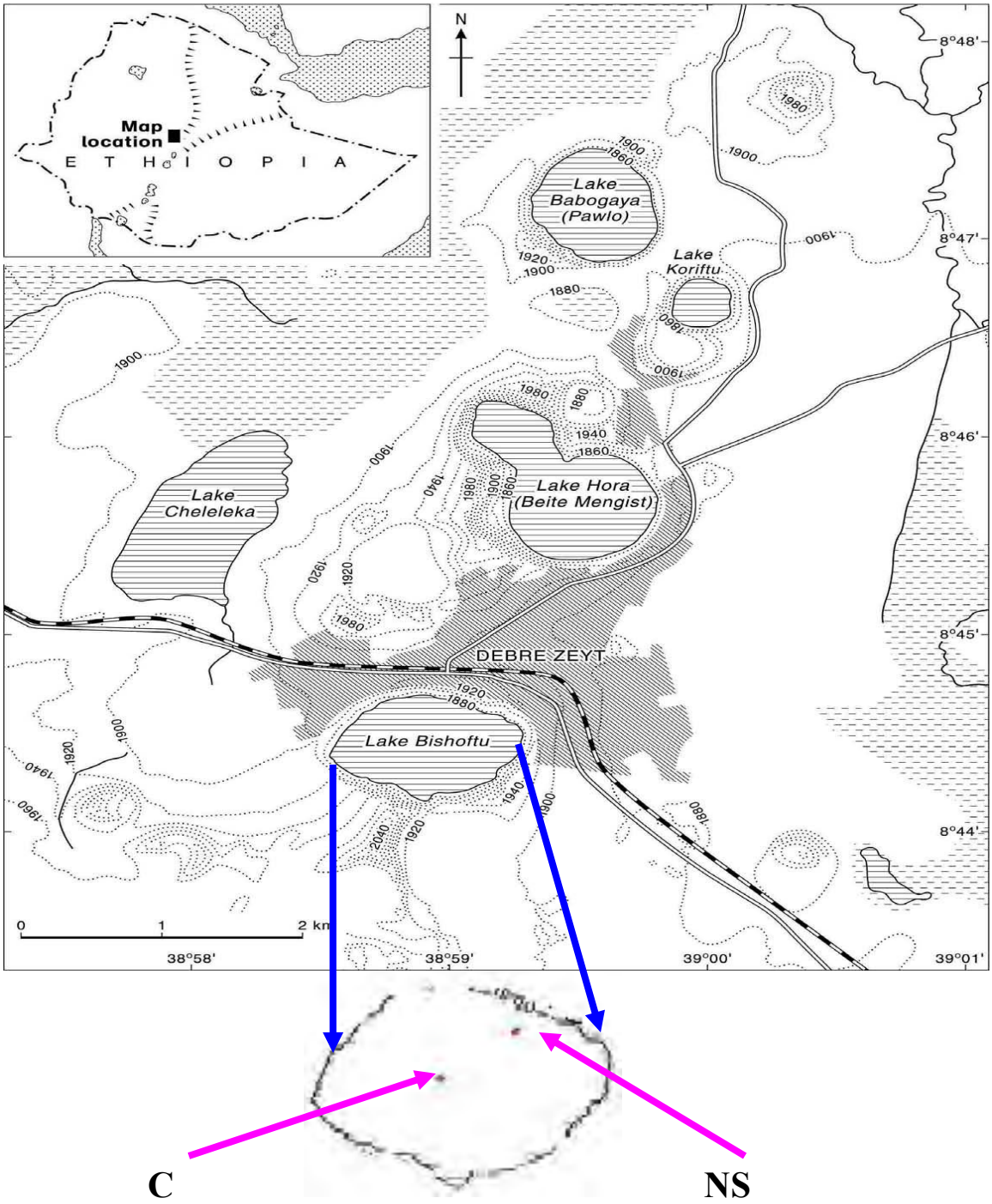



Fig.1. Location of Lake Bishoftu, in relation to other Bishoftu (Debre-Zeit) Crater Lakes (Source; Lamb, 2001), with sampling stations (C- central, NS -Near-shore) indicated.

On the basis of total electrolyte concentration, Lake Bishftu is grouped with 12 Ethiopian and Rift Valley lakes that are considered as saline in the salinity series and lacking surface out flow (Wood and Talling). The water was found to be alkaline with a pH of 9.2, with the erosion of basaltic and hyper-alkaline rocks surrounding the lake playing an important role in increasing the alkalinity of the water (Prosser *et al*., 1968). Carbonate-bicarbonate is the major anion whereas $Na^+$ is the dominant cation (Rippey and Wood, 1985).

The phytoplankton community is dominated by blue-green algae, particularly *Microcystis aeruginosa* (Wood and Talling, 1988; and present study), while the zooplankton is composed mainly of copepods [*Lovenula africana (*Daday), (Green, 1986; Afeworki Ghebrai, 1992).The two zooplanktivorous fish, *Aplocheilichthys sp*. (Pisces: *Cyprinidae*) and *Oreochromis niloticus* (Pisces: *Cichlidae*) are present in this Lake (Afeworki Ghebrai, 1992). There has been very few fishing activites, only around the shores on Tilapia (*Oreochromis niloticus* L.) (Personal observation) and even the existing zooplanktivorous fish are confined to the shores as the lake is very deep (85 m) and anoxic below 10 m depth as confirmed from depth profile of dissolved oxygen measurement centre, and the shore has littoral area for spawning.

## 1.4. OBJECTIVES

### General Objective

- To investigate the temporal dynamics in the community structure and primary production of phytoplankton in relation to water quality in Lake Bishoftu

### Specific Objectives

- To generate data on dominant plankton composition of the lake.
- To determine the temporal changes in the species composition, biomass and primary production of phytoplankton in Lake Bishoftu.
- To assess temporal and spatial variations in the physico-chemical conditions of the lake over the study period.
- To identify factors of overriding importance in determining the temporal changes in the species composition, biomass and photosynthetic production of phytoplankton in Lake Bishoftu.
- To generate water quality and biological data, which may be useful in developing management and conservation strategies of our aquatic resources.

# 2. MATERIALS AND METHODS

## 2.1. Sampling Protocol

The study lake is roughly circular and enclosed by a steep crater wall on all sides. Human interference is more intense on the sides facing the town, Debre Zeit. On the east- west side there is access to the lake for recreation and watering of livestock. From near the top of the crater wall where resorts and residences are found, domestic wastes are dumped and small-scale activities like traditional tannery activities are carried out. Therefore, two sampling stations (Fig. 1) were selected on the basis of the extent of human interference. One was roughly central (C) in position (about 85m depth), which was assumed to be less impacted and the other was near-shore (NS) (about 20m in depth) and considered as more impacted.

Water samples collected and field measurements were made at both stations at about monthly intervals. For qualitative analysis, identification of dominant plankton species, nets were used, and for quantitative ones such as determination of alkalinity and analysis of inorganic nutrients, estimation of phytoplankton abundance, primary production and biomass as Chl a concentration, composite samples were used. Composite samples were prepared for both stations using samples collected by a bottle sampler (Kemmerer) from different depths distributed within the euphotic zone and mixed in equal proportions in a large bucket. Preparation of composite samples was required to make the analyses of samples manageable as the analysis of samples collected from different depths for biomass and nutrient requires a lot of time and resources. Some of the composite samples were poured in one litre plastic bottles and placed in an ice box for later use.

## 2.2. Measurement of Physico-Chemical Parameters

Different physical and chemical parameters were measured *in-situ* or analyzed in the laboratory using available instruments and appropriate methods. The various equations used in the estimation of different parameters are shown in Appendix 18.

### 2.2.1. In-situ measurements and calculation of secondary data

Depth profiles of temperature and oxygen were determined using an oxygen meter connected to oxygen-temperature combination probe (model HI 9143). pH of surface water was measured using a digital pH meter (Hanna 9024). All the meters were calibrated every time before taking measurements. Water transparency (vertical visibility) of the lake was estimated with a standard Secchi Disc of 20 cm diameter. Underwater down-welling irradiance (PAR) was measured *in-situ* using LI- COR nderWater Quantum Sensor (LI-192 SB) connected to LI-185 B photometer. From the under water irradiance measurements, the mean extinction coefficients of down welling irradiance ($K_d$) were calculated. Using the calculated values of $K_d$, euphotic depth ($Z_{eu}$), the depth at which the down-welling irradiance is 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 range from 0.006 to 0.018 (Kirk, 1975; Dubinsky and Berman, 1981). The intermediate value, 0.016 (Dubinsky and Berman, 1976) was used for the calculation of Ks in this study. Integral irradiance, PAR incident on a horizontal surface during the period of incubation for primary production measurements was measured with LI-COR quantum sensor (LI- COR190SB) connected to LI-510B Integrator, which was placed on the shore and the readings of the integrator were recorded at 15-minute interval and the integral PAR was determined according to the equation in Kalf (2002).

### 2.2.2. Chemical Analysis

**Alkalinity**

Total and Phenolphthalein alkalinity of the lake were determined by titration with 0.01N HCl to a pH of 4.5 using Phenolphthalein and Bromcresol green - methyl red indicator solutions within a few hours after sample collection and expressed as meq $L^{-1}$ according to Wetzel and Likens (2000). Free $CO_2$ (mg $L^{-1}$) was estimated using alkalinity and pH according to Rainwater and Thatcher (1960; cited in Lind, 1979).

**Analysis of inorganic nutrients in the laboratory.**

Inorganic nutrients, which are important for the growth and reproduction of phytoplankton, were analyzed using standard methods (APHA *et al*., 199; Wetzel and Likens, 2000; Lind, 1979; Nelson *et al*., 1954). The regression equation of the standard curve produced by plotting absorbance against concentrations of standard solutions was used to determine the concentrations of each nutrient in the water samples (see equation 7-10 in App. 18). Composite samples that were collected from depths distributed within the euphotic zone filtered with Glass Fibre filter Paper (GF/F) within 5-6 hours of sample collection were used for the analysis of inorganic nutrients. The absorbances of reduced colored solutions were measured with a spectrophotometer (Model PYE UNICAM SP6-350 visible spectrophotometer) and the concentrations of inorganic nutrients were determined using regression equations produced for each nutrient.

Nitrate + Nitrite-nitrogen ($NO_3$ + $NO_2$-N) concentration was determined using Zinc Reduction method (Nelson *et al.,* 1954). $NH_4^+$ + $NH_3$ –N was analyzed by the Phenate Method (Wetzel and Likens, 2000). Dissolved $SiO_2$ (only Molybdate reactive Silica) was determined using Molybdosilicate method (APHA *et al*., 1999). Soluble reactive phosphate (SRP) and total phosphate (TP) were

determined by the Ascorbic Acid method (APHA *et al*., 1999). TP was determined by the Ascorbic Acid method after persulfate digestion of the sample. A molar concentration of total nitrogen was calculated from $NO_3$ + $NO_2$-N and $NH_4^+$ + $NH_3$ –N compounds for the estimation of Redfield Ratio of TN: TP.

### 2.3. Biological Parameters

#### 2.3.1. Identification of species and estimation of abundance of plankton

For the estimation of phytoplankton abundance, composite samples prepared for two stations using 1L bottle sampler were used. From the composite samples, 100 ml aliquots were removed and placed in a brown bottle (125ml) for both stations and preserved with Lugol's iodine solution. These were transported to the laboratory and transferred to a sedimentation chamber (measuring cylinder of100 ml) and stored in darkness for sedimentation. After a period of 24 hours, the upper 90ml of the sample was siphoned off and the remaining 10ml was mixed to make it homogenous. Of which 1ml sample was pipetted into Sedgwick-Rafter cell and cells within 30-40 grids were counted randomly under an inverted microscope (Nikon) at a magnification of150 x. The cell number (cells $ml^{-1}$) of the lake water was calculated according to Hotzel and Croome (1999) and Wetzel and Likens (2000) (see Equation. 11 in Appendix 18). The cell counts of major phytoplankton species were added together to give total abundance.

Both preserved and fresh samples taken with phytoplankton net (10µm pore size) were used for the identification of major phytoplankton taxa using the identification keys of Whitford and Schumacher (1973), Gasse (1986), Komarek & kling (1991), Cronber & Komarek (2004) and Komarek and Anagnostidis (2000).

Zooplankton samples were collected from both stations by towing upward from 4 meter depth using a # 25 townet (64 µm) and preserved with 5% formaldehyde

solution in dark glass bottles of 125 ml capacity. Four meter depth was selected to relate zooplankton abundance within this depths with that of phytoplankton within the euphotic zone. In the laboratory, the sample was homogenized and 20 ml sub-sample was taken with a wide mouthed pipette and placed in a gridded Petri dish. Zooplankton including their developmental stages (napuli and copepodites) in three to four grids were counted under a binocular microscope (40 x magnifications) and estimation of individual and total (sum of individuals) abundance in four occasions (study months) were calculated using the formula of Edmondson and Winberg (1971, cited in Kassahun Wodajo and Amha belay, 1984 and Green, 1986) (Equation. 12 in Appendix 18). Identification of the major zooplankton genera or species was done using keys in Defaye (1988) and Fernando (2002)

### 2.3.2. Phytoplankton Biomass as Chlorophyll a concentration

Chlorophyll a concentration (uncorrected for phaeopigments) was determined by measuring the absorbance of pigment extracts. Appropriate volumes of composite samples of the lake water were gently filtered through 47 mm diameter Glass Fibre Filter paper (Whatman grade GF/F: 0.6 -0.7 µm pore size) with the aid of electrically operated suction pump (Model SPEEDIVAC 2). The filters were manually ground in a test tube with a glass rod with a small volume of 90% acetone and transferred to parafilm-covered centrifuge tube and centrifuged at 3000 rpm for 10 minutes. The extract was then decanted into a 25 ml volumetric flask and made up to the mark with 90% acetone. The optical density of sample extract (absorbance) was then measured against a blank at 665 and 750nm 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 (Equation 13 in Appendix 18) of Talling and Driver (1963) and the euphotic zone chlorophyll a ($\sum B$) was estimated by multiplying B with $Z_{eu}$ (Erikson *et al*., 1991).

### 2.3.3. 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). The composite samples of the lake water were transferred to transparent (light) and opaque (covered with dark and thick plastic sheath) boro-silicate glass bottles (250 ml capacity), and suspended *in-situ* at different depths within the euphotic zone (0.0, 0.25, 0.5, 1.0, 1.5, 2.0, 2.5, 2.75, 3.0 and 3.25 meters) for periods of 2-3 hours beginning from 11 A.M. Duplicate bottles containing samples were fixed with Winkler reagents immediately after incubating the light and dark bottles to serve as initial bottles. After the end of incubation periods, bottles were taken out and fixed with Winkler reagents and transported to the laboratory in light-proof boxes.

The concentration of oxygen (mg $O_2$ $L^{-1}$) in each bottle (Initial, Dark and Light bottles) was determined by titration with standard Sodium thiosulfate solution (0.0125N) (without modification) that was prepared following the procedures ioutlined in Lind (1979) and using starch as an indicator solution. Using the concentration of $O_2$ determined from initial, dark and light bottles net and gross photosynthetic rates and respiration were estimated (Equation 14, 15, 16 &17 in Appendix 18) and the concentration of $O_2$ was converted to assimilated Carbon to calculate photosynthetic efficiency on caloric basis. Conversion of the rates of oxygen released to the rates of carbon assimilated was made assuming a photosynthetic quotient of 1.2 (Wetzel and Likens, 2000). Different related photosynthetic parameters were estimated using different equations. The volumetric rates of gross photosynthesis were converted to areal rate of gross photosynthesis using Grid Enumeration Technique (Olson, 1960), which determines the area of the curve formed by plotting gross photosynthesis against depth. 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 estimated by dividing volumetric rates of gross photosynthesis.by phytoplankton biomass. Photosynthetic efficiency of light utilization was calculated (as %) by converting the calculated assimilated carbon and integral irradiance to calorie (see Appendix 18).

### 2.4. Statistical Analysis

Different statistical computer programs such as Sigma Plot 2000, MINITAB 14 student, SPSS and Microsoft Excel were used for statistical analysis. The significance of the difference in each variable between the two sampling stations was tested using paired t-test. The interdependency of variables was analyzed using regression and correlation.

### 2.5. Description of symbols

$Z_{SD}$ ……. Secchi depth (m)

$Z_{eu}$ …….. Depth of euphotic zone (m)

$K_d$ …….. Mean downward extinction coefficient (ln unit $m^{-1}$)

Ks …….. ….. Biomass specific extinction coefficient, ln units $m^{-1}$ (chl a)$^{-1}$.

$K_w$ ……. Attenuation coefficient of non–biological components of the water

Chl a ……. Chlorophyll a (mg $m^{-3}$ or µg $L^{-1}$ or µg $L^{-1}$)

B …….. Phytoplankton biomass (mg Chl a $m^{-3}$)

GP …….. Gross photosynthesis (mg $O_2$ $m^{-3}$ $h^{-1}$)

NP ……. Net photosynthesis per unit water volume, (mg $O_2$ $m^{-3}$ $h^{-1}$)

A …… Gross photosynthesis per unit water volume, (mg $O_2$ $m^{-3}$ $h^{-1}$)

$A_{max}$ …… Light- saturated rate of gross photosynthesis per unit volume, (mg $O_2$ $m^{-3}$ $h^{-1}$)

P……. (A/B) Specific rate of gross photosynthesis per unit biomass, 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, mg $O_2$ (mg Chl a)$^{-1}$ $h^{-1}$

Φ ……Photosynthetic efficiency or light utilization of phytoplankton (%)

∑A……Hourly areal rate of gross photosynthesis, mg $O_2$ $m^{-2}$ $h^{-1}$

∑∑A …… Daily areal rate of gross photosynthesis, mg $O_2$ $m^{-2}$ $d^{-1}$

PAR …… Photosynthetically Active Radiation (E $m^{-2}$ $h^{-1}$)

$I_o$ …….. …. ..... Surface irradiance, (μE$m^{-2}$ $s^{-1}$ )

$I_Z$ ..... Downwelling irradiance at depth Z (μE$m^{-2}$ $s^{-1}$)

C……. Central station

NS…….. .... Near shore station

PA …… Phenolphthalein alkalinity (meq $L^{-1}$)

TA ……Total alkalinity (meq $L^{-1}$)

TP……..Total Phosphorus

## 2.6. Meteorological Data

Fig 2 shows the temporal variations in total monthly rainfall, and the monthly mean minimum and maximum air temperature of the study area. The mean minimum air temperature varied from 8.4 in November to 13.8 $^oC$ in August, 2006, and that of the mean maximum air temperature declined from a maximum of 29.3 in March, 2007 to a minimum of 23.6 $^oC$ in September, 2006. Wind speed data are important in analyzing mixing conditions of the ater column, however, in this study wind speed data are not included considering that wind most probably has low effect because of the long crater rims of the lake.

Between Feb and June, 2007 (a period of low rainfall) mean maximum air temperature continued at its peak and then declined from July, 2006 to Jan, 2007(a period of peak precipitation). The peak of mean maximum air temperature, Feb to May, 2007, coincided with low rainfall periods while the period of low mean maximum air temperature corresponded to months of high monthly total rainfall (June to December, 2006).

Total monthly rainfall ranged from 5.2 in Nov to 329 mm in July, 2006. No rainfall was recorded in Feb, March and May, 2007. The seasonal peak of rainfall continued from June to Dec, 2006 and showed its lower levels from Feb to May, 2007.

Based on these data, the study area received precipitation with low air temperature from June to Dec and continued to be dry with low rainfall from Feb to May, 2007. Variations in rainfall have direct effects on lakes where surface or seepage outflow is a small component of the water budget compared to a relatively constant evaporation (Talling and Lemoalle, 1998). Lake Bishoftu, which has no obvious inflow or outflow, depends on rainfall as water source. Thus, seasonal dynamics of physico-chemical and related biological variables depend principally on rainfall. The temporal change in temperature is important in the study of productivity of phytoplankton since the higher tropical photosynthetic rate arises from increased temperature values (Lemoalle, 1981).

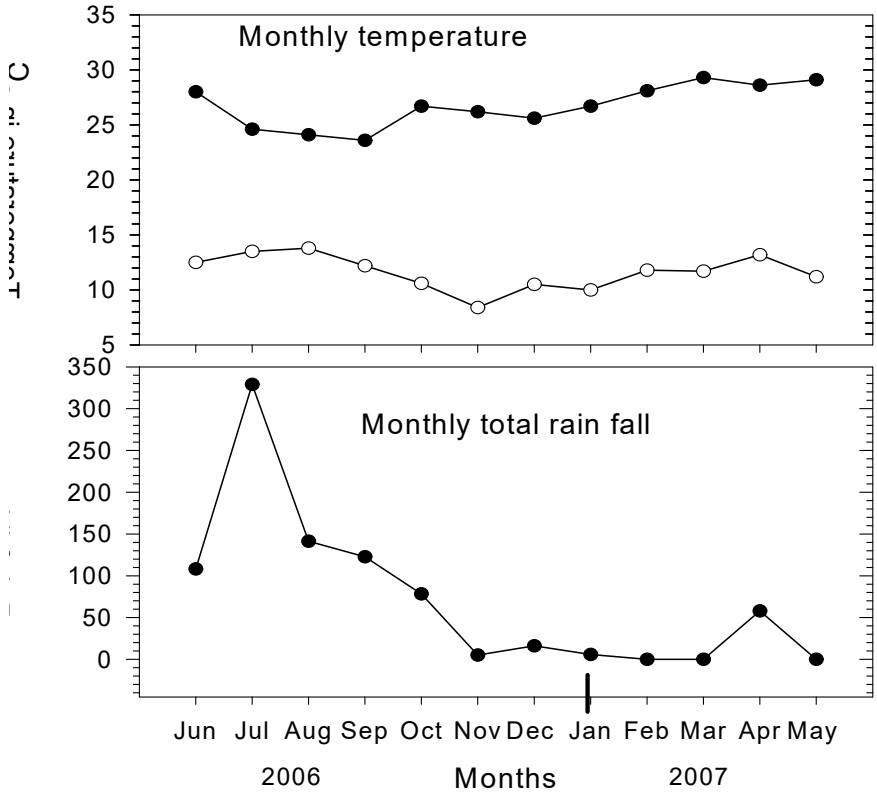



Fig.2. Monthly rainfall and mean minimum (open circle) and maximum (solid circle) temperature of the study area from June, 2006 to May, 2007.

# 3. RESULTS AND DISCUSSION

## 3.1. Physico- chemical features

### 3.1.1. Depth profiles of Temperature and Oxygen

The depth profiles of temperature and dissolved oxygen of the study lake are shown in Fig 3 (see also Appendix 1). Surface water temperature varied from the lowest value of 22.22 $^{o}$C in December, 2006 to a maximum value of 25.8 $^{o}$C in May, 2007. On all the sampling dates, the water temperature at the deepest depth of measurement (15-17m) ranged from a minimum of 18.9 $^{o}$C at 17m in May, 2007 to a maximum of 20.85 $^{o}$C at 15m in November, 2006 and the ranges of temperature for the surface water and around 17m depth are slightly higher than the previously reported values, with surface values ranging from19.2 to 24.5 $^{0}$C and the bottom temperature being almost constant (19.2-19.4 $^{o}$C) (Wood *et al.*, 1976). The slight increase in temperature is probably associated with different types of measurements.

The range of surface water temperature is broadly similar to those of Lakes Babogaya (22.3-26.8 $^{0}$C; Yeshiemebet Major,2006), Awassa (20.5-28.4; Demeke Kifle, 1985), Ziway (18.5- 27.5; Girma Tilahun, 1988) (for more see Appendix 2 ) and slightly lower than the lowest value of the range for Lake George (26-36 $^{0}$C; Ganf and Horne,1975) in East Africa. The decline in temperature per metre of depth by about one or more than one $^{o}$C with increasing depth was observed near the surface in the 0-2 m depth layer in all months of the sampling period except in October, 2006 and January, 2007. In October, 2006 and March, 2007 no superficial stratification was seen whereas in January, 2007 the afore-said decline in temperature with increasing depth was seen around 2-3 m depth layer. In April, 2007 the drop in temperature by more than 1 $^{0}$C per depth was seen between 0 and 1m depth and around 8-10 m depth indicating the presence of double thermoclines with superficial and deep-seated thermal stratification. In the 0-1m depth layer, temperature gradients varied from1 $^{0}$C in November to 1.9 $^{0}$C in

August, 2006. Superficial thermal stratification near the water-surface was generally observed with thermoclines between 0-3 m depths (see Fig. 3).

Temperature difference between surface and 15m depth was 2.42 $^0$C in October, 2006 and 4.1 $^0$C in March, 2007, the latter representing the largest temperature difference between zero and 15m depth of the column of the lake water.

Deep-seated stratification is often distinct, resulting in an upper warm epilimnion, and a lower cool hypolimnion (Wetzel, 1983). It has been stressed by Wood *et al*. (1984) that distinguishing the epilimnion is difficult on purely thermal ground. Wood *et al*. (1984) observed multiple and sometimes diffuse thermoclines in lakes Pawlo and Bishoftu. The tropical crater lakes Bunyoni and Edward are stratified and had anoxic hypolimnia, although there was no clear thermocline (Beadle, 1963). Well-marked and persistent thermal stratification may have occurred in Lake Bishoftu in parts of the water column deeper than the cable of the oxygen-temperature meter used in the present study could reach. Although the present information on the thermal regime of L. Bishoftu is limited, the results support reports of previous studies.

Pronounced and deep-seated thermal stratification has also been previously reported for the Ethiopian lakes, Lake Bishoftu and Pawlo (Wood *et al*., 1984) and Lake Awassa (Elizabeth Kebede and Amha belay, 1994). In Lakes Bishoftu and Pawlo, which have steep-sided crater walls, thermal gradients occupied the upper 0-20m zone and the superficial diurnal stratification merged with a deep-seated stratification (Baxter *et al*., 1965).

Well-marked thermal stratification between 0.5-1.25m with the temperature dropping from 25 to 21.2 $^o$C and dissolved oxygen (DO) from supersaturation to 4.2 mg $L^{-1}$ at 4m was seen in Lake Abijata (Elizabeth Kebede *et al*., 1994). Thermal stratification with thermoclines extending between 2 and 7m in Lake

Kilole was also observed in 1990-1991 (Brook Lemma, 1994); which was associated with the increased depth attained after diversion of River Mojo and the cone-shaped water basin, which prevented wind-induced mixing. Similarly, Lake Bishoftu has great depth and taller crater rims, which probably contributed to the observed stratification. Steeper thermal gradients are often observed in East African lakes including the Ugandan lakes Muntanda and Bunyoni (Baxter *et al*., 1965).

Two types of thermal stratification, superficial and deep-seated, were observed in East African lakes at altitudes of 1500-2000 m (Baxter *et al*., 1965). Superficial stratification is generated daily by solar heating and destroyed by nocturnal cooling and mixing, which affects the 0-3 m stratum in which steep gradients of temperature can develop during calm weather. According to Baxter *et al*. (1965) in lakes with maximum depth in excess of 15-30m like Langano, Pawlo and Bishoftu may show pronounced and deep seasonal stratification with complete or nearly complete mixing.

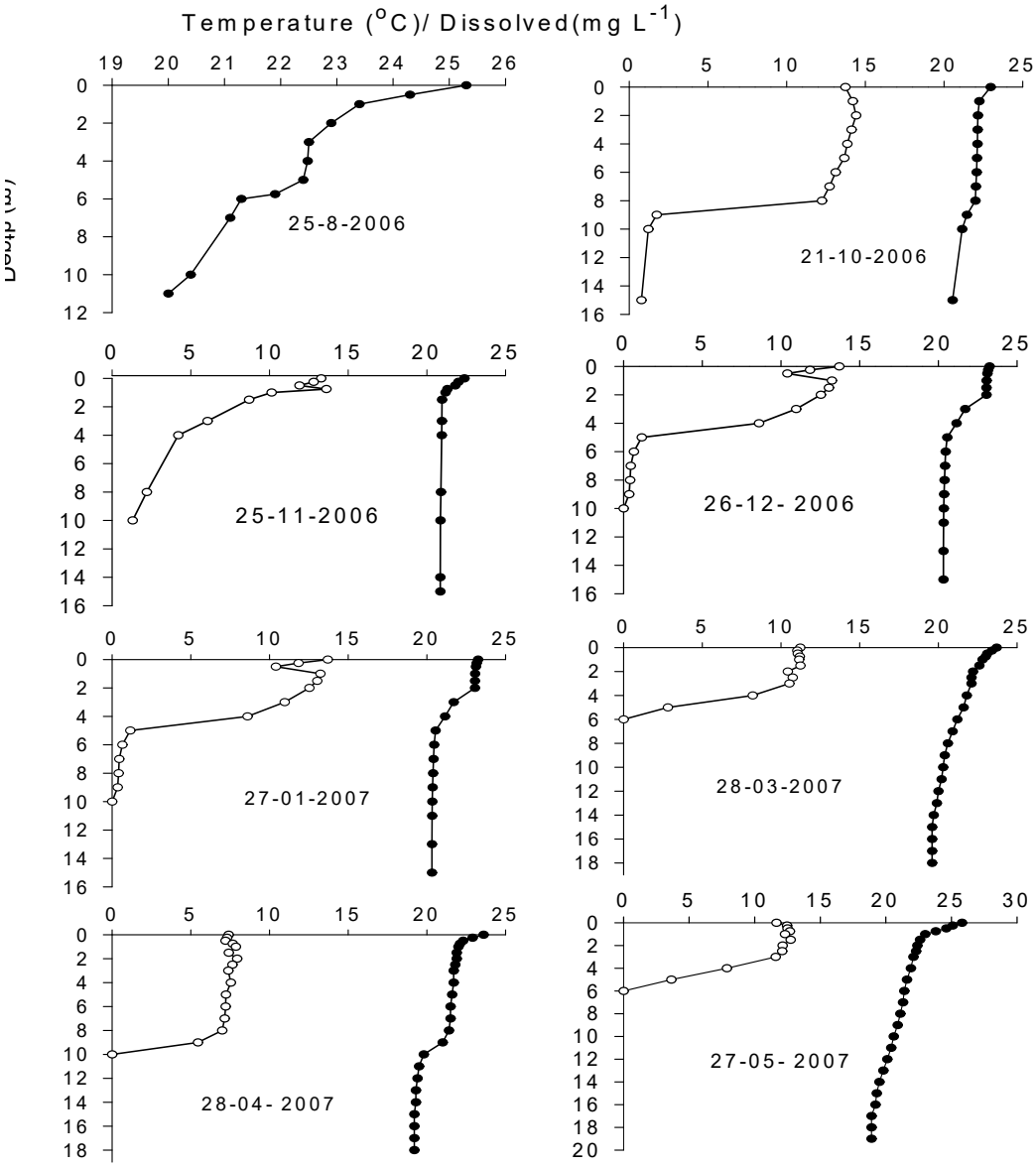



Fig 3. Depth profiles of temperature (solid circle) and dissolved oxygen (open circle) during the study period at central station of Lake Bishoftu.

Depth profiles of temperature and dissolved oxygen during the study period at central station of Lake Bishoftu

Dissolved oxygen (DO) of surface water varied from 7.4 in April, 2007 to a maximum of 13.73 mg/L in October, 2006. Oxygen-maxima were observed between 0.5 -2 m depths (Fig. 3). The maximum concentration of DO recorded in

this study was slightly higher than the previously reported highest concentration, while the minimum surface value was 7.4 mg $L^{-1}$, which is also higher than the previously reported value. The low concentration of DO in April, 2007 was associated with increased photoinhibition (deduced from high % reduction of photosynthetic rate from $A_{max}$), low phytoplankton abundance and biomass and prominent stratification with two thermoclines. The higher concentration of DO in October, 2006 was probably associated with increased areal biomass and presence of incomplete mixing as can be seen from depth profiles of temperature (without thermocline) and DO. High algal biomass produces more dissolved oxygen in aquatic systems (Margaleff, 1996).

On all the sampling days, the values of DO were low in the part of the water column between the surface and the depth of oxygen maxima, a situation observed in Lake Kilole after attaining higher depth due to diversion of River Mojo into it (Brook Lemma, 1994). The decline in oxygen concentration near the water surface in some tropical lakes is accentuated by the influence of rising temperature on the saturation concentration (Baxter *et al*., 1965) and photoinhibition (Melack, 1979a; Goldman *et al*, 1963).

Abrupt drops in DO (Oxyclines) corresponded to the depth of thermocline following thermal stratification. Similarly, DO showed sharp discontinuities between 0.5-1.5 m and between 3-4.5 m with complete deoxygenation below 5 meter in Lake Abijata (Elizabeth Kebede *et al*., 1994) and also in Lake Kilole (Brook Lemma, 1994). In stratified Ethiopian lakes, Pawlo and Bishoftu, oxygen depletion was associated with the barrier of thermal gradients and the highest concentration of DO found in Lake Bishoftu was <12 mg $L^{-1}$ (Wood *et al*., 1984).

Oxygen-maxima were observed between 0.5 -2 m depths (Fig. 3). The value of oxygen-maximum varied between 7.94 mg $L^{-1}$ in April, 2007 and 14.41 in October, 2006. In March and May, 2007 DO was depleted at 6 meter depth; below which

the water column was completely anoxic. Except in October, when 0.77 mg $L^{-1}$ $O_2$ was recorded around 15m depth, on all sampling days the water column was anoxic below 13m depth. Oxygen-maximum was found at a shallow depth near the surface (at 0.25m depth) in December, 2006.

Depth maximum of oxygen can be formed when thermal gradient in the water column occurs within the photosynthetic zone (Baxter *et al*., 1965). From the study of oxygen depth profiles of six Ethiopian lakes including Lake Bishoftu, Baxter *et al*.(1965) indicated that most of the lakes showed an oxygen maximum in the uppermost 0-5 m layer, a similar phenomenon observed in this study. The observed oxygen-maximum was associated with a superficial thermal stratification, which usually implies a steep temperature gradient in the uppermost 0-3 m stratum during warm and calm weather, and this gradient is a barrier to turbulent mixing resulting in *in-situ* accumulation of oxygen produced by photosynthesis.

Generally, depth profiles of DO and temperature differences between surface and bottom waters in Lake Bishoftu (with a maximum depth of 85 m: present study) do not indicate the presence of complete mixing. Any incidences related to water turnover such as fish kill, a situation observed in Lake Bunyoni, a volcanic barrier lake in Uganda, in 1964 and associated with partial mixing (Beadle, 1981), were also not seen during the study period. In his survey of 16 crater lakes in western Uganda, Melack (1978) found that all lakes over 5 m depth were characterized by an anoxic hypolimnion, and concluded that complete mixing in the deeper crater lakes is rare, but it can occur under unusual conditions (e.g. stron wind) (atlomixis).

Similarly, it was indicated that the East African lakes such as Lake Bunyoni, Ndalaga and Luhondo in the high lands of Uganda and Lakes Bishoftu and Pawlo of Ethiopia (Baxter *et al*., 1965; Talling and Talling, 1965) are

characterized by infrequent complete mixing (oligomictic) or lack of complete mixing, and these features are governed by local conditions such as being small in area, lying in depressions and presence of steep-sided crater wall, which affect wind fetch. Depth of the lake affects mixing in deep tropical lakes such as Lake Tanganyika and Nyasa (Baxter *et al*., 1965). Beadle (1981) argued that the major determinant of circulation in tropical lakes is wind rather than the seasonal fluctuations of illumination and atmospheric temperature. However, the wind regime over the Bishoftu lakes seems to have little effect apart from facilitating cooling by evaporation (Wood *et al*., 1984) as the lakes are sheltered within crater rims.

The absence of superficial thermal gradient near the surface in October, 2006 has probably enhanced mixing of the surface water. Despite superficial circulation during this period, the water column was devoid of oxygen down to16 m depth. Beadle (1981) suggested that there may be other more gradual processes providing some slow mixing in deep tropical lakes, but are not rapid enough to override oxygen consumption in the deep hypolimnion. In Lake Mainit-Philippines (Lewis, 1973a) circulation is not vigorous enough to offset oxygen consumption leading to continuous deep water anoxia (Lewis, 1973b).

### 3.1.2. Optical Characteristics of Lake Bishoftu

The seasonal variations in optical parameters measured during the study period are indicated in Fig.4 and Appendix 3.

#### *Secchi ($Z_{SD}$) and Euphotic ($Z_{eu}$) Depths*

Water transparency ($Z_{SD}$) varied from a minimum value of 0.50 and 0.46 m in December, 2006 to a maximum of 1.05 and 1.0 m in April, 2007 at the central and near-shore stations respectively. All values, except the seasonal maxima, were below 1 m with a mean value of 0.73 m (Fig.4, Appendix 3). High values of

water transparency coincided with dry periods (with low precipitation) whereas low values were recorded during rainy months. The difference in $Z_{SD}$ between the two stations was statistically significant ($t(8) = 6.36$, $P = 0.0002$). A lot of human activities including swimming, washing clothes, watering animals and damping of solid and liquid wastes were observed on the shores around the near-shore station. These activities, which introduce and cause resuspension of particles, have probably contributed to the significant difference in water clarity between the two stations.

Reported $Z_{SD}$ transparencies range from a few centimetres in turbid lakes to over 40 meters in few clear lakes with values for most lakes in the range of 2 to 10 m (Wetzel and Likens, 2000). The water transparency of the present study lake is within the range of $Z_{SD}$ given for eutrophic lakes by Carlson (1977) in his description of trophic state index. The observed water transparency of Lake Bishoftu is very similar to the reported range for lake Awassa (0.65 – 0.95 m; Demeke Kifle and Amha Belay, 1990). The maximum $Z_{SD}$ is closer to the value reported for Lakes Hayq (1.24m; Baxter and Golabitsch, 1970) while the minimum is closer to the water transparency recorded for Lake Abaya (0.43 m ; Elizabeth Kebede *et al*, 1994). The lake has $Z_{SD}$ higher than the shallow east African lake; Lake George (0.4cm; Ganf and Viner, 1973). More values of $Z_{SD}$ of other lakes are given for comparison in Appendix 4.

The increase in water transparency was associated with periods dominated by large copepod zooplankton grazers which presumably removed the phytoplankton biomass in March, 2007 while decreased transparency coincided with the highest $K_d$ due to large non-biological turbidity in December, 2006.

The euphotic depth ($Z_{eu}$), the depth at which 1% of the surface PAR is detected, was calculated from the relation $Z_{eu} = 4.6/K_d$ (Kalff, 2002). It ranged from 1.59 m of December, 2006 to 3.65 m of May, 2007 with a mean value of 2.57. Higher values were seen during March to May, 2007. The present range of $Z_{eu}$ of Lake

Bishoftu is broadly similar to the range reported for Lake Awassa in 1985 ($Z_{eu}$=1.59 -2.7m; Demeke Kifle and Amha Belay, 1990) but higher than those recorded for other East African lakes such as Lakes Arenguade (0.15-0.27m; Talling *et al*., 1973), Kilole (0.24-0.38m; Talling *et al*., 1973), Ziway (0.4-1.06 m; Girma Tilahun, 1988), Chamo (0.67-1.25 m; Eyasu Shumbulo, 2004), Nakuru (0.22-0.41m; Vareschi, 1982) and Lake George (0.7 m; Ganf, 1975). The lowest $Z_{eu}$ of Lake Bishoftu is about three times lower than the lowest values of Lake Shalla (4.93 m; Amha Belay and Wood, 1984) and the nearby crater lake Babogaya (4-15 m; Yeshiemebet Major, 2006) (for more see Appendix 5)

**PAR, $K_d$ and Ks**

Integral Photosynthetically Available Radiation (PAR) varied from a minimum of 2.07 in March, 2007 to a maximum of 5.64 E $m^{-2}$ $h^{-1}$ in December, 2006 with a mean value of 4.11 E $m^{-2}$ $h^{-1}$.

Mean vertical extinction coefficient of down-welling irradiance ($K_d$) varied between a minimum of 1.26 in December, 2006 and a maximum of 2.9 ln units $m^{-1}$ in May, 2007 and had a mean of 1.92. The calculated biomass-specific light extinction coefficient or fractional extinction coefficient ($k_s$) varied from 7.3% in December to 20.1% (chl a) $^{-1}$ $m^{-1}$ in October, 2006 (Fig. 4; App. 3) while light extinction due to non-biological components ($K_w$) (see App. 3) ranged from 79.9 to 92.7% in October and December; 2006 respectively. Light attenuation due to non-algal turbidity was high in four Ethiopian Rift valley lakes, Langano (94-98%), Shalla, Ziway and Abijata (78%) (Wood *et al*., 1978), a situation observed in Lake Bishoftu. $K_d$ was positively and significantly correlated with areal chl a (r=0.80, p=0.016). High values of light extinction coefficient are typical of lakes with dense algal crops or with suspended silt and produce shallow euphotic zones (Ganf, 1972; Talling *et al*., 1973). Similarly, roughness of the water surface and cloud cover influence the transfer of light into the water,

and the water itself plus the seston and solutes determine the light attenuation (Melack, 1979).

$K_d$ values of natural lake waters range from nearly 0.2 $m^{-1}$ in such clear lakes as Crater Lake and Tahoe in USA (Smith *et al*., 1973) to about 4 $m^{-1}$ in highly stained lake waters with high biogenic turbidity (Wetzel, 2001). The observed value of $K_d$ for Lake Bishoftu is within this range. However, it showed seasonal variation which was related to different biological and non-biological factors. Values of biomass specific extinction ($K_s$) vary with the taxonomic composition of the phytoplankton, their physiological state (Dubinsky and Polna, 1976), geometry (Kirk, 1976) and cell size (Jewson, 1977), large cells tending to have lower specific extinction coefficient-$K_s$ (Kirk, 1975), as well as with depth dependent changes in the spectral properties of the underwater light field (Smith and Baker, 1978).

In December, the maximum $K_d$ observed was not contributed by $K_s$ rather by $K_w$, and $K_s$ had higher percentage contribution (20.1) to $k_d$ in October, 2006. $K_s$ followed the seasonal pattern of areal biomass (Fig. 4) than volumetric biomass, being much more positively correlated with ∑B (r=0.58, P=0.13) than B (r=0.045, p=0.92). The association of biomass with $K_d$ is consistent with the finding that indicates the increment of $K_d$ as a linear function of chl a (Megard *et al*., 1979).

In January both chla and $K_w$ were large and during dry periods Chla was low but $K_w$ high. In many lakes where $k_w$ (back ground extinction) and chl a are both large, much of $K_w$ is caused by dissolved organic materials derived from the algal population itself (Megard *et al*., 1979). When phytoplankton biomass is small, background extinction of light by non-algal material may be the main component of $K_d$ (Jones, 1977). In their study of light utilization efficiency by phytoplankton, Dubinsy and Berman (1981) observed low water transparency and high attenuation of irradiance, which was attributed to higher concentration of algal cells and chlorophyll. Similarly, high densities of algae create biogenic turbidity

(i.e., self-shading) (Holmes, 2000). In the present study on Lake Bishoftu, the maximum $K_d$ was found to correspond with minimum $Z_{SD}$ and shallow $Z_{eu}$ , and the minimum was associated with highest $Z_{eu}$ and $Z_{SD}$. The observed shallow $Z_{eu}$ and the coincidence of minimum $Z_{SD}$ with maximum $K_d$ and minimum $Z_{eu}$ in December, 2006 were associated with increased non-biological turbidity ($K_w$= 92.7%) (See App. 3). In other similar investigations low $Z_{SD}$ corroborated the high $K_d$ in lakes Nakuru and Elementeita (Melack and Kilham, 1974).

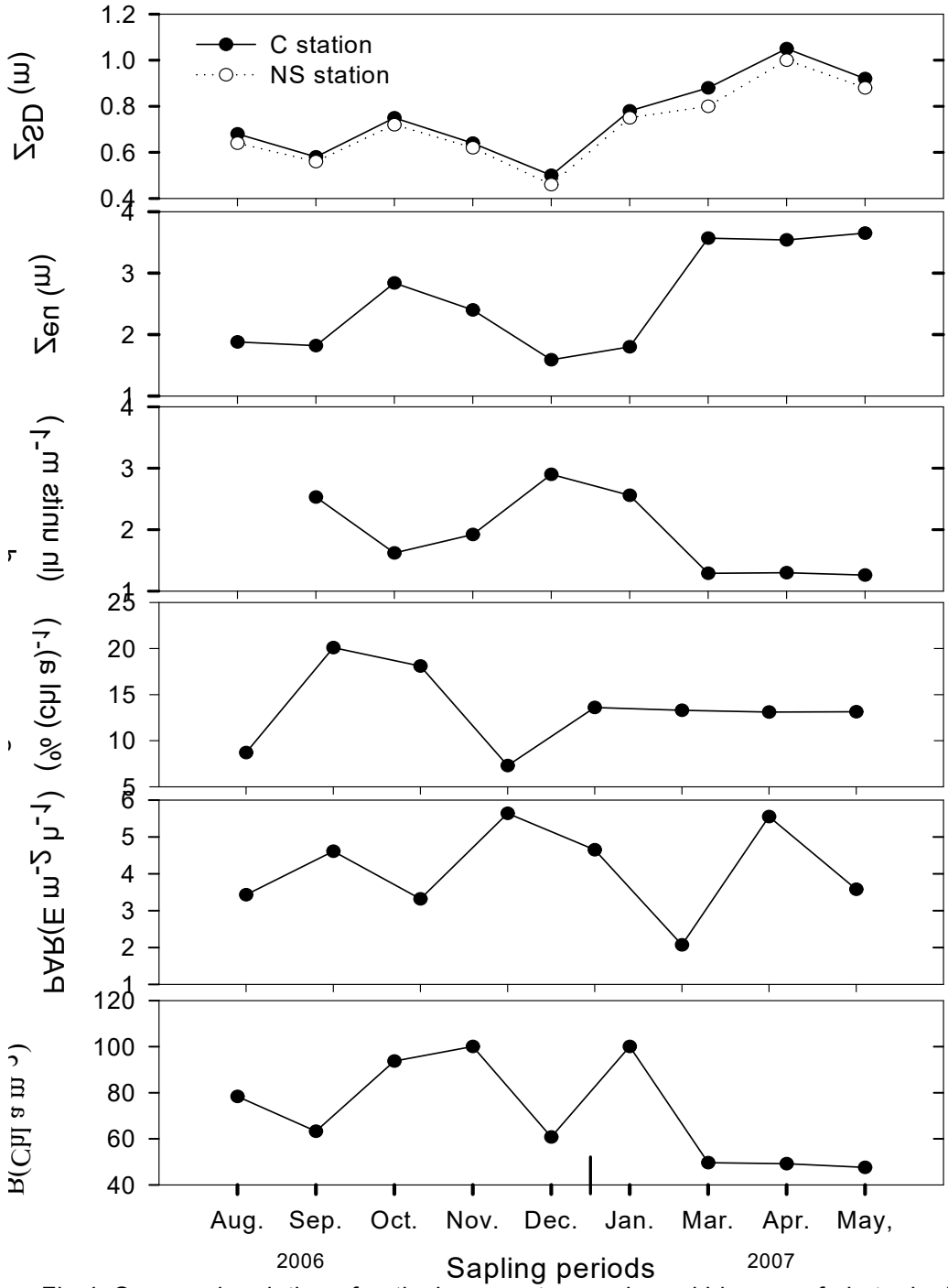



Fig.4. Seasonal variation of optical parameters and areal biomassof phytoplankton.

### 3.1.3. pH, alkalinity and free $CO_2$

pH of surface water showed small temporal variation ranging from 9.17 in December to 9.54 in September, 2006. Carbonate bicarbonate alkalinity varied from 13.7 to 16.8 meq $L^{-1}$ in October and September, 2006 respectively (Table 2). Free $CO_2$ calculated from the relationship between pH and alkalinity at a specific temperature (Lind, 1979) varied from a minimum of 0.13 in September to 0.41 mg $L^{-1}$ in December, 2006. This level of free $CO_2$ is lower as compared to the values reported for Legedadi Reservoir (0.21 – 3.2 mg $L^{-1}$; Adane Sirage, 2006).The observed total alkalinity of lake Bishoftu (mean value 15.4 meq $L^{-1}$) is slightly lower than the previously reported values (20 meq $L^{-1}$; Prosser *et al.*, 1968) and (17 meq $L^{-1}$: Zinabu Gebre-Mariam, 1994). From the decline in alkalinity/chloride ratio in Bishoftu crater lakes Rippey and Wood (1985) suggested that the decline was associated with the precipitation of calcium and magnesium carbonate. Von Damm and Edmond (1984) also suggested that over half of the loss of alkalinity in East African lakes could be due to 'reverse weathering'.

The range of total alkalinity of Lake Bishoftu is higher than those values reported for other Ethiopian Rift Valley Lakes such as Lakes Chamo (9.2; Eyasu Shumbulo, 2004), Awassa (7.7-9.1; Demeke Kifle, 1985), the Bishoftu crater Lake Babogaya (Pawlo) (6.4 – 12.1; Yeshiemebet Major, 2006) and the Kenyan Lake Naivasha (3.31; Talling and Talling, 1965). The alkalinity of lake Bishoftu is comparable to that of the nearby crater Lake Hora (16.8; Zinabu G. - Mariam, 1994), but lower than the alkalinity of lake Arenguade (54; Zinabu G. - Mariam, 1994) (see App.6). This alkalinity level most probably puts Lake Bishoftu in the third stage of alkalinity next to Lake Hora and the most alkaline lake Arenguade among the Bishoftu crater lakes.

The expected total alkalinity (TA) in nature is 0.4 to 40 meq $L^{-1}$ (Lind, 1979). The highest TA of Lake Bishoftu is closer to half of the expected maximum boundary value (40 meq $L^{-1}$).

pH of surface water is strongly and positively correlated with alkalinity ($R^2$ =0.41 (r=0.64), p<0.001). The study on most Ethiopian and East African lakes by Wood and Talling (1988), and alkaline lakes world wide (Hammer, 1981) showed that pH, alkalinity and salinity are strongly correlated. Dense phytoplankton biomass and vigorous photosynthesis and respiration can shift pH upwards through more than one pH units (Talling *et al*., 1973). However, in this study lake, due to strong pH and alkalinity relation, the strong buffering reduces pH excursions (Talling *et al*., 1973), the seasonality in pH and level of free $CO_2$ is relatively low and were not associated with seasonal change in photosynthetic rates. Slightly reduced $CO_2$ level coincided with the occurrence of $A_{max}$ at a shallow depth (0.25m) in September, 2006 although it was not the peak photosynthetic rate observed in the present study. In general, the low $CO_2$ level in Lake Bishoftu throughout the study period was probably due to high photosynthetic rates and capacity ($P_{max}$) of the phytoplankton community dominated by cyanobacteria, which are known to reduces $CO_2$ level to outcompete others(Shapiro, 1997).

The level of $CO_2$ in a body of water determines the structure and composition of phytoplankton communities because of the differential response of phytoplankton to changes in $CO_2$ concentration (Shapiro, 1997). Shapiro (1997) indicated that $CO_2$ concentration induces competition among algae for C-sources and initiates blue green algal dominance in lakes. When blue green algae dominate in the lakes (Shapiro, 1997), like Lake Bishoftu, $CO_2$ is taken much more efficiently than when phytoplankton community is composed of non-blue-greens and that blue greens ensure their dominance by reducing concentration of $CO_2$ to levels available only to themselves. Correlations between low $CO_2$ concentration in lakes and dominance of blue green algae, similar to the situation in Lake Bishoftu,

are well documented (Shapiro, 1973). Low $CO_2$ concentration could stimulate increased buoyancy of various blue-green algae thereby contributing to surface bloom formation (Spencer and King, 1987), which enables the blue greens to efficiently utilize light and nutrient sources and shade subsurface phytoplankton populations (Reynolds, 1984).

Table 2: pH, alkalinity (meq $L^{-1}$), free carbon dioxide (mg $L^{-1}$), carbonate and bicarbonate ions (meq $L^{-1}$) and conductivity of central station of Lake Bishoftu.

| Sampling date | pH | PA | TA | $CO_2$ | $CO_3^{2-}$ | $HCO_3^-$ |
|---|---|---|---|---|---|---|
| 25/8/06 | 9.41 | 3.50 | 16.50 | 0.18 | 7.00 | 9.50 |
| 19/9/06 | **9.54** | 3.80 | 16.80 | 0.13 | 7.60 | 9.20 |
| 21-10-06 | 9.30 | 1.90 | 13.70 | 0.23 | 3.80 | 9.85 |
| 25/11/06 | 9.24 | 1.52 | 15.00 | 0.34 | 3.04 | 11.98 |
| 26/12/06 | **9.17** | 0.92 | 13.90 | 0.41 | 1.84 | 12.06 |
| 27/1/07 | 9.33 | 1.80 | 15.80 | 0.29 | 3.60 | 12.20 |
| 28/3/07 | 9.27 | 1.10 | 15.00 | 0.34 | 2.20 | 12.80 |
| 28/4/07 | 9.22 | 1.90 | 16.00 | 0.37 | 3.80 | 12.20 |
| 27/5/07 | 9.23 | 2.20 | 15.80 | 0.32 | 4.4 | 11.4 |

### 3.1.4. Inorganic Nutrients

The seasonal variations in the concentrations of major algal nutrients in Lake Bishoftu at two stations measured from August, 2006 to May, 2007 are given in Fig.6.

Nitrate nitrite-nitrogen concentration ranged from a minimum of 6 in May, 2007 to a maximum of 110 µg $L^{-1}$ in October, 2006 and from 6.7 in May, 2007 to 80 µg $L^{-1}$ in December, 2006 at the central and near shore stations respectively, with a mean value of 44 µg $L^{-1}$. The present maximum $NO_3$ + $NO_2$-N concentrations of Lake Bishoftu are higher than earlier reported concentrations 25 µg $L^{-1}$ (Zinabu Gebre-Mariam, 1994). Concentrations of $NO_3$ +$NO_2$-N exceeding 20 µg $L^{-1}$ were

observed in October-December in Lake Babogaya (Pawlo) (Wood *et al*., 1984). This value of nitrate concentration is very high compared to values reported for lakes Ziway,0-9, Awassa, 0-7 and Chamo, 1-7 μg $L^{-1}$ (Girma Tilahun, 2006).

The minimum concentration of $NO_3$ + $NO_2$-N coincided with low algal biomass in April and May, 2007 but the maximum concentration of $NO_3$ + $NO_2$-N did not coincide with the highest or lowest biomass. Algal biomass and $NO_3$ + $NO_2$-N are positively but poorly correlated (r =0.16, p=0.68), but other nutrients were negatively correlated. This is because algal growth preferably uses the alternative source of nitrogen, ammonium-nitrogen (Fisher *et al*., 1988). In general $NO_3$ + $NO_2$-N concentrations and algal biomass were higher during the rainy months (see Fig.6). Thus, the seasonal changes in $NO_3$ + $NO_2$-N concentration in Lake Bishoftu seem to be controlled by the introduction of nutrients from external sources through runoff. In Bishoftu crater lakes inorganic nitrogen ($NO_3^-$ and $NH_4^+$) was seldom detectable in surface waters (Wood *et al*., 1984). The present high concentrations of $NO_3$ + $NO_2$-N (compared to the previous values) seem to indicate the increased external loading of nitrogen which most probably originated from domestic sewage dumped on to the top of the crater rims.

Domestic wastes, both solid and liquid, animal drops and dead bodies are dumped on the top of the crater rims, which may eventually reach lake water through runoff during the rainy period thereby increasing the level of nitrogen compounds in the lake. It is known fact that nitrogen can become important in waters receiving agricultural runoff, wastewater through runoff, failure on-site septic systems, runoff from animal manure storage areas, and industrial discharges that contain corrosion inhibitors (USEPA, 1991).

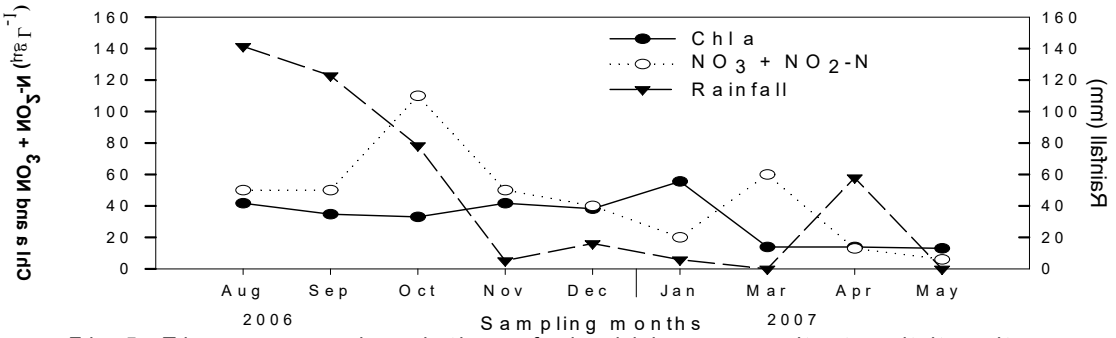



Fig.5. The seasonal variation of algal biomass, nitrate-nitrite-nitrogen and rainfall during the study periods at the central stations

Ammonium + ammonia-nitrogen concentrations varied from 40 to 406 µg $L^{-1}$ at the central station and 10 to 406 µg $L^{-1}$ at the near-shore in December and April, 2007 respectively. The highest values of $NH_4^+$+$NH_3$ –N corresponded to low algal biomass, to the period of low rainfall and deep-seated thermal stratification. Algal biomass was negatively but insignificantly correlated with ammonium-ammonia nitrogen (r= -0.37, p=0.32). Closer values to the present concentration of $NH_4^+$+$NH_3$ –N was reported for lakes Ziway, Awassa and Chamo (Girma Tilahun, 2006).

Ammonium concentrations are much lower than nitrate-nitrogen concentrations in most productive lakes after periods of circulation (Wetzel, 2001). The concentration of $NH_4^+$-N in well oxygenated water is also usually low relative to other forms of inorganic nitrogen due to its ability to be readily oxidized (Kalff, 2002), and its rapid and preferential uptake by phytoplankton (McCarthy, 1980). Prochazkova *et al*. (1970), in his study on fresh waters, also observed phytoplankton preference for $NH_4^+$_N over $NO_3$-N even when the concentration of $NO_3$_N exceeds that of $NH_4^+$_N by six-fold. Conway (1977) has also demonstrated the inhibitory effect of $NH_4^+$ on the uptake of nitrate by phytoplankton.

The concentration of $NH_4^+$ +$NH_3$ –N was low during the rainy period, when there was higher algal biomass but high during the period of low algal biomass in dry months. In general, $NH_4^+$+$NH_3$–N concentrations in Lake Bishoftu were associated with changes in algal biomass and the stability of the water column.

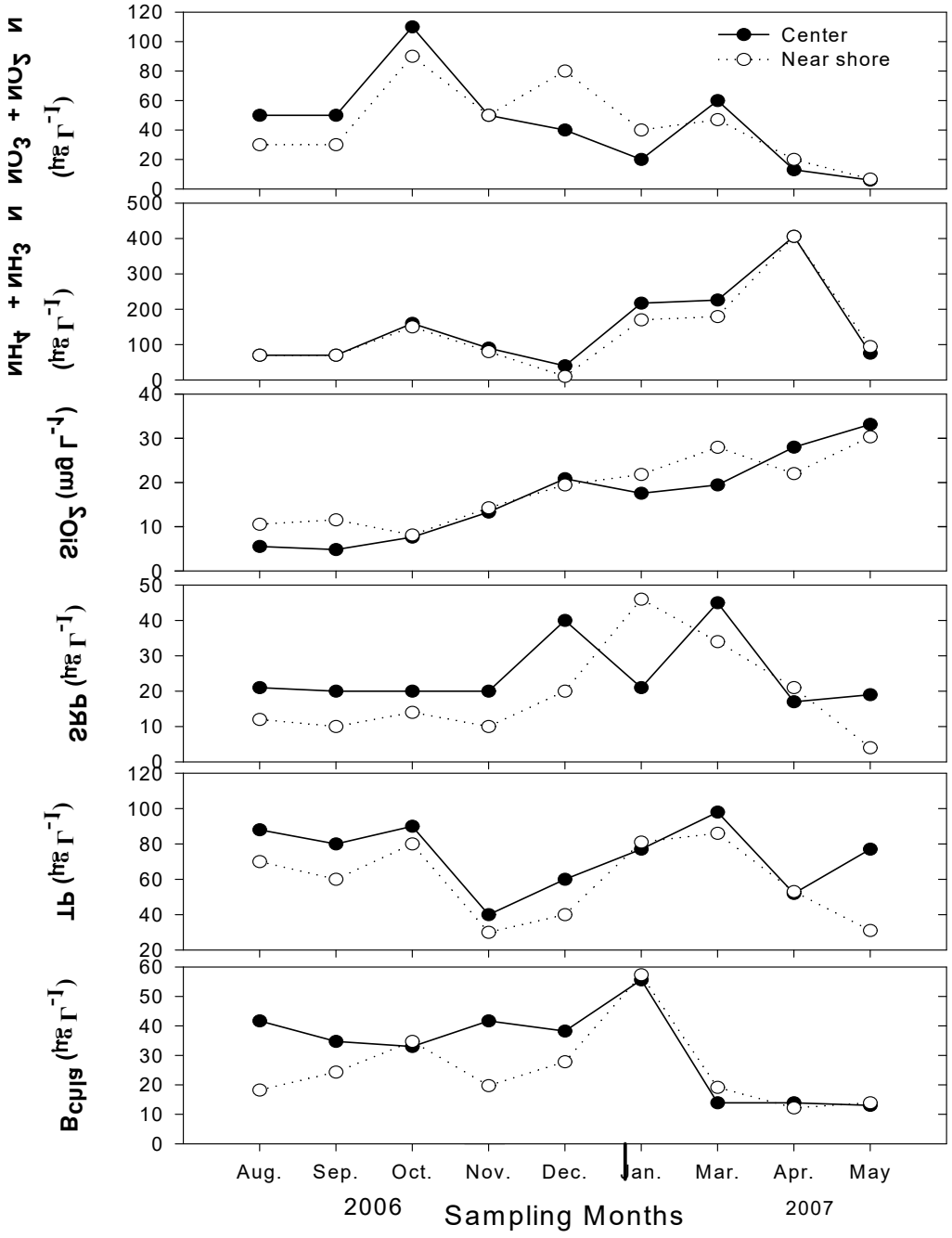



Fig.6. Spatial and Temporal variations of inorganic nutrients and phytoplankton biomass of Lake Bishoftu during the study period.

Soluble Reactive Phosphate-phosphorus (SRP-P) varied between a minimum of 17 in April and a maximum of 45 μg $L^{-1}$ in March, 2007 and between 4 in May and 46 μg $L^{-1}$ in January, 2007 at C and NS stations respectively with a mean value of 22 μg $L^{-1}$. The minimum at the central station coincided with the period of deep thermal stratification (April, 2007), while the minimum at the near-shore station was observed during the period of superficial stratification in May, 2007. The seasonal maximum at NS station corresponded to a peak of algal biomass, while maximum at the central station coincided with low algal biomass. SRP-P of Lake Bishoftu was negatively and poorly correlated with algal biomass ($r = -0.17$, $p=0.66$). Similarly, in the productive Lake Ziway at a time of high Chl a (154 μg $L^{-1}$) $PO_4$-P concentration below detection limit was reported (Elizabeth Kebede *et al*., 1994). A very high level of $PO_4$-P was, however, observed in the saline Lake Chitu in spite of its concurrent high algal biomass (Elizabeth Kebede *et al*., 1994). Talling and Lemoalle (1998) also presented data that support the inverse relation between phytoplankton abundance and soluble reactive phosphorus concentrations.

The seasonal concentration of total phosphate (TP) varied from the minimum levels 40 and 30 μg $L^{-1}$ in November, 2006 at the central and near-shore stations respectively to the maximum levels 98 and 86 μg $L^{-1}$ in March, 2007, at the central and near-shore stations respectively with a mean value of 66 μg $L^{-1}$. The maximum values of the two stations coincided with the time of thermal stratification, low algal biomass and higher zooplankton relative abundance. Regeneration of P by zooplankton can be high enough to raise the ambient concentration to a level capable of supporting algal growth (Morris, 1980), which is not well studied in African lakes (Thornton *et al*., 1986).

The variation of SRP-P between two stations was not statistically significant ($t(8) = 1.3$, $P=0.23$) but that of TP was significant ($t(8) = 3$, $p= 0.02$) with larger values

observed at the central station. The relation between algal biomass and TP was insignificant and negative correlation (r= -0.12, p=0.59).
The concentration of algal biomass was not significantly variable between the two stations, but that of TP was. The lower concentration of TP near shore is most probably associated with its high reactivity with colloidal particles as these particles and suspended solids join the water at shore from surrounding steep crater wall resulting in increased possibility of reactants with phosphorus.

The maximum concentrations of SRP-P observed in this study are much higher than those recorded in previous studies (28 μg $L^{-1}$; Zinabu Gebre-Mariam, 1994, and < 5 μg $L^{-1}$; Prosser *et al*., 1968). From this fact it can be concluded that the level of phosphorus is increasing through time in Lake Bishoftu. In the nearby lake Babogaya, Yeshiemebet Major (2006) observed a maximum of 18 μg $L^{-1}$ SRP_P, which is less than the mean value of this study. A range of concentration similar to that of Lake Bishoftu was reported for Lake Awassa (5 - 42 μg $L^{-1}$; Demeke Kifle, 1985). The values of SRP_P of Lake Bishoftu and other Ethiopian and East African lakes are given in Appendix 9 for comparison.

Relative to lakes such as Chamo (Eyasu Shumbulo, 2004), Ziway (Getachew Beneberu, 2005), Arenguade (Zinabu G. - Mariam, 1994), and Nakuru (Talling and Talling, 1965), the present concentrations of SRP_P in Lake Bishoftu are low, which is probably due to the anaxic conditions that phosphorus forms precipitate with iron and sediment down. Similarly, low concentrations of soluble reactive phosphate were recorded from productive Kenyan soda lakes of Elementeita and Nakuru (Vareschi, 1982) and Lake Abijata, in Ethiopia (Belay and Wood, 1984). In lakes Pawlo and Bishoftu SRP_P values below 5μg $L^{-1}$ were recorded during stratification (Wood *et al*., 1984). The level of SRP_P in lakes varies with co-precipitation with calcite (Baxter *et al*., 1965; Wood *et al*., 1984). The release of phosphate from anaerobic sediments (Mortimer, 1971) and its subsequent transport to the epilimnion during mixing contributes to the high level of

phosphate in the epilimnion; however, the reverse seems to be true for Lake Bishoftu as the result of the present study and those of Baxter *et al*. (1965) did not show the occurrence of complete mixing.

The mean ratio of TN to TP (Redfield ratio) varied from 5:1 in December, 2006 to 41:1 in April, 2007 (See App. 7). 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; Foreberg *et al*., 1984). If ambient N: P ratios are greater than 15 -17:1 by weight, 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.

Nitrogen may be limiting to algal growth in Lake Bishoftu in August, September, and December, 2006, because the ratios of total nitrogen to total phosphorus were below Redfield ratio, 10:1. However, algal biomass was relatively high, which may be resulted from the negative relation of algal biomass and readily usable ammonium-nitrogen. The ratio was in excess of 15-17:1 in April, 2007, indicating P limitation to algal growth as it coincided with minimum chlorophyll a. The intermediate ratio, 14:1 coincided with maximum algal biomass. TN: TP ratios that are well in excess of Redfield ratios occur widely in the world's lakes and oceans (Guilgford and Hecky, 2000). Similar to the situation in Lake Bishoftu, limitation of algal growth by N and P have been reported for other east African lakes. Melack *et al*. (1982) showed that P was more limiting than $NH_4^+$-N in two Kenyan lakes, Elementeita and Sonachi.

Nitrogen is most likely to be limiting to algal growth in the tropics because higher temperatures in the lower water column in tropical waters enhance microbial metabolism resulting in increased denitrification, which releases free nitrogen to the atmosphere thereby reducing the level of inorganic (reduced) nitrogen in the water column (Talling and Talling, 1965; Lewis, 1996). Bioassay experiments in

sub-tropical lakes also indicated that nitrogen was the most frequently limiting nutrient for phytoplankton growth (Philips *et al*., 1996). The ratio of Dissolved Inorganic Nitrogen (DIN): TP was lowest in saline lakes, Chitu, Shalla and Metehara (Elizabeth Kebede *et al*., 1994), a situation observed in Lake Bishoftu in April, 2007, indicating that N-limitation seems more likely to occur in tropical lakes. Cyanophytes, especially nitrogen-fixers, were prominent in lakes with high phytoplankton biomass (> 10 mg/L), an indication that nitrogen probably limits algal production (Elizabeth Kebede & Willen, 1998).

The ambient mean ratio of TN to TP was found to be greater than the Redfield ratio (> 15-17) in April, 2007 indicating the probable limitation to algal growth by P as algal biomass was also very low. Phosphorus has been suggested to be the primary nutrient limiting phytoplankton production in lakes (Schindler, 1977), It was also shown that phosphate can limit concentration of phytoplankton biomass in Lake Sonachi (Melack *et al*., 1982; Kalff, 1983).

Dissolved silica (Molybdate reactive silica) of the study lake varied from 4.81 of September, 2006 to 33.15 mg $L^{-1}$ of May, 2007 at the central station whereas at NS station it varied from 8.11 in October, 2006 to 30.31 mg $L^{-1}$ in May, 2007 with a mean concentration of 18 mg $L^{-1}$. At both stations the higher values, in excess of 20 mg $L^{-1}$, corresponded to the dry and low rain periods (December, 2006 to May, 2007), while the lower values, less than 15 mg $L^{-1}$ were associated with wet months (August to November, 2006). Although the concentrations varied between the two stations, the difference was not statistically significant ($t(8) = -1.1$, $p= 0.3$). The minimum value observed in October, 2006 coincided with the period lacking thermal stratification.

Dissolved silica showed negative but fairly strong correlation with biomass ($r=-0.59$, $p=0.09$) although the relation was not significant. In Lake Chamo, Belay and Wood (1982) found a relation between decreasing silica concentration and larger diatom growth, and concluded that sever depletion of silica was associated with increasing

diatom growth and lower dissociation rates of silicic acid from diatom frustule. A ten-fold decline in $SiO_2$ as a result of increased algal production was also observed in Lake Victoria (Hecky, 1993). It was also described from the lakes Victoria (Talling, 1966) and Chad (Lemoalle, 1978) that silica depleted during the abundance of main abstractors, diatoms.

Although the contribution of diatoms to the algal community in Lake Bishoftu was low relative to blue greens of phytoplankton throughout the study period. The variation of silica between wet and dry months is probably attributable to the favourable conditions for blue greens, superficial mixing and availability of other nutrients during wet seasons, resulting in efficiently uptake of silica by the existing diatom species and the *Chrysochromulina* species. Similarly, from the study on Ethiopian saline lakes Wood and Talling (1988) indicated that the low abundance and contribution of diatoms to the phytoplankton communities relative to other groups of phytoplankton is related to the saline nature of the lakes since diatoms play more role as phytoplankters in the less saline waters where their presence influences the variation of silica concentration in surface water.

The present maximum levels of silica recorded for Lake Bishoftu are closer to that previously reported for the same lake 38 mg $L^{-1}$ by Prosser *et a*l. (1968) and Wood and Talling, 1988) although they are still much higher than the value recorded relatively recently (15 mg $L^{-1}$) by Zinabu Gebre-Mariam (1994). A similar decline in silica level was observed in the nearby Lake Babogaya (Yeshiemebet Major, 2006). The values of dissolved silica in Lake Bishoftu as compared to other Ethiopian and East African lakes are indicated in Appendix 8. Lake Bishoftu has low silica values relative to the recently studied Ethiopian lakes (Amha Belay and Wood, 1982; Demeke Kifle, 1985; Wood and Talling, 1988; Zinabu Gebre-Mariam, 1994) and Kenyan lakes (Vareschi, 1982). Concentrations over 10 mg $L^{-1}$ silica are common in African Lakes (Talling and Talling, 1965; Talling, 1992).

Silica values exceeding 100 mg $L^{-1}$ were found in the Ethiopian alkaline saline lakes (Elizabeth Kebede *et al*., 1994) such as Lakes Abijata, Chitu and Shalla (Wood and Talling, 1988). The observed silica values are high by world standard, which is the feature of East African lakes but still low compared to other Ethiopian crater lakes with high alkalinity. In Rift valley lakes of East Africa concentrations exceeding 100 mg $L^{-1}$ were recorded, especially in lakes without outlets (Gasse *et al*., 1983; Wood and Talling, 1988) and in the Ethiopian alkaline saline lakes (Elizabeth Kebede *et al*., 1994) such as Lakes Abijata, Chitu and Shalla (Wood and Talling, 1988).

Different factors were suggested as being responsible for the high silica level and its reduction from earlier reported levels in other East African lakes. Hutchinson (1957) suggested the enhancement of the dissolution rate of silica by temperature in the tropics. In their study on Ethiopian lakes, Wood and Talling (1988) observed that most of the lakes have very high concentration of silica, which is attributable to the greater mobility of silicate in most tropical soils and porous volcanic lavas associated with high temperature, the importance of ground input for many lakes and the enhanced dissolution of solid silicates in saline waters of high alkalinity and pH (Talling and Talling, 1965).

Lake Bishoftu being one of the east African lakes with deep-seated thermal stratification (Baxter *et al.,* 1965; Wood *et al.*, 1976), the absence of complete mixing for prolonged periods nutrient including silica have probably been locked up in the sediments by the phenomenon of ‘reverse weathering’, a major process in closed basins of Ethiopian lakes (Von Damm and Edmond, 1984; Wood *et al*., 1984) resulting in the reduction of silica through time. Active dissolution of diatom frustules is also inhibited by organic matter accumulation in the sediments (Hecky and Kilham, 1973) in some alkaline east African lakes.

### 3.2. Biological Parameters

#### 3.2.1. Species composition and abundance of plankton.

The different species of plankton (both phytoplankton and zooplankton) identified in Lake Bishoftu are given in Table 3.

The identified phytoplankton species (22 species) belonged to five divisions, six classes and 15 genera according to the classification system of Prescott (1978). Among the identified phytoplankton groups, blue green algae, with 9 species were the most dominant algae throughout the study period with their contributions to the total abundance of phytoplankton ranging from 58 % in March, 2007 to 99.85% in January, 2006 with most values in excess of 90% at central station and from 61% in March, 2007 to 99.5% in December, 2006 at the near-shore station.

In this study, the abundance of blue-greens was almost exclusively constituted by species of Microcystis, Coelosphaerium and Merismopedia represented the blue greens in estimating percent abundance throughout the study period. Diatoms (primarily represented by *Nitzschia sp*.) followed the blue greens contributing more (41% at central and 38% at near-shore stations) around March, 2007 associated with the absence of well-marked thermal stratification and with their seasonal minimum contribution in December to January. The other minor groups, Chlorophyceae, Dinophyceae, and Haptophyceae had very low representation with less than 1% contribution throughout the study period. Fig.7 shows the temporal variations in the contributions of different taxonomic groups to the abundance of total phytoplankton in Lake Bishoftu. (See also Appendix 10).

Although phytoplankton abundance varied between two the stations, it was not statistically significant ($t(8) = -0.55$, $p = 0.6$). Differences in algal concentration between shore and open waters in small lake are minimized by wind-induced circulation (Ganf, 1974). Similar to abundance, algal biomass measured as chl a did not show significant variation between two stations either.

Table 3: List of identified species of phytoplankton and zooplankton of Lake Bishoftu.

## Phytoplankton Species

**Cyanophyceae (Blue green Algae )**

- *Microcystis spp*.
  - ⇨ *M. aeruginosa* (Kutz.) Kutz.
  - ⇨ *M. flos-aquae* (Wittr.)Kirchen.
  - ⇨ *M. botrys* Teil.
- *Coelosphaerium* cf. *kuetzingianum* Näg.
- *Cylinderospermopsis raciborskii* (Wolosz.)seenayya et Subba Raju
- *Anbaena lemmermanni* (uterm) Kom-legn
- *Aphanocapsa holsatica* Lemm.
- *Planktolyngya circumcreta* (G.S. West) Anagn. &Kom.
- *Merismopedia punctata* Meyen
- *Limnothrix redekei* (Goor) Meffert
- *Chroococcus* cf. *aphanocapsoides* Skuja

**Chlorophyceae (Green Algae )**

- ⇨ *Quadrigula lacustris* (Chod.) Smith
- ⇨ *Cosmarium humlle* Kleine Zieralge
- ⇨ *Tetraedron minimum Hansg*

**Bacillariophyceae**(Diatoms)

- *Cymbella affinis* Kutz.
- *Navicula lapidosa* Krasske
- *Cyclotella comensis* Grun
- *Nitzschia spp.*

**Dinophyceae** (Dinoflagellates)

- *Peridinium spp.*

**Chrysophyta (Haptophyceae)**

- *Chrysochromulina sp*

**Cryptophyceae**

- *Cryptomonas erosa* Ehr.
- *C. ovata* Ehr.

## Zooplankton Species

**Copepods**

- *Lovenula africana* Dussart
- *Afrocyclops gibsoni* (Kiefer)

**Rotifers**

- *Asplanchna seiboldi* (Leydig)
- *Brachionus calyciflorus* Pallas
- *B. urceolaris* Ehrb
- *Lepadella patella* Ehrb
- *Keratella tropica* (Apstein)
- *Hexarthra jenkinae* De Beauchamp

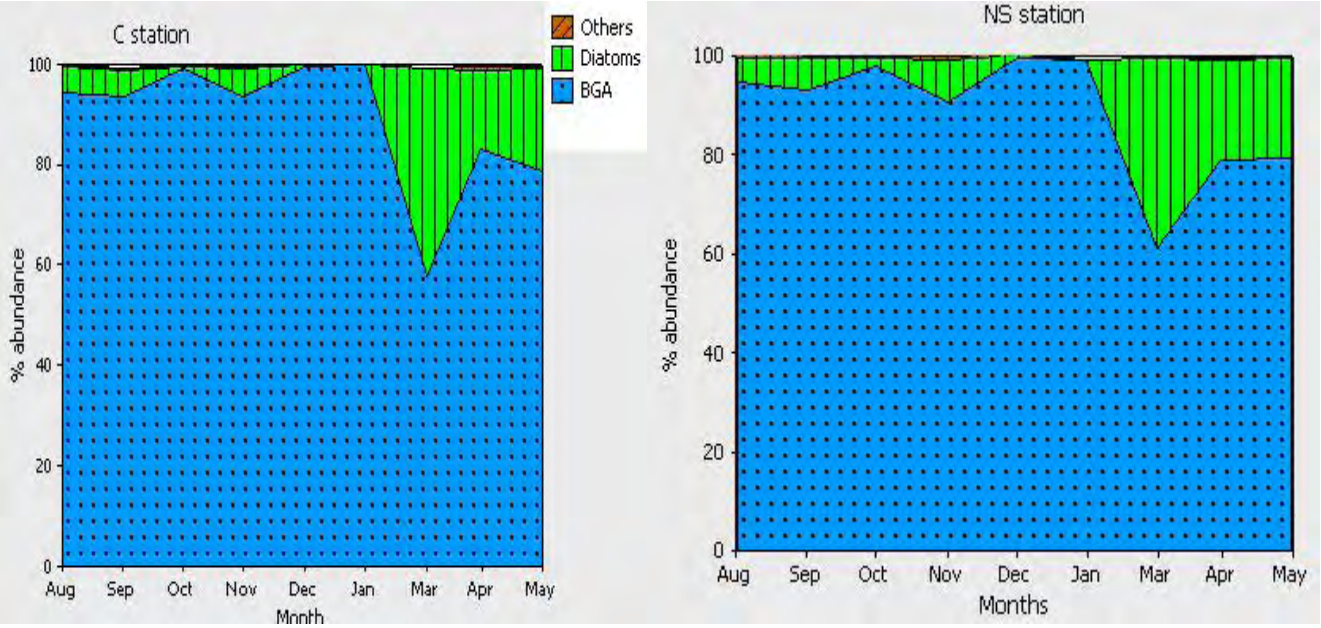



Fig.7. Seasonal variations in the percentage contribution of different taxonomic groups to the total abundance of phytoplankton in Lake Bishoftu.

The seasonal trends of cell count of individual species were indicated in Fig 8 and Appendix 11. Although different species showed peaks at different months, the cell count of each algal species (cells $ml^{-1}$) followed the same pattern as that of percentage abundance of groups. *Microcystis spp*. were persistent throughout the study period even though their cell number declined during minor rain and dry months (January, March, April, May, 2007). Dominance of most groups including *Mirocystis spp*. in relatively high rainy months (August, September, and October, 2006) is associated with availability of nutrients and superficial mixing. Similarly dominance of *Microcystis aeruginosa* during mixing and rainy period than a period of thermal stability was observed in lake Awassa (Girma Tilahun, 2006), Harbeespoort in South Africa (Robarts and Zohary, 1984). Increased photosynthetic rates in Kenyan lakes coincided with rainfall (Melack, 1979) due

to the fact that the supply of nutrients was increased by rains and subsequently enhanced growth of phytoplankton.

*Peridinium* and *Chrysochromulina spp*., which were common in wet months with a peak in August 2006 declined to the level of zero during dry months. *Quadrigula lacustris* (Chlorophyte) and *Merismopedia punctata* cell gained numerical importance towards the end of the rainy months even though their cell number was still very low relative to blue greens and diatoms. *Nitschia spp*. showed peak level in August, 2006, a rainy month, however, their percentage contribution to algal community was high in March, 2007. Absence of stratification in March, 2007 and high ammonium and SRP-P concentration resulting from low abundance of other competing algal groups and biomass most probably favoured the dominance of diatoms. Wet period dominance, is probably associated with superficial mixing resulting from nocturnal cooling in spite of the presence of weak superficial stratification. Silica was not limiting in all the study periods although lower values were recorded during wet months, which may be associated with uptake by diatoms and the genus Chrisocromulina. Diatoms dominate water columns in the presence of strong mixing (Talling, 1986). Other minor groups (Dinophyceae and Haptophyceae) were frequently seen during wet periods.

In study of African phytoplankton dynamics, Melack (1976) and Livingstone and Melack (1984) has described large inter-annual changes in the soda lakes involving multiple shifts of dominant algal species against a background of changing salinity, zooplankton abundance, and nutrient dynamics. Insignificant contribution of dinoflagelates is associated with high conductivity of the lake (1600µ S $cm^{-1}$) because dinoflagellates dominate in waters of low conductivity containing significant concentrations of divalent cations ($Ca^{2+}$ & $Mg^{2+}$) (Wood and Talling, 1988); their deficiency inhibits flagellar activity (Nultsch, 1979). In

Ethiopian and other East African lakes the scarcity of flagellates is associated with a rich development of small blue green algae (Talling, 1986)

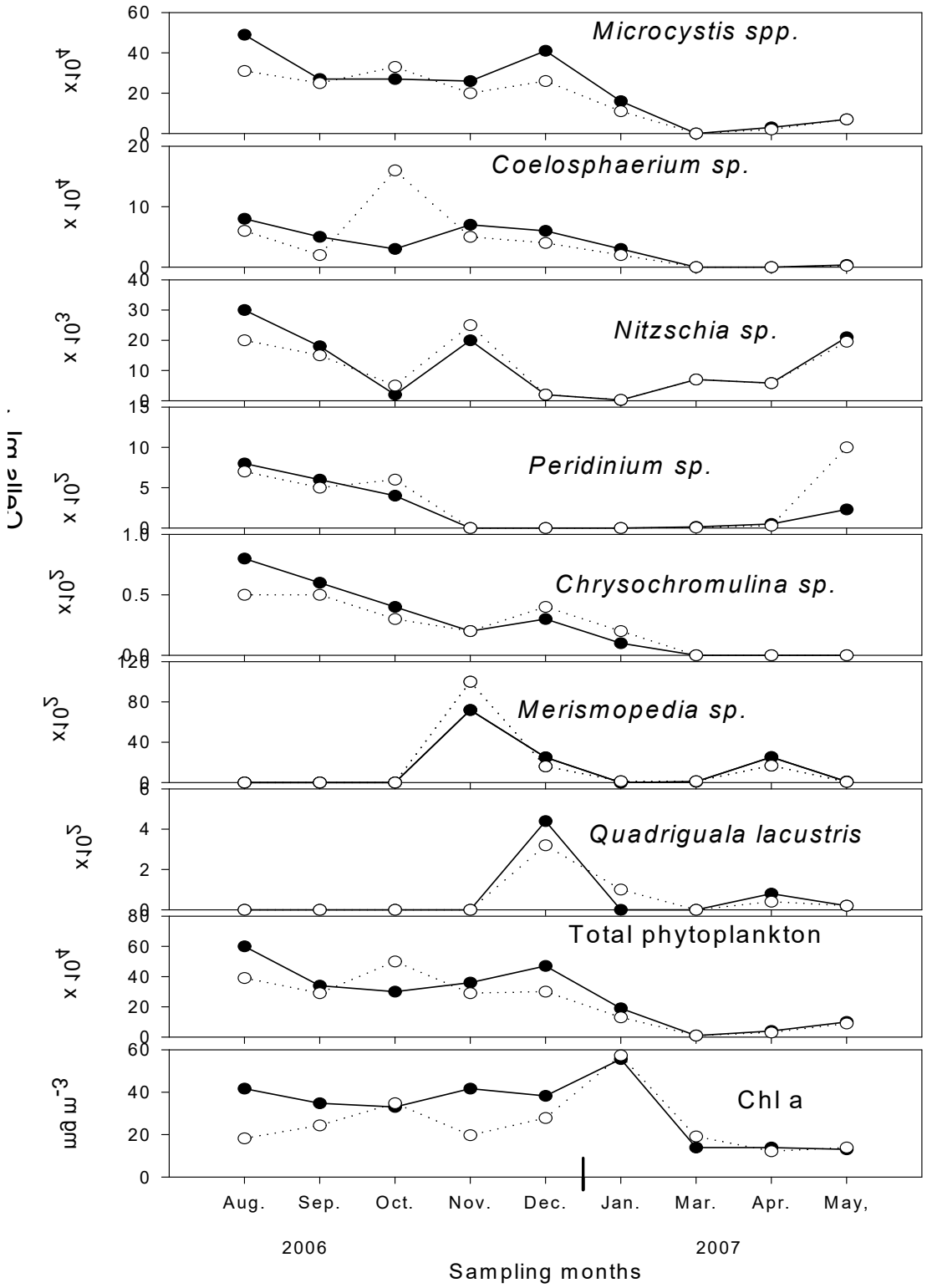



Fig.8. Temporal dynamics of phytoplankton species at the central (solid circle) and near-shore (open circle) stations in Lake Bishoftu.

The decline in phytoplankton cell number was observed towards the dry and small rainy months, from January to April, 2007 corresponded with the low algal biomass and increased abundance of rotifer and copepod zooplankton grazers, which are important source of mortality for phytoplankton and in bringing about seasonal changes in the abundance of phytoplankton (Reynolds, 1984). In January, 2007, algal biomass peaked but cell count of individual species per ml decreased. Lack of correspondence between algal biomass estimated as chl a and cell count in January, 2007 most probably arose from the fact that biomass as chl a could be overestimated in the presence of degradation products resulting from the disintegration of algal pigments during the collapse of an algal bloom since correction was not made for degradation products. It also seems that algal biomass should decrease as cell count did because during this period rotifer zooplankton grazers reached their population maximum.

Phytoplankton seasonality in larger and deeper African lakes is influenced by external factors (e.g. biological) and periodic changes in the hydrographic structure of the water column (Talling, 1986; Reynolds, 1984), which is more influential in closed water bodies like Lake Bishoftu. Temporal patterns in phytoplankton with some environmental aspects observed in Lake Malawi by Harding (1963) and Iles (1960) indicated that highest abundance occurred in June- July (rainy) (related to cooling and vertical entrainment) and the lowest in January-March (dry), which was related to high (28 $^{o}$C) surface temperature and pronounced stratification.

The finding of present study indicating the dominance of blue greens is consistent with earlier studies, which stress the dominance of *M. aeruginosa* in the three less saline(relative to lakes Arenguade and the then Kilole) Bishoftu crater lakes, Lakes Pawlo, Bishoftu, and Biete Mengest (Wood *et al*., 1988). Hammer *et al*. (1983) also indicated the dominance of *M. aeruginosa* due to its wide range salinity tolerance.

Although species diversity index for phytoplankton of Lake Bishoftu was not calculated, the Lake can be regarded as having low species diversity in light of the number of species identified in comparison with those of Ethiopian Rift Valley lakes (Elizabeth Kebede & Willen, 1998). The Lake is on the verge of being dominated by a few species of a single genus Microcystis due to water column conditions favouring their growth. In the study of Ethiopian Rift Valley lakes across a range of salinities and alkalinities, lower number of species was recorded for Lakes of higher salinity and alkalinity levels, reaching an almost unialgal population in the most saline, alkaline Lake Chitu; highest number of species was recorded in Lake Koka, the most dilute lake in the series, and Lake Awassa with a low salinity.

The relevant factors for dominance of blue greens in Lake Bishoftu appear to be low $CO_2$, superficial mixing and nutrient availability. Talling (1986) suggested the dominance of blue greens under shallow thermal stratification, which is consistent with high number of blue greens observed at the time of superficially thermal stratifications observed in rainy period. Shapiro (1984) in his competition studies, indicated that low $CO_2$ concentration, which was relatively also low in the present study, can readily lead to cyanobacterial dominance and to the formation of surface scum of *M. aeruginosa* (Paerl, 1983). Others, Badger and Price (2003) also indicated *M. aeruginosa* dominance due to its well developed and most effective $CO_2$ concentrating mechanisms (during $CO_2$ limitation. During diurnal thermal stratifications of the water column, cyanobacteria become concentrated in the upper layer where they use more of daily light (Kohler, 1992), which favour their dominance. It was also observed that deep mixing, lacking in Lake Bishoftu, prevented the formation of Microcystis bloom in Ham's Lake, Oklahoma (Toetz, 1981) and Lake Nieuwe Meer, Netherlands (Visser *et al*., 1997).

Other investigations also stressed cyanobacterial dominance associated with different factors such as shallow mixing (Ganf, 1974; Reynolds, 1987), low light

(Smith, 1986), high temperature (Shapiro, 1990), low $CO_2$ (Carco and Miller, 1998), high total phosphate (Watson *et al*., 1997), luxury consumption of phosphorus (Peterson *et al*., 1993), ability to minimize grazing (Hanlay, 1987),and buoyancy regulation (Reynolds, 1987). The dominance of cyanobacteria resulting from high nutrient loading and low N: P ratio, observed in most occasions in the present study, was observed in shallow South African lakes (Thornton, 1987). High levels of temperature favour optimal growth of cyanobacteria, especially Microcystis in lakes and reservoirs of the temperate and tropical regions (Roberts and Zohary, 1987; NSW, 2000).

Copepod and rotifer zooplankton grazers were prominent during the dry periods, from January to May, 2007. However, the data are not sufficient conclude that zooplankton grazing is strong enough to regulate blue-green abundance and biomass.

The zooplankton community of Lake Bishoftu was composed mainly of Calanoid and Cyclopoid copepods and rotifers. During the study period, nine species of zooplankton (copepod and rotifers) were recorded (see Table 3). Cladocerans were not found throughout the study period. The copepod *Lovenula africana*, the Calanoid, and the rotifer *Brachionus calciferous* were the dominant zooplankton taxa identified in samples from the present study Lake.
Generally, in Lake Bishoftu, although species diversity index was not calculated, Zooplankton species diversity is low as that of phytoplankton is, by simply comparing the observed number of species with those of other crater and Rift Valley lakes of Ethiopia.

The percentage abundance of rotifers (estimated as the sum of rotifer species) in four occasions showed a peak in January, 92% at central and 90% at near-shore stations, and thereafter it progressively declined towards May, 2007, whereas calanoid copepods with previous low percentage abundance (8 at near-shore

and 9% at central stations) increased to a maximum level, completely dominating the zooplankton community, in March to May, 2007 (see Fig.9; Appendix 12). The alternating dominance of the two groups seems to indicate the presence of seasonality in the species composition of zooplankton in Lake Bishoftu. Similar increase in zooplankton abundance from March to April, 1992 and its seasonality was observed in this lake by Afeworki Ghebrai (1992). The dominance of larger calanoid copepods during dry months coincided with decreased algal biomass implying that grazing by these groups together with thermal stability and climatic factor enhanced biomass reduction. During this period ammonium-nitrogen and SRP-P were high; hence it seems that grazing induces more controlling effect. It was indicated that dense populations of algae-consuming grazers may lead to negligible algal biomass in spite of high levels of nutrients (Steinman, 1996). However, in order to conclude confidently that grazing (top-down effect) controls algal biomass in this lake, zooplankton grazing, especially by rotifers and copepods should be studied in detail.

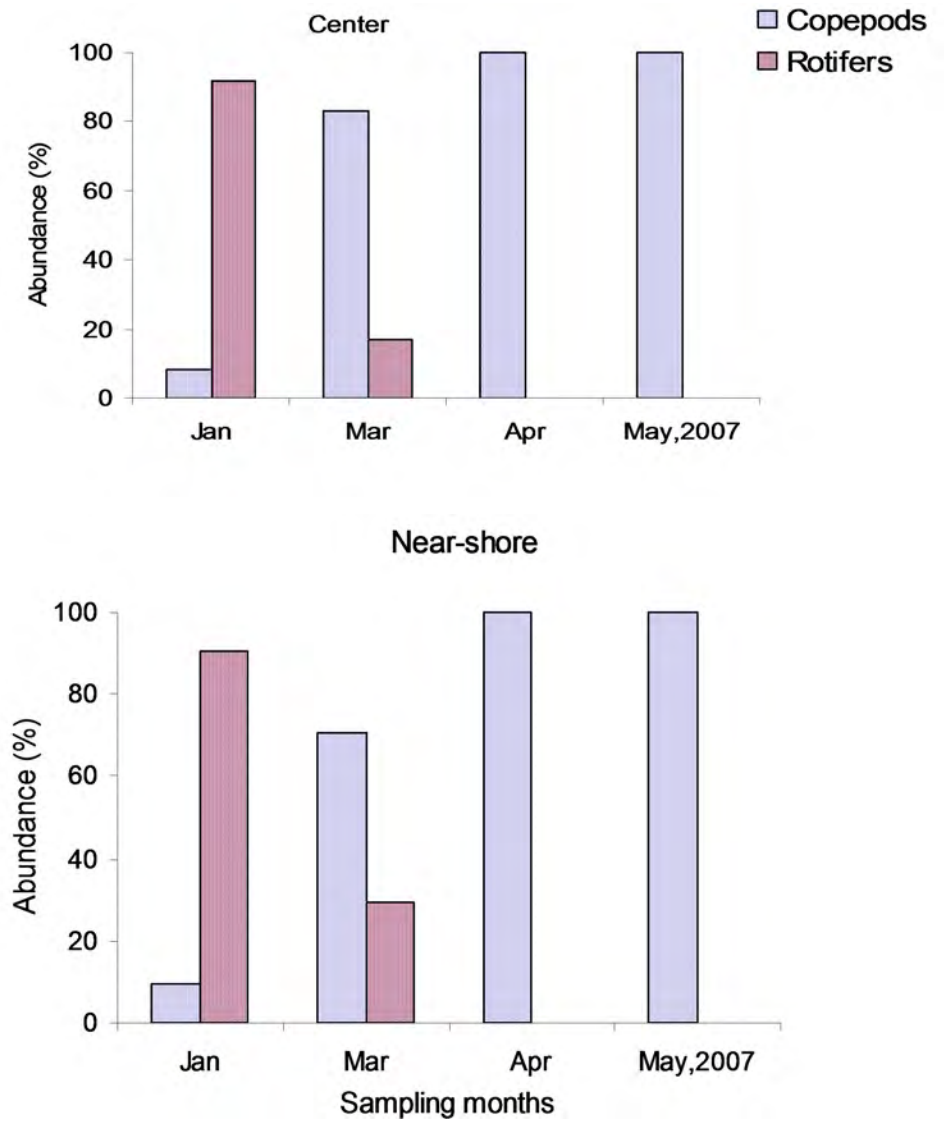



Fig.9. Temporal changes in two groups of zooplankton at the two sampling stations of Lake Bishoftu.

Although there appeared to be differences in the abundance of zooplankton between the two stations, it was not statistically significant ($t(8) = 0.89$, $p=0.44$).

The copepod, *Lovenula Africana* Daday is dominant in some soda lakes, including Lakes Arenguade and Kilole in Ethiopia and in other East African Lakes

(La Barbera and Kilham, 1974). The dominance of copepods, *Lovenula Africana* Daday and *Afrocyclops gibsoni* Brady (Green, 1986), and rotifers (Geen and Seyoum Mengistou, 1991), which was associated with waters of high salinity (Wood and Talling, 1988; Green and Seyoum Mengistou, 1991) was reported in the nearby lake Kilole. Features such as high conductivity (1000 μ S/cm,$k_{20}$), high productivity and dominance of phytoplankton community by *M. aeruginosa* (Wood and Talling, 1988) and of zooplankton by *Lovenula Africana* Daday (Green, 1986; Wood and Talling, 1988) are typical features of volcanic crater lakes (e. g. Lake Pawlo or Babogaya; Wood and Talling, 1988). In a comparative study of zooplankton in two soda lakes of Ethiopia, Afeworki Ghebrai (1992) observed the dominance of *Lovenula africana* in Lake Bishoftu, which is consistent with the finding of the present study.

The slightly low abundance at the near-shore station and the total absence of cladocerans at both stations is most probably related to removal by plaktivorous fish since the two zooplanktivorous fish, *Aplocheilichths sp*. (Pisces: *Cyprinidae*) and *Oreochromis niloticus* (Pisces: *Cichlidae*) are commonly found in this lake (Afeworki Ghebrai, 1992) and were also observed in present study while a few local people were fishing using line and hooks. Planktivorous fish exert high selective pressure on zooplankton in more eutrophic lakes because planktivorous fish seem to be more abundant as a result of vast littoral area offering vast spawning grounds and shelter (Kerfoot, 1974).

Similarly, the absence of large cladocerans from other tropical lakes is well recorded (Green, 1967; Fernando, 1980), which is often attributed to the high selective pressure exerted by planktivorous fish upon preys. Fish predation is an evident factor for the absence of larger cladocerans and for the size-distribution of zooplankton in Lake Bishoftu (Afeworki Ghebrai, 1992).

### 3.2.2. Phytoplankton Biomass as Chl a

Phytoplankton biomass estimated as chlorophyll a varied from a minimum of 13.03 at central in May and 12.16 in April, 2007 at near-shore station to a maximum of 55.6 at central and 57.34 at near-shore station in January with a mean value of 30 mg Chl a $m^{-3}$ (Fig.6; Appendix 7). The observed maximum concentration coincided with high light utilization efficiency of phytoplankton and high light-saturated rate of photosynthesis. Higher values above 33 mg Chl a $m^{-3}$ were estimated during wet months while lower values were in dry months (see Fig.5). Although slightly higher values were estimated for the central station, the Chl a level were not significantly ($t(8) = 1.83$, $P = 0.11$) different from the values recorded for near-shore station. There was no strong and significant relationship between ambient concentration of algal nutrients and Chlorophyll a (see Appendix 13 for statistical relation). Although their relation is not significant, silica and ammonium + ammonia-nitrogen are more strongly and negative correlated with biomass than the other nutrients ($r=-0.59$ for Silica, and -0.37 for ammonium) accounting for 35 and 14% of the changes in biomass. Pearson correlation of algal nutrients with biomass shows negative correlation except with nitrate, which had insignificant but positive correlation indicating its low effect on algal biomass.

The mean algal biomass measured as chl a in the present study (30 mg Chl a $m^{-3}$) is half of the value (60 mg Chl a $m^{-3}$) reported by Zinabu Gebre-Mariam (1994) although it is still very close to that value (34 mg Chl a $m^{-3}$) reported earlier by Wood and Talling (1988). The maximum values of chl a recorded for both stations are, however, similar to that reported by Zinabu Gebre-Mariam (1994). Decline in chl a concentration was reported in the nearby Lakes Babogaya (Yeshiemebet Major, 2006) and Arenguade (Demeke Kifle *et al.,* unpublished), and Koka Reservoir (Elizabeth and Willen, 1998). The mean chlorophyll a concentration of Lake Bishoftu is comparable to the concentrations reported for the nearby Crater Lake Hora (29; Zinabu G. Mariam and Taylor, 1997) and Lake

Metehara (27: Elizabeth Kebede *et al.,* 1994) but is higher than the values for Lake Babogaya (4-24; Yeshiemebet Major, 2006). Lake Bishoftu has higher concentration of Chl a compared to other Ethiopian lakes such as Shalla (6: Amha Belay and Wood, 1984), and Awassa (10 -25: Tadesse Fetahi, 2004) and Lake Tanganyika (0.2-20.4: Hecky and Kling, 1981) (for more, see Appendix 14).

The temporal dynamics of algal biomass, with higher values during rainy and post rainy periods and lower values in dry months, is associated with change in levels of nutrients and thermal conditions of the water column. The period of superficial mixing and nutrient availability from external sources favoured increased algal biomass. As a result, hydrographic features and nutrients related to climatic conditions are more important controlling factors of algal growth in Lake Bishoftu, as higher values were recorded during periods of superficial mixing and precipitation.

Areal biomass, estimated from volumetric biomass within the euphotic zone, showed peaks in November, 2006 and January, 2007 following the increase in the volumetric biomass and euphotic depth (Fig. 4). In dry months, although euphotic depths were high, areal biomass decreased following the decrease in volumetric biomass.

### 3.2.2. Photosynthetic Productivity

Photosynthetic production of the lake was estimated by the oxygen method owing to the trophic status of the lake. In eutrophic waters, like Lake Bishoftu, the large phytoplankton biomass produces measurable oxygen over short periods so that assessment of net production is possible by the Winkler method of oxygen determination (Wetzel and Likens, 2000). All photosynthetic parameters were

estimated for the central station only. In the estimation of photosynthetic production along the vertical profile using composite samples, the same amount of algal biomass was presumably exposed to the same levels of algal nutrients but to different temperature and light conditions.

#### 3.2.3.1. Depth-Profiles of Gross Photosynthesis

For the central station, *in-situ* measurements of depth profiles of photosynthetic rates estimated as gram of $O_2$ evolved per unit volume are shown in Fig.9 (see also Appendix 15).

Depth-profiles of gross photosynthetic rates-A (g $O_2$ $m^{-3}$) showed a typical pattern for phytoplankton with three distinct regions- light-inhibited near surface zone, light-saturated and light-limited zones. Estimation of percentage reduction of photosynthesis at the surface from the volumetric rate of gross photosynthesis at light-saturation ($A_{max}$) below water surface showed low values, 3.2 % (50 mg $O_2$ $m^{-3}$) in August, 20%(202 mg $O_2$ $m^{-3}$) in September and 15.5%(250 mg $O_2$ $m^{-3}$) in December, 2006, coincident with cloud cover and relatively low light intensity during rainy the season. In December, in spite of high PAR (5.64 E $m^{-2}$ $h^{-}1$) low reduction in photosynthesis was observed, which was probably associated with cloud cover. Similarly, Melack (1979) observed depth profiles of photosynthesis lacking a region with reduced rates near the surface during a cloudy day, which had the maximal integral PAR. High percent reduction (92.75: 380 mg $O_2$ $m^{-3}$) was seen in April, which corresponded with high water clarity, integral PAR and low algal biomass. On all occasions, below the depths of $A_{max}$, volumetric rates of gross photosynthesis (A) declined progressively to very low levels. It extended to a more depths of 3 to 3.5m from March to May, 2007. In rainy months the curve terminated at shallower depths following low water clarity, which affected light penetration.

Reduced surface photosynthetic rate during measurement of primary productivity in water bodies have been documented for many African lakes including those in Ethiopia (Amha Belay and Wood, 1984; Girma Tilahun, 1988; Demeke Kifle and Amha Belay, 1990; Eyasu Shumbulo, 2004; Getachew Beneberu, 2005), in Kenya (Melack, 1981; Vareschi, 1982) and in Tanzania (Melack and Kilham, 1974).

Exposure to inhibiting irradiance for prolonged periods has been shown to increase the effect of photoinhibition (Takahashi *et al*., 1971; Dubinsy and Berman, 1981). Harris and Piccinin (1977) showed that high rates of photosynthesis were maintained for only 10-20 minutes at irradiance level of 800-1000 μ E $m^{-2}$ $s^{-1}$(2.88 – 3.6 E $m^{-2}$ $h^{-1}$) whereas high levels of irradiance and long duration of exposure caused photoinhibition (Morris, 1980). In the present study the measured PAR were high in most cases and the incubation time also exceeded the above range, hence there was high possibility for photoinhibition.

Other authors argue that the magnitude of photoinhibition can be associated with the previous light history of phytoplankton cells (Kok, 1956) and their strategy for photo-acclimatization (Behrenfeld *et al*., 1998).

The depth profiles of photosynthesis had steep curves at the shallow depths associated with dense phytoplankton as differences in biomass influence the shape of the depth-profiles (Talling and Lemoalle, 1998). Similar depth profiles of photosynthesis with similar pattern of photosynthetic curves were observed for productive tropical lakes, Kilole (Brook Lemma, 1994) in Ethiopia, Big Momela and Magad in Tanzania (Melack and Kilham, 1974), Edward (Talling, 1965), Nakuru and Chad (Vareschi, 1982). In Lake George and many soda lakes of East Africa with abundant phytoplankton (Talling *et al*., 1973; Melack and Kilham, 1974), the euphotic zone is less than 1m deep and photosynthetic depth profiles are correspondingly condensed. Such kind of dense phytoplankton assemblage with a condensed photosynthetic zone can have implications for intense $CO_2$-

demand by photosynthesis per unit water volume, and such demand leads to considerable $CO_2$-depletion (Talling and Lemoalle, 1998).

In general, the observed photosynthetic rates were high, a feature of tropical lakes. From the comparative studies of photosynthetic rates of temperate and tropical lakes Lemoalle (1981) concluded that the generally higher tropical rates stem mainly from higher values of photosynthetic capacity associated with higher temperature. And also others suggested that nutrient regeneration is more rapid and primary production is high in tropical than in temperate lakes (Beadle, 1981; Hecky and Kling, 1987) due to high temperatures at all depths.

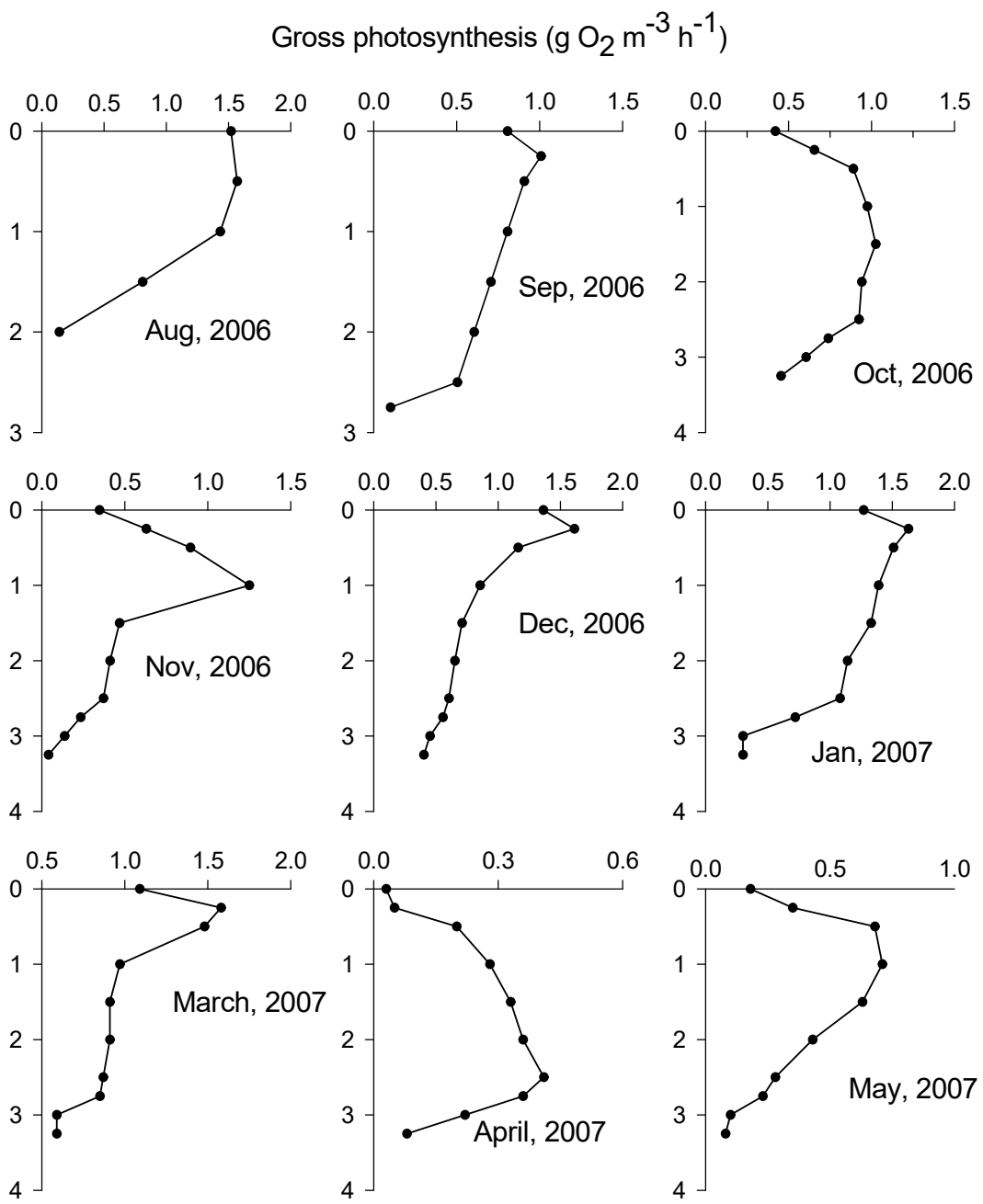



Fig.10. Depth profiles of gross photosynthetic rates at the central station of Lake Bishoftu

### 3.2.3.2. Light-Saturated rates of gross photosynthesis ($A_{max}$, mg $O_2$ $m^{-3}$ $h^{-1}$), Photosynthetic Capacity ($P_{max}$, mg $O_2$ (mg Chl-a)$^{-1}$ $h^{-1}$), and Light Utilization efficiency (Φ, in %) of phytoplankton.

Photosynthetic rates at light-saturation varied from 410 in April, 2007 to the highest value of 1630 mg $O_2$ $m^{-3}$ $h^{-1}$ in January, 2007 (Table 4). This range of values of $A_{max}$ is broadly comparable to those reported for Lakes Chamo (716-1789; Eyasu Shumbulo, 2004) and Victoria (400-910 mg $O_2$ $m^{-3}$ $h^{-1}$: Talling, 1965; Melack, 1979) but higher than those reported for Lakes Awassa (Demeke Kifle and Amha Belay, 1990), Babogaya (Yeshiemebet Major, 2006), Abijata (Amha Belay and Wood, 1984), Naivasha and Oloidein (Melack, 1979). Much higher values were reported for other Ethiopian and East African lakes as Lakes Arenguade and Kilole (Talling *et al*.,1973), Ziway (Amha Belay and Wood, 1984), George (Ganf, 1975), and Nakuru (Melack and Kilham, 1974) (see Appendix 16). The statistical relationship between photosynthetic parameters and others related parameters are indicated in Appendix 13.

Temporal variations in $A_{max}$ seem to be influenced more by the concentration of algal biomass, SRP-P, $Z_{SD}$ and light utilization efficiency (Φ) of phytoplankton. $A_{max}$ was positively and significantly correlated with Φ ($r=0.78$, $p=0.022$) the later accounting for 61% of the variation in $A_{max}$. It was also strongly and positively correlated with SRP-P, Chl a, and negatively with $Z_{SD}$ although their relation was not statistically significant (see Appendix 13). The relationship between other algal nutrients and $A_{max}$ was very poor. Similarly, strong and positive correlations between $A_{max}$ and chl a have been observed for lakes in Kenya (Melack, 1979) and Wales (Pentecost and Happey-Wood, 1978) and Sri Lankan reservoirs (Amarasinghe and Vijverbg, 2002). Weak and insignificant positive correlations between $A_{max}$ and Chl a were also observed for Lakes Ziway ($r= 0.09$, Girma Tilahun, 1988) and Chamo ($r=0.09$, Eyasu Shumbulo, 2004) in Ethiopia. Smith (1979) has shown the presence of strong and positive correlation between $A_{max}$ and inorganic nutrients (N and P). However, in this study, the relation with N was

positive but not strong. From his studies on tropical African lakes, Melack (1979a) concluded that euphotic depth was inversely correlated with maximum photosynthetic rates, a situation observed in present study.
In general, increased light-utilization efficiency at shallow depth and availability of SRP_P and hence high algal biomass are controlling factors of light-saturated rate of photosynthesis in Lake Bishoftu.

Biomass-specific rate of gross photosynthesis at light saturation ($P_{max}$, $A_{max}/B$, mg $O_2$ (mg chl a)$^{-1}$) $h^{-1}$) has been used to estimate the photosynthetic capacity (assimilation number) of phytoplankton (Morris, 1980). It ranged from a minimum of 29 in September, 2006 and January, 2007, associated with high algal biomass to a maximum value of 91 mg $O_2$ (mg Chl a)$^{-1}$) $h^{-1}$ in March, 2007(Table 4), which was associated with low biomass and PAR. Mean value of $P_{max}$ was found to be close to the minimum value, which is comparable to values reported for productive lakes such as Lakes, Kilole (Talling *et al*., 1973) and Victoria (Melack, 1979) in East Africa. In contrast, the observed maximum values are unusually high compared to those of other Ethiopian and East African lakes (see Appendix 16). Various authors have suggested explanations for the unusually high values of photosynthetic capacity obtained from tropical waters (Talling, 1973; Lemoalle, 1981).

The observed very high and unusual values of $P_{max}$ probably resulted from underestimation of chl a due to analytical errors or due to strong association of $P_{max}$ with many environmental factors. Strong correlation was seen with SRP, $CO_2$, chl a, temperature, PAR and to some extent with TP (Appendix. 13). It was positively and significantly correlated ($r=0.77$, $p=0.016$) with SRP-P and strongly and negatively correlated with Chl a and PAR. The relation with other algal nutrients was positive but weak. Examples of inverse correlation between $P_{max}$ and algal biomass were documented for tropical lakes including Lake George (Ganf, 1972) and Lake Ebrie (Dufour, 1982).

In a study of photosynthetic rates in relation to light, strong correlation between $P_{max}$ and temperature, similar positive correlation although not very strong in lake Bishoftu, was observed (Reynolds, 1975; Jewson, 1976) in other lakes. Nutrient availability, particularly P- compounds seem to control photosynthetic capacity more than temperature in this lake. This is consistent with the argument that nutrient availability is more important than temperature in controlling photosynthetic capacity of phytoplankton populations (Falkowuski and Stone, 1983). Positive correlation of $P_{max}$ with temperature and inverse correlation with biomass was also reported by Harrison and Platt (1980) in their study of environmental control of assimilation number and in Kinnego Bay, by Jones (1977). Temperature was the dominant environmental covariate (independent factor) affecting $P_{max}$ accounting for 40% of the observed variation in some Lakes (Platt and Jassby, 1976; Harrison and Platt, 1980).

Absence of apparent relationship between $P_{max}$ and solar radiation was observed by Mandelli *et al.* (1970) and Harrison and Platt, (1980) in their seasonal studies of $P_{max}$ and light. However, in this study the observed inverse and strong relation between $P_{max}$ and PAR is probably associated with inhibition of $P_{max}$ at high PAR as it was observed that the unusual peak of $P_{max}$ corresponded with low PAR in March, 2007.Takahashi *et al*. (1971) suggested light and temperature inhibition of $P_{max}$ at higher temperatures. In general, SRP-P, algal biomass, $CO_2$ and light and temperature seem to be responsible for the observed temporal dynamics of $P_{max}$ in Lake Bishoftu.

Photosynthetic efficiency or light utilization efficiency (Φ in %) of phytoplankton estimated as percent of PAR used to assimilate unit calorie of carbon, showed a maximum value of 5.4 in January, which coincided with high chl a and a minimum of 0.81 % in March, 2007 (Table 4). The observed range of Φ is

higher than the range reported, 0.51-3.34%, for highly productive lakes by Talling *et al*. (1973).

The seasonal change in Φ was strongly and negatively correlated with PAR (r= -0.67, p=0.068), indicating a reduction of light utilization efficiency, and hence production of phytoplankton upon exposure to high light. It was also strongly and positively related to $P_{max}$ and SRP (see Appendix 13). Similarly, Melack (1979) found an inverse relation between light utilization efficiency of phytoplankton and irradiance in Lake Victoria. In Lake Kinneret, higher Φ was observed at higher algal density close to the surface because most of the down welling irradiance was absorbed by phytoplankton pigments and relatively little of the light energy was dissipated by non-biological absorption or scattering (Pollingher and Serruya, 1976).

Table 4: Photosynthetic parameters: Hourly (∑A) and daily (∑∑A) areal gross photosynthetic rates (g $O_2$ $m^{-2}$ $h^{-1}$ and g $O_2$ $m^{-2}$ $d^{-1}$ respectively), Maximum gross photosynthetic rate $A_{max}$ (mg $O_2$ $m^{-3}$ $h^{-1}$), Photosynthetic capacity, $P_{max}$ (mg $O_2$ (mg Chl-a)$^{-1}$ $h^{-1}$), and light utilization efficiency (Φ) at the central station of Lake Bishoftu in 2006/7.

| Sampling date | ∑A | ∑∑A | $A_{max}$ | $P_{max}$ | Φ (%) |
|---|---|---|---|---|---|
| 25/8/06 | 2.31 | 20.81 | 1570 | 37.65 | 2.86 |
| 19/9/06 | 1.80 | 16.20 | 1008 | 29.01 | 1.89 |
| 21-10-06 | 2.68 | 24.08 | 1025 | 31.05 | 2.78 |
| 25/11/06 | 1.83 | 16.43 | 1250 | 29.98 | 2.39 |
| 26/12/06 | 2.50 | 22.50 | 1613 | 42.19 | 4.10 |
| 27/1/07 | 3.88 | 34.88 | 1630 | 29.32 | 5.40 |
| 28/3/07 | 3.13 | 28.13 | 1280 | 91.40 | 0.81 |
| 28/4/07 | 0.89 | 8.03 | 410 | 29.50 | 2.86 |
| 27/5/07 | 1.400 | 12.60 | 710 | 54.50 | 2.00 |

### 3.2.3.3. Areal Photosynthetic rates

The hourly rate of gross photosynthesis per unit area (∑A) estimated from depth profiles of gross photosynthesis and daily rates (∑∑A), which were obtained from hourly rates by multiplying with constants derived by Talling (1965), showed seasonal variations in relation to different environmental variables. ∑A varied from 0.89 in April to 3.88 in January, 2007 with a mean value of 2.27 g $O_2$ $m^{-2}$ $h^{-1}$. The pattern of variation in daily rates followed that of hourly rates, changing from 8.03 in April to 34.88 g $O_2$ $m^{-2}$ $d^{-1}$ in January, 2007. Comparison of the areal rates of photosynthesis of Lake Bishoftu with other Ethiopian and east African lakes is given in Appendix 17.

There was weak and negative correlation between ∑A and algal nutrients, silica and ammonium-ammonia-nitrogen but strong positive correlation was found with SRP-P, TP, nitrate + nitrite-nitrogen, Chl a and $A_{max}$. ∑∑A was also strongly and positively correlated with Chl a and $A_{max}$ (see Appendix 13). The correlation of $A_{max}$ with both hourly and daily rates was statistically significant ($r=0.82$, $p=0.007$). In addition ∑∑A was strongly and negatively correlated with calculated euphotic depth. The direct linear relationship of ∑A with $A_{max}$ and $Z_{eu}$ has been demonstrated for East African lakes (Talling, 1965). However, in this study, the relation between ∑A and $Z_{eu}$ was inverse indicating that ∑A was more related to $A_{max}$ and volumetric biomass at shallow depth where light energy can be efficiently used for production. At high $Z_{eu}$, low algal biomass and light energy result in insufficient algal growth, because the lake was dominated by buoyant blue greens, which can trap light and nutrients near the surface and maintain their biomass at shallow depth, hence going down biomass and photosynthetic area are low.

Talling (1965) indicated that variation in ∑A can be accounted for by the variation in ∑A independent ratio, B x $p_{max}$ / $k_{min}$. The dependence of ∑∑A on $A_{max}$ and $K_d$ was also documented by other investigators (e.g. Megard, 1972).

In East Africa higher photosynthetic rates occurred in lakes with higher Chl a concentrations and vice-versa (Melack, 1979). An increase in B of phytoplankton can bring about a corresponding increase in ∑A (Jones, 1977).

Euphotic biomass was positively correlated with areal production (r=0.48, p=0.19) accounting for 23 % production. Lemoalle (1981), similarly, showed positive correlation of areal biomass content with higher values of areal production, which was governed by higher value of photosynthetic capacity. Talling *et al*. (1973) observed high rate of areal photosynthesis (0.5-2.4 g $O_2$ $m^{-2}$ $h^{-1}$) in Lake Kilole with high phytoplankton biomass, but shallow $Z_{eu}$. The present areal rates are comparable to these values although the biomass values are not. These comparable values of ∑A may be associated with increased $A_{max}$ and $P_{max}$ in Lake Bishoftu in contrast to that in Lake Kilole.

## 4. GENERAL DISCUSSION

Lake Bishoftu, the deepest ($Z_{max}$=85m) lake among the Bishoftu crater lakes lying within the depression of steep crater wall, shows interesting hydrographic features. Depth profiles of temperature showed both superficial and deep-seated thermal stratification with two thermoclines in some occasions, as well as ill-marked thermoclines in other occasions. Apart from the ill-defined thermoclines (thermoclines that do not demarcate the epilimnion and hypolimnion regions clearly), isothermal conditions down the water column have not been observed on all occasions indicating the absence of complete mixing. Absence of complete mixing and thermal stratification, some times with undefined thermoclines is a feature of some east African lakes including Lake Bishoftu (Baxter *et al*., 1965; Talling and Talling, 1965), which is attributable to weak wind effect due to their steep crater walls and great depth. Very shallow mixing and high light energy, observed in this study, favour growth of blue greens (Heck, 1993). The decline of

phytoplankton abundance in dry periods appears to be attributable to deep and superficial stratification.

As can be seen in the depth profiles of oxygen, the water column was anoxic below certain depths away from the surface while oxygen maxima were observed near the surface. As a consequence, biomass and photosynthetic production are confined to the near to the surface region, resulting in condensed depth profiles of photosynthesis.

Absence of complete mixing has negative consequence on nutrient cycling and mixing-dependent algal groups such as diatoms (Reynolds, 1984: Wood *et al*., 1984). The summary of a revisit of some parameters measured in different years (Table 5) shows the decrease in certain parameters and the increase in others. The progressively reduced values of dissolved silica and alkalinity observed in the present study compared to previously reported values are probably associated with reverse weathering (see below) resulting from the absence of complete mixing of the water column. In contrast, nitrogen and P compounds are progressively increasing with time from their undetectable previous concentration, which are obviously associated with the enrichment of the lake from domestic wastes containing N and P compounds. Algal biomass is still high and may have increased to levels much higher than the values reported earlier by Zinabu Gebre-Mariam (1994) since the present sampling was not frequent enough to detect short-term changes

$Al_2Si_2O_5(OH)_5$ (Kaolinite- soluble silica) + $5Mg^{2+}$ + $Si(OH)_4$ + $10CO_3^{2-}$ + $5H_2O \longrightarrow Mg_5Al_2Si_3(OH)_8$ (Chlorite- precipitate containing silica) + $10HCO_3^-$ (Reverse weathering: Wood and Talling, 1988).

Table 5: Comparison of the concentration of inorganic nutrients (µg $L^{-1}$, unless otherwise indicated), alkalinity (meq $L^{-1}$) and biomass as chl a (µg $L^{-1}$) repeated for different years. (Data source: the 1963 data are from Prosser *et al*., 1968; the 1990-92 are from Zinabu Gebre-Mariam, 1994).

| Parameters | Apr/May,1963 | Apr, 1990-92 | Present study |
|---|---|---|---|
| $NO_3$ - N | 20 | 25 | 13 – 110 (44) |
| $PO_4^-$ - P | <5 | 28 | 10 – 46 (22) |
| TP | - | - | (66) |
| $SiO_2$ (mg/L) | 38 | 15 | 5 – 28 (18) |
| Alka. ($CO_3$ + $HCO_3$) | 20 | 17 | 13.70 – 16.8 (15) |
| B (mg Chl a $m^{-3}$) | 28 | 60 | 12 - 57 (**30**) |
| | | 34 [Wood and Talling (1988)] | |

Mean Values are given in bracket - **( )**

The phytoplankton community of Lake Bishoftu is characterized by the persistent dominance of blue-greens, whose abundance was largely constituted by species of the nuisance bloom-forming genus Microcystis.

Cyanbacterial dominance is associated with the various survival mechanisms of the organisms. Buoyancy regulation is considered to be important in contributing to the success of cyanobacteria in a wide range of aquatic ecosystems (Reynolds and Walsby, 1975; Reynolds, 1984) because it provides the advantage of being able to alter position in the water column through physiological changes. Ganf and Oliver (1982) showed how buoyancy regulation allowed cyanobacteria to overcome the vertical separation of light and nutrients in a stratified lake. Under stratified conditions, PAR, carbon dioxide and inorganic nutrient supplies are limiting along well-defined vertical gradients (Walsby and Booker, 1980). Under such environmental constraints, buoyancy-mediated vertical migration provides an effective means of rapid cell reorientation.

Persistent positive buoyancy in cyanobacteria leads to the accumulation of surface-scum populations in stabilized, near surface water layers (Paerl, 1983),

and such populations can effectively trap more of incoming PAR and atmospheric $CO_2$ and inorganic nutrients while shading subsurface populations of non-buoyant phytoplankton (Van Liere and Walsby, 1982). Cyanbacteria bloom species are known to possess effective ways of protecting their photosynthetic apparatus and other labile cellular constituents against photooxidation in UV-rich surface waters (Pael and Kellar, 1979). Surface scum formation a means for optimal utilization of various environmental resources while contemporaneously restricting PAR transmittance and $CO_2$ diffusion to potentially competitive sub-surface phytoplankton populations (Paerl, 1988).

At high pH, which is associated with increased photosynthesis and hence reduced $CO_2$ level, a denser cyanobacterial scum due to elevated buoyancy was observed during the experiment carried out to explain the occurrence of blue green algae scum by Paerl and Ustach (1982). In investigation of the role of $CO_2$ in regulating photosynthetic and buoyancy responses, it has been shown that scum formation at elevated pH levels is a direct effect of $CO_2$ depletion (Walsby and Booker, 1976; Pael and Ustach, 1982). Elevated pH levels normally result from depletion of $CO_2$, during periods of vigorous

photosynthesis in cyanobacterial-dominated waters (Kellar and Paerl, 1980). At low pH (high $CO_2$ level), cyanobacteria have lost their competitive advantage over eukaryotic algae, because adequate supplies of $CO_2$ are available (Paerl and Ustach, 1982), and under these conditions, generally higher growth rates of eukaryotic algae (Fogg *et al.,* 1973) allow them to out-compete the cyanobacteria quickly. However, in waters of high pH, the ability to dominate surface waters becomes more important especially under prolonged calm conditions during which scum formation is often pronounced (Paerl and Ustach, 1982).

In spite of its unfavourable morphometric and hydrographic conditions such as great depth, absence of complete circulation and weak wind effect, Lake Bisuoftu is a eutrophic lake and found near the upper border of eutrophic level, according to the indices of the classification system forTrophic States developed by Carlson

(1977) based on three parameters: water clarity, Chl a, and total phosphorus (Fig.11).

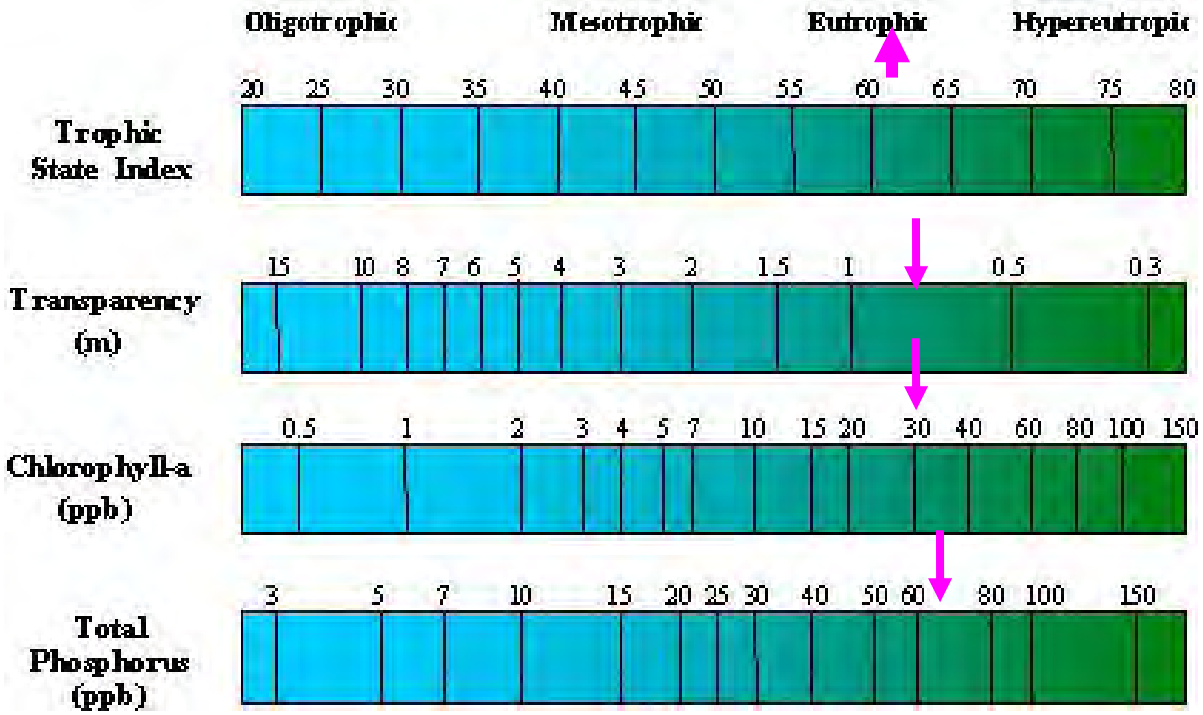



Fig.11. Carlson's Trophic State Index used to show the trophic status of Lake Bishoftu (which has $Z_{SD}$=0.7m, Chl a=30, and TP=66 µg $L^{-1}$ (ppb-equivalent unit).

## 5. CONCLUSIONS AND RECOMMENDATIONS

The depth profiles of oxygen and temperature of Lake Bishoftu showed the prevalence of deep-seated and superficial thermal stratification as well as thermal regimes with ill-defined thermoclines and nocturnal cooling and mixing, which occupied shallow regions (around 0-3m depths) of the water column. The depth profiles of Oxygen and temperature show the absence of complete mixing in this deep and sheltered crater lake.

The phytoplankton community of Lake Bishoftu are composed of Cyanophyceae, Bacillariophyceae, Dinophyceae, Chlorophyceae, Cryptophyceae and Haptophyceae. The present data on algal species composition and abundance indicate the predominance of cyanobacteria with genus Microcystis as the most important taxon throughout the study period. The zooplankton community was composed of Calanoid and Cyclopoid copepods and rotifers with the dominant species *Lovenula africana* (genus Diaptomus) and *Brachionus calciferous (*genus Brachionus).

Lake Bishoftu has relatively high algal biomass, inorganic nutrients and primary productivity, features of saline-alkaline lakes of East Africa. Algal biomass as chlorophyll a and abundance, and nutrient availability seemed to be influenced mainly by hydrological conditions, with their high levels associated with rainy and post rainy periods.

The dynamism of phytoplankton community is controlled by interaction of different water quality factors related to human interventions as well as natural processes. In addition to the natural conditions, human interventions are aggravating the dominance of algal community by blue-greens. Major algal nutrients, which are controlled by rain-induced input from external sources and water column conditions, are of over-riding importance in algal dynamics. Light, temperature and water column stability are the second route controlling the

species composition of algae. The other minor line is zooplankton grazing by Calanoid copepods and rotifers. The two routes, thermal stability and nutrient input are the major routes regulating phytoplankton composition. These conditions, favouring towards single genus, are creating unialgal community in the lake, indicating the eutrophic state of the lake. The parameters used to indicate the trophic states confirmed eutrophic situation and the possibility of changing to the risk of hypereutrophic state if the present conditions allowed to continue. In general, Lake Bishoftu is a thermally stratified, cyanobacteria dominated and eutrophic crater lake that needs further and integrated studies and monitoring because different developmental activities are being carried out in the proximity of its shores, which possibly cause negative effects in contrast to its significance.

**Recommendations.**

The dominance of aquatic ecosystems by blue greens, especially the genus *Microcystis* is considered as an indication of the changing of aquatic ecosystems by human interventions. Nutrient introduction from dumping site on the top of crater rim through runoff is one way of enhancing situation. Unless efforts are made to reduce factors favouring the dominance of Microcystis, the lake will be completely dominated by nuisance blue greens resulting in irreversible change of the ecosystem. Then, the lake which is now being used for different purposes will no longer be of any services. Therefore, in order to reduce man-made causes of degradation, some feasible mitigation and control measures should be taken by the concerned bodies in collaboration with local community. Thus, the following recommendations are made:

- The Debre-Zeit city administration in collaboration with the Ministry of Water Resources and Ethiopian Environmental Agencies should be able to disseminate awareness-creating education into the community that has

settled on the catchment areas. At the same time, domestic waste disposal system should be arranged and made available for each locality. Resort hotels along the lake sides that are directly discharging liquid and solid wastes should be able to use an alternative way of waste disposal such as septic tanks.

- There should be established legal body that controls all developmental activities being carried out on the catchment of the lake.
- Environmental authority should give prior attention to biological and ecological effects of human intervention on lakes that are in the vicinity of flourishing cities such as Debre-Zeit.
- Limnological studies should be carried out continuously to generate baseline data to closely monitor the water quality of the lake regularly before the occurrence of ecological crisis.
- Further statistical analysis should be done to decide the factors that govern dynamics of phytoplankton in Lake Bishoftu.
- Further study on hydrographic conditions, particularly on depth profiles temperature and dissolved oxygen, and on topdown effect of phytoplankton dynamics should be carried out.

## 6. LIST OF CITED REFERENCES


Adane Sirage. (2006).*Water quality and Phytoplankton Dynamics in Legedadi Reservoir.*M.Sc thesis Addis Ababa University, Addis Ababa 109pp.

Afeworki Ghebrai (1992*). Zooplankton structure and dynamics in two contrasting soda lakes (Debbre Zeit crater lakes, Ethiopia*).Unpublished M.Sc. thesis, Addis Ababa University.98pp.

Amarasinghe, P.B. and Vijverberg, J. (2002). Primary production in a tropical reservoir in Sri Lanka. *Hydrobiologia,* 487:85-93.

Amha Belay and Wood, R.B. (1982). Limnological aspects of algal bloom on Lake Chamo (Gamu Goffa Administrative region, Ethiopia). SINET: *Ethiop. J. Sci*. **5(1**) 1-19.

Amha Belay and Kassahun Wodajo (1982). Limnological aspects of an algal bloom on Lake Chamo in Gamo Gofa administrative region of Ethiopia in 1978. *SINET: Ethiopian J.Sci*. **5**:1-19.

Amha Belay and Wood**,** R.B. (1984). Primary production of five Ethiopian Rift Valley lakes. *Verh. Internat. Verein. Limnol.* **22**:1187-1192.

American Public Health Association, APHA, American Water Works Association, AWWA and Water Environment Federation, WEF (1999). *Standard methods for the examination of water and Waste water* 20th ed. New York.

American Public Health Association, APHA (1992). *Standard methods for the examination of water and wastewater.* 18th ed. Washington, DC.

American Public Health Association, APHA (1995). *Standard Methods for the Examination of Water and Wastewater,* 19th ed. Washington, DC.

Badger, M.R. and Price, G.D.(2003). $CO_2$ concentrating mechanisms in cyanobacteria: molecular components, their diversity and evolution. *J Exp Bot.*, **54:** 609-622.

Baxter, R.M., Prossor, M.V., Talling, J.F. and Wood, R. B. (1965). Stratification in tropical African lakes at moderate altitudes (1500-2000). *Limnol. Oceanogr*. **, 10:**510- 520.

Baxter, R. M. and Golobistch, D. L. (1970). A note on the limnology of Lake Hayq, Ethiopia. *Limnol.Oceanogr*. **15:144**-149.

Behrenfeld, M.J., Prasil, O., Kolber, Z. S., Babin, M., and Falkowski, P.G. (1998). Compensatory changes in PSII electron turnover rates protect photosynthesis from Photo inhibition. *Photosynthesis Research*, **56**:259-68.

Beadle, L. C., (1963). Anaerobic life in a tropical crater lake. *Nature* **200**: 1223–1224.

Beadle, L. C. (1966). Prolonged stratification and deoxygenation in tropical lakes. I. Crater Lake Nkugute, Uganda, compared with Lakes Bunyoni and Edward. *Limnol. Oceanogr*. **11**: 152–163.

Beadle, L.C. (1981). The inland waters of tropical Africa, 2nd ed. Longman Inc.., New York. 457pp.

Brook Lemma (1994). Changes in the limnological behavior of a tropical African explosion crater lake: L. Hora-Kilole, Ethiopia. *Limnologica* 24 (1):57-70.

Brook Lemma (2002). Contrasting effect of human activities in aquatic habitats and biodiversity of two Ethiopian lakes. *Ethiop.J. Nat. Res*.**4** (1): 133-144.

Camp Dresser & McKee. (1999). Lake Merced Water Sanitary Survey November 1999 Report. San Francisco Public Utilities Commission.

Caraco, N. and Miller, R (1998). Direct and Indirect effects of $CO_2$ on competition between a cyanobacteria and eukaryotic phytoplankton. *Can. J. Fish. Aquat. Sci*. **55:**54-62.

Carlson, R.E. (1977).A trophic state index for lakes. *Limnol. and Oceanogr.* **22**:361-369.

Chapman, D. (1997). Water Quality Assessment: A Guide to the Use of Biota, Sediments and water in Environmental Monitoring. Second Edition. E & FN Spon, London.

Conway, H. L. (1977). Interactions of inorganic nitrogen in the uptake and assimilation by marine phytoplankton. *Mar. Biol*., **39**:221-232.

Crisman, T.L. and Streeyer, W.J. (1996). The legacy and future of tropical limnology. In: *Perspectives in Tropical Limnology*, pp 27-42 (F. Schiemer, and K.T. Boland, eds). SPB Academic Publishing b.v., Amesterdam. The Neatherlands.

Cronber, G. & Komarek, G. (2004). Some nostocalean cyanoprokaryotes from lentic habitats of Eastern and Southern Africa. *Nova Hedwigia* **78**:71-106.

Defaye, D. (1988). Contribution a laconnaissance des crustaceas copepods d'Ethiopiae. *Hydrobiologia.***164**: 103-147.

Demeke Kifle .(1985). Variation in phytoplankton primary production in relation to light and nutrients in Lake Awassa. *M. Sc. Thesis*, Addis Ababa University, Addis Ababa: 108pp.

Demeke Kifle and Amha Belay. (1990). Seasonal variation in phytoplankton primary production in relation to light and nutrients in Lake Awassa, Ethiopia. *Hydrobiologia* **196:**217-227.

Dubinsky, Z. and Berman, T. (1981). Light utilization by phytoplankton in Lake Kinneret (Israel). *Limnol. Oceanogr*. **26**(4):660-670.

Dubinsky, Z. and Berman, T. (1976). Light utilization efficiencies of phytoplankton in lake Kinneret (Israel). *Limnol. Oceanogr*. **24**:652-663.

Dubinsky, Z. and Polna, M. (1976). Pigment composition during a perineum bloom in lake Kinneret (Israel). *Hydrobiologia* **51**:239-243.

Dufour, P. (1982). Modéles semi-empiriques de la production phytoplanktonique en Meilieu lagunaire tropical (Cóte-de'Ivoire). *Actaoecologica, Oecol. Gener*. **3**:223-239.

Dussart, B. (1989). Crustaces Copepodes Calanoides des eaux interieures africaines. *Crustaceana*, Suppl. 15, pp 1 – 205.

Effler, S. W., C. M. Brooks, M. T. Auer, and S. M. Doerr. (1990). "Free ammonia and toxicity criteria in a polluted urban lake". *Journal Water Pollution Control Feb* **62**: 771-779.

Elizabeth kebede .(1996). *Phytoplankton in a salinity-alkalinity series of lakes in the Ethiopian Rift valley*. Ph.D. Thesis, Uppsala University, Uppsala, Sweden.

Elizabeth Kebede and Amha Belay. (1994). Species composition and plankton biomass in a tropical African lake (Lake Awassa, Ethiopia). *Hydrobiology*, **288**:13-32.

Elizabeth Kebede and Willén, E. (1998). Phytoplankton in a salinity-alkalinity series of lakes in the Ethiopian Rift Valley. *Algological studies*, **89**: 63-96.

Elizabeth Kebede, Zinabu G-Mariam and Ahlgren, I. (1994). The Ethiopian rift valley lakes: chemical characteristics of a salinity-alkalinity series. *Hydrobiol*. **288**:1-12.

Erikson, R., Hooker, E. and Meija, M.(1991). Underwater light penetration, phytoplankton biomass and photosynthetic activity in Lake Xolotlan (Managua). *Hydrobiol. Bull*. **25**(2), 137-144.

Eyasu Shumbulo.(2004**).***The temporal and spatial variations in the biomass and photosynthetic production of phytoplankton in relation to some physico- chemical variables in Lake Chamo Ethiopia*. M.Sc.Thesis, Addis Ababa University, Addis Ababa. 72pp

Falkowski, P.G. and Stone, D.P. (1983). Nitrate uptake in marine phytoplankton: energy sources and the interaction with carbon fixation, *Mar. Biol*., **32:**77-84.

Fernando, C.H. (1980). The fresh water zooplankton of Sri Lanka with a discussion of tropical fresh water zooplankton composition. *Int. Rev. ges. Hydrobiol*. **65**(1):85-125.

Fernando, C.H. (2002). *A guide to tropical freshwater zooplankton*: Identification, ecology and impact on fisheries. 290pp.

Fisher, T.R., Doyle, R.D. and Peele, E. R. (1988). Size-fractionated uptake and regeneration of ammonium and phosphate in a tropical lake. *Verh .int. Verein. Limnol*.**23**:637-641.

Fogg, G.E., Stewart, W.D.P., Fay, P., and Walsby, A.E. (1973). *The Blue Green Algae.* Academic Press. London.

Forsberg, C. & Ryding, S.O. (1980). Eutrophication parameters and trophic state indices in 30 Swedish waste-water receiving lakes. *Arch. Hydrobiol*.**89**:189-207.

Ganf, G.G. (1974). Diurnal mixing and vertical distribution of phytoplankton in shallow equatorial lake (Lake George, Uganda). *Ecology,* **62**:611-629.

Ganf, G.G. and Horne, A.J. (1975). Diurnal stratification, photosynthesis and nitrogen-fixation in a shallow equatorial lake (Lake George, Uganda). O*ecologia* **18:** 165-183**.**

Ganf, G.G. (1972). The regulation of net primary productivity in Lake George, Uganda, East Africa. In: *Productivity problems of freshwaters*, pp.693-708, (Z. Kajak and A. Hilbricht- Ilkowska, eds.), Polish Scientific Publishers. Krakow,

Ganf, G.G.and Viner, A.B. (1973).Ecological Stability in a Shallow equatorial lake (Lake George, Uganda).*Proc.Roy.Soc*. (B) **184**:321-346.

Ganf, G.G. (1975). Photosynthetic production and irradiance photosynthesis relationships of phytoplankton from a shallow equatorial lake (Lake George, Uganda). *Oecologia* **18**: 165 – 183.

Gasse, F. (1986). *East African Diatom Taxonomy, Ecological Distribution*. In der Gebrüder Borntraeger Verlagsbuchhandlung. Berlin Stuttgart, 201pp.

Gasse,F., Talling ,J.F.and Kilham, P.(1983). Diatom assemblages in East Africa: classification, distribution and ecology. *Rev. Hydrobiol. Trop*. **16**:3-34.

Getachew Beneberu (2005). *Nutrient and plankton dynamics in the littoral and offshore zones of Lake Ziway.* M.Sc Thesis. 67 pp.

Girma, Tilahun. (1988). *A seasonal study on primary production in relation to light and nutrients in Lake Ziway, Ethiopia*. M.Sc. Thesis, Addis Ababa University, Addis Ababa, 62 pp.

Girma Tilahun. (2006).Temporal Dynamics of the Species Composition, Abundance and Size-Fractionated Biomass and primary production of Phytoplankton in Lakes Ziway, Awassa and Chamo (Ethiopia). PhD. Thesis Addis Ababa University, Addis Ababa. 201pp.

Goldman, C. T. Mason, R., D. and. Wood, B. J. (1963). Light injury and inhibition in Antarctic freshwater phytoplankton. *Limnol. Oceanogr*.**8**: 313-322.

Green, J. (1967). The distribution and variation of *Daphnia lumholtzic* (Crustacea: Cladocera) in relation to fish predation in Lake Albert, East Africa. *J. Zool. London* **15**1:181-197.

Green, J. (1986). Zooplankton associations in some Ethiopian crater lakes. *Fresh wat. Biol.* **16**: 495-499.

Green, J., and Seyoum Mengistou (1991). Specific density and community structure of Rotifera in a salinity series of Ethiopian inland waters. *Hydrobiologia* **209**:95-106.

Guildford, S.J. and Hecky, R.E. (2000). Total nitrogen total phosphorus, and nutrient limitation in lakes and Oceans: is there a common relationship? *Limnol.Oceanogr*. **45**(6):1213-1223.

Hammer U.T., Shamess and Haynes, R.C. (1983). The distribution and abundance of algae in saline lakes of Saskatchewan, Canada. *Hydrobiologia* **105**:1-26.

Hanley, J. F. (1987). Field studies on zooplankton-cyanobacteria interactions. New Z. *J. Mar. Feshwat. Res***, 21**:467-475.

Harding, D. (1963). Report on the hydrobiology of Lake Nyasa and associated rivers. In: *A report on the Fish and Fisheries of Northern Nyasa*, pp.8-44 (P.B.N. Jackson, D.Harding, G. Fryer and T.O. Iles, eds). Government Printer, Nyasaland.

Harris, G.P. and Lott, J.N.A.(1973). Light intensity and photosynthetic rates in phytoplankton. *J. Fish. Res. Bd. Can*., **20**; 1771-1778.

Harrison, W.G. and Platt,T. (1980). Variations in assimilation number of coastal marine phytoplankton: effects environmental co-variates. *J. Plankt.Res*. **2**(4):249-260.

Hecky, R.E. (1971). The Paleolimnology of the alkaline saline lakes on the Mt. Meru I.ahar. *Ph.D. Thesis*, Duke Univ. 209pp.

Hecky, R.E. and Kilham, P. (1973). Diatoms in alkaline saline lakes: ecology and geochemical implications. *Limnol. Oceanogr*. **18**:53-71.

Hecky, R.E. (1993).The eutrophication of Lake Victoria .*Verh.Int .Verein .Limnol*.,**25**: 39-48.

Hecky, R.E. and Kling, H.J. (1981). The phytoplankton and the Proto-zooplankton of the eutrophic zone of Lake Tanganyika: species composition, biomass, chlorophyll content and spatio-temporal distribution. *Limnol.Oceanogr*. **26**:548-564.

Hecky, R.E. and Kling, H.J. (1987). Phytoplankton ecology of the great lakes in the rift valleys of Central Africa. In: *proceedings of the symposium on the phycology of large lakes of the world. Arch. Hydrobiol. Beih.* **25**:197-228 (M. Munawar, ed).

Holmes, J. A. (2000). Seasonal Succession of Phytoplankton**.** *Environmental Research and Teaching*. Environmental Information Office, I. E. S, Toronto

Hotzel,G. and Croome,R.(1999).A phytoplankton counting methods manual for Australian freshwaters.Land and Water Resource Research Development Corporation Canberra,51pp.

Howarth, R. W. (1988). Nutrient limitation of net primary production in marine ecosystem.*Annual Rev. Ecol. Systemat*. **19**:898-1110.

Hutchinson, G. E. (1957). A treatise on limnology,v. 1.Wiley and Sons, New York.540pp.

Iles, T.D. (1960). Activities of the organization in Nyasaland. In: *Joint Fisheries Resaerch Organization, Annual Report No.9*, pp. 7-41. Northern Rhodesia,

Jensen, P., Jeppensen, E. Olrik, K. and Kristensen, P. (1994). Impact of nutrients and physical factors on the shift from cyanobacterial to chlorophyte dominance in shallow Danish Lakes.*Can. J. Fish. Aquat*. Sci., **51**:1692-1699.

Jewson, D.H. (1976). The interaction of components controlling net phytoplankton Photosynthesis in a well-mixed lake (Lake Neagh, Northern Ireland). *Freshwat. Biol.* **6**:551-576.

Jewson, D.H. (1977). Light penetration in relation to phytoplanktonic content of the euphotic zone of Lough Neagh, N.Ireland. *Oikos* **28**; 74-83.

Jones, R.I. (1977). Factors controlling phytoplankton production and succession in a highly eutrophic lake (Kinnergo Bay, Lough Neagh):II. Phytoplankton *J.Ecol*. **65**(2):561-577.

Kalff, J. (1983). Phosphorus limitation in some tropical African lakes. H*ydrobiologia,* **100**:101-112.

Kalff, J. (2002). *Limnology: Inland water Ecosystems*. Prentice-Hall, Inc, NJ. 592pp.

Kassahun Wodajo. (1982). Comparative limnology of Lake Abijata and Lake Langano in relation to primary and secondary production. *M. Sc.thesis*. Addis Ababa University Addis Ababa.

Kassahun Wodajo and Amha Belay (1984). Species composition and seasonal abundance of zooplankton in two Ethiopian rift valley lakes: lakes Abiata and Langano. *Hydrobiologia* **113**:129-136.

Kellar, P. E., and Paerl, H. W. (1980). Physiological adaptations in response to environmental stress during $N_2$-fixing *Anabaena* bloom. *Appl. Environ. Microb.* **40**: 587-595.

Kerfoot, W.C. (1974). Egg-size cycle of a cladoceran. *Ecology* **55**:1259-1270.

Kilham, P., (1971). Biogeochemistry of African lakes and rivers. *Ph.D. dissertation*, Duke University, Durham, N.C. 199 pp.

Kizito, Y. S., A. Nauwerck, L. J. Chapman & W. Koste, (1993). A limnological survey of some western Uganda crater lakes. *Limnologica* **23**: 335–347.

Kling, G. W. (1988). Comparative transparency, depth of mixing and stability of stratification in Lakes of Cameroon, West Africa. *Limnol. and Oceanog.* **33**(1):27- 40.

Kirk, J.T.O. (1975). A theoretical analysis of the contribution of algal cells to the attenuation of light within natural waters. II. Spherical cells. *New Phytol*. **75**:21-36.

Kirk,J.T.O. (1976). A theoretical analysis of the contribution of algal cells to the attenuation of light within natural waters: cylindrical and spheroidal cells. *New Phytol*. **77**:341-358.

Kirk, J.T. (1983). Light and photosynthesis in aquatic ecosystems. Cambridge.

Kohler, J. (1992). Influences of turbulent mixing on growth and primary production of *Microcystis aeruginosa* in the hypereutrophic Bautzen Reservoir. *Archiv fur Hydrobiol*. **123**:413-429.

Kok, B. (1956).On the inhibition of photosynthesis by intense light. *Biochem. Biophys. Acta*, **21**:234-244.

Komárek, J. and Anagnostidis, K. (2000). *Cyanoprokaryota* : subwasserflora von Mitteleuropa.Spektrum Akademischer Verlag Heidelberg, Berlin.548pp.

Komare, J. & kling, H. (1991). Variations in six planktonic cyanophyte genera in Lake Victoria (East Africa). *Algological Studies* **61**:21-45.

La Barbara, M. C. and Kilham, P. (1974). The chemical ecology of copepod distribution in the lakes East and Central Africa. *Limnol.Oceanogr*.**19**:459-465.

Lamb, H.F. (2001). *Multi-proxy records of Holocene climate and vegetation change from Ethiopian Crater Lakes.* Institute of Geography and Earth Sciences, University of Wales Aberystwyth, http://WWW.ria.ie/cgi-bin/ria/papers.

Leman, J.T. (1988). Selective herbivory and its role in the evolution of phytoplankton growth strategies. In: *Growth and Reproductive Strategies of Fresh water Phytoplankton,* pp.369-386, (C.D. Sandgren, ed). Cambridge University Press. Cambridge.

Lemoalle, J. (1981). Photosynthetic production and phytoplankton in the euphotic zone of some African and temperate lakes. *Rev. Hydrobiol. trop*., **1:** 31-37.

Lemoalle, J., A. Aoenije, P. Compere, G.G. Ganf, J. Melack and J.F. Talling, (1981). Phytoplankton. In: The ecology and utilization of African inland waters, (Symmoens, J.J., M. Burgis and J.J. Gandet, eds). UNEP, Nairobi.

Lind, T. O. (1979). *Handbook of common methods in Limnology*, 2nd ed. The C.V. Mosby Company. 199 pp.

Lewis, W. M. Jr. (1973a). A limnological survey of Lake Mainit, Philippines. *Hydrobiol*. **58**: 801–818.

Lewis, W. M. Jr. (1973b). The thermal regime of Lake Lanao (Philippines) and its theoretical implications for tropical lakes. *Limnol.Oceanogr*. **18**: 200–217.

Lewis, W.M. (1996). Tropical lakes: How latitude makes a difference. In: *Perspective in Tropical Limnology,* pp 43-64 (Schierner, F, and Boland, K.T., eds). SPB. Academic Publisher, Amesterdam.

MacCarthy, J.J. (1980). The physiological ecology of phytoplankton. In: *Studies in Ecology* Vol.7, pp. 191-234 (Morris, I., ed.). .Blackwell.

MacIntyre, S. & Melack, J. M. (1982). Meromixis in an equatorial African soda lake. *Limnol. Oceanogr*. **27**: 595–609.

Mandelli, E.F., Burkholder, P.R., Doheny, T.E. and Brody, R. (1970). Studies of primary productivity in coastal waters in Southern Long Island, New York. *Mar. Biol*. **7**:153-160.

Margaleff, R. (1996). *Limnology Now: A Paradigm of Planetary Problems.* Elsevier, Amsterdam. pp. 220-222.

Mays, L. W. (1996). *Water Resources Handbook. McGraw*-Hill. New York, pp: 92

Megard, R.O., Combs, W.S., Smith, P.D. and Knoll, A.S. (1979). Attenuation of light and daily integral rates of photosynthesis attained by planktonic algae. *Limnol. Oceanogr.* **24**(6):1038-1050.

Megard, R.O. (1972). Phytoplankton photosynthesis and phosphorus in lake Minnetonka, Minnesota. *Limnol. Oceanogr*. **17**:68-87.

Melack, J.M. (1976). *Limnology and dynamics of phytoplankton in Equatorial African lakes*. Ph.D. Thesis. Duke University Durham, N.C, 453 pp.

Melack, J. M., 1978. Morphometric, physical and chemical features of the volcanic crater lakes of western Uganda. *Arch. Hydrobiol*. **84**: 430–453.

Melack, J.M. (1979a). Photosynthetic rates of four tropical African freshwaters. *Freshwat. Biol.,* **9**: 555 – 571.

Melack, J.M. (1979b). Photosynthesis and growth of *Spirulina platensis* (Cyanophyta) in an equatorial lake (Lake Simbi, Kenya). *Limnol. oceanogr*., **24**: 753 – 760.

Melack, J.M. (1979c).Temporal variability of phytoplankton in tropical lakes *ecologia,* **44:1**-7.

Melack, J.M. (1981).Photosynthetic activity of phytoplankton in tropical Africa Soda lakes. *Hydrobiologia,* **158**:1-14.

Melack, J.M. (1996). Recent developments in tropical limnology. *Verh.int.ver. Limnol*. **26**:211-217.

Melack, J.M. and Kilham , P.(1974). Photosynthetic activity of phytoplankton in tropical African soda lakes. *Hydrobiologia,* **81**:71-85.

Melack, J.M. (1984).Amazon floodplain lakes: Shape, fetch, and stratification, *Verh. Int .Verein. Limnol*.**22**:1278-1282.

Melack,J.M. and Kilham ,P.and Fisher, T.R. (1982). Response of phytoplankton to experimental fertilization with ammonium and phosphate in an African soda lake. *Oecologia* **52**:321-326.

Melaku Mesfin, Tudorancea, C. and Baxter, R. M. (1988). Some limnological investigations on two Ethiopian hydroelectrical reservoirs: Koka , Shewa

Administrative District) and Ficha (Wolega Administarive District). *Hydrobiologia*, **157**:47-55.

Mohr, P.A. (1961). The geology, structure and origin of the Bishoftu explosion crater lakes, Shoa, Ethiopia. *Bull. Geophys. Obs*., *Addis Ababa* **2**:65-101.

Morel, A.(1978). Available, usable and stored radiant energy in relation to marine photosynthesis. *Deep sea Res*. **25**:673-688.

Mortimer, C. H. (1971). Chemical exchanges between sediments and water in the great Lakes-speculation on probable regulatory mechanisms. *Limnol. Oceanogr*. **16**:296-313.

Morris, I. (1980). *The physiological ecology of phytoplankton*. *Blackwell Scientific Publications.* 625 pp.

NSW (2000). *Algal Information Department of Land water Conservation*. National Standard of Water, U. S.

Nelson, J. L., Kurtz, L. T., and Bray, R. H. (1954). Rapid Determination of nitrates and nitrites. *Anal. Chem.*, **26**: 1081-1082.

Nultsch, W. (1979). Effect of external factors on phototaxis of *Chlamydomonas reinhardtii* III. Cations. *Archs.Microbiol*. **123**:93-99.

Ochumba, P.B.O. (1987). Periodic massive fish kills in the Kenyan part of Lake Victoria. *Wat.Qual.Bull*. **12**:119-122.

Olson, F.C.W. (1960). A system of morphometry. *Hydrogr.Rev*. **37**:147- 155

Paerl, H. W. (1983). Partitioning of carbon dioxide fixation in colonial cyanobacterium, *Microcystis aeruginosa:* mechanism promoting formation of surface scums. *Appl. Environ. Microbiol.* **46**:252-259.

Paerl, H.W.,and Kellar, P.E.(1979). N-fixing Anabaena: Physiological adaptations instrumental in maintaining surface blooms. *Science* **204**:620-622.

Paerl, H. W. and Ustach, J. F. (1982) Blue green algal scums: An explanation for their occurrence during fresh water blooms. *Limnol. Oceanogr*. **27**:212-217.

Patterson, G. and Wilson, K.K. (1995). The influence of diel climatic cycle on the depth-time distribution of phytoplankton and photosynthesis in a shallow equatorial lake (Lake Baringo, Kenya). *Hydrobiologia* **304**:1-8.

Pentecost, C. and Happey-Wood, C.M. (1978). Primary production studies in two linked but contrasting Welsh lakes. *Freshwat. Biol*. **8**:9-23.

Pettersen, K., Herlitz, E. and Istvanovics, V. (1993). The role of *Gloeotrichia echinulata* in the transfer of phosphorus from sediments to water in Lake Erken. *Hydrobiologia*, **253**:123-129.

Philips,J.E., Cichra, M., Havens, K., Hanton, C., Badylak, S., Rueter, B., Randall, M. and Hansen, P. (1996). Relationships between phytoplankton dynamics and the availability of light and nutrients in a shallow sub-tropical lake. *Freshwat. Biol*.**11**:15-23.

Platt, T. and Jassby, A. D. (1976). Mathematical formulation of the relationship between photosynthesis and light for phytoplankton. *Limnol. and Oceanogr.* **21**, 540-547.

Polingher, U and Serruya, C. (1976). Phased division of *Peridinium cinctum fa.westii* and the development of the blooms in Lake Kinneret. *J. Phycol*. **11**:155-162.

Prescott, G.W. (1978). *How to know the fresh water algae*. Brown Co. publishers. 450pp.

Prochazcova, L., Blazca, B. and Kralova, M. (1970). Chemical changes involving nitrogen metabolism in water and particulate matter during primary reduction experiments. *Limnol. Oceanogr*. **15**:797-807.

Prosser, M.V., Wood, R.B., and Baxter, R.M.(1968). The five Bishoftu cater lakes. *SINET: Ethiop. J. Sci*. **8**: 9-29.

Reynolds, C. S. (1984). *The ecology of fresh water phytoplankton.* Cambridge University Press, Cambridge.

Reynolds, C. S. and Walsby A. E. (1975) Water blooms. *Biol. Rev. Cambridge Philos. Soc.*, **50**:437–481.

Reynolds, C. E. (1987). Cyanobacterial water blooms. In: *Advances in Botanical Research,* Vol. 13, pp. 67-143 (Callow, J. ed.). Academic Press, London..

Reynolds, C. S. (1989). Physical determinants of phytoplankton succession. In: *Plankton Ecology: succession in plankton communities*, pp.9-56 (U. Sommer, ed). Springer-Verlag, N.Y.

Rippey, B. and Wood, R.B. (1985). Trends in major ion composition of five Bishoftu crater lakes. *SINET: Ethio.J.Sci*. **8:** 9-29

Roach, J. (2004). Source of half Earth's oxygen gets little credit. *National Geographic News,* National Geographic Society Press.

Robarts, R.D and Zohary, T. (1984). *Microcystis aerugino* as and underwater light attenuation in hypereuthrophic lake (Hartbeespoort, South Africa). *J.Ecol.* **72**:1001-1017.

Robarts, R.D and Zohary, T. (1987). Temperature effects on Photosynthetic capacity, respiration, and growth rates of bloom forming cyanobacteria. *N.Z.J. Mar. fresh water Res.* **21:**391- 399.

Sakamoto, M. (1966). Primary production by phytoplankton community in some Japanese lakes and its dependence on lake depth. *Arch.Hydrobiol*. **62**:1-28.

Schardt, J. and Ludlow, J. (2000). A beginner's guide to water management: the ABCs, circular 01, plant management in Florida waters. Florida Lake watch.

Schindler, D.W. (1977). Evolution of phosphorus limitation in lakes. *Science*, **195**: 260-262.

Shapiro, J. (1973). Blue green algae: why they become dominant? *Science,* **179:**382-384.

Shapiro, J. (1984) Blue-green dominance in lakes: the role and management significance of pH and $CO_2$. *Int. Rev. Ges. Hydrobiol.*, **69:**765–780.

Shapiro, J. (1990). Biomanipulation: the next phase making it stable. *Hydrobiologia,* **200**: 13-27.

Shapiro, J. (1997). The role of carbon dioxide in the initiation and maintenance of blue green dominance in lakes. *Freshwater biology,* **37**:307-323.

Smayda, T. J. (1980): Phytoplankton species succession. In: *The Physiological Ecology of Phytoplankton*, p. 493–570 (I. Morris, ed). Blackwell Scientific Publications, Oxford.

Smith, R.C., Tyler, J.E. and Goldman, C.R. (1973). Optical properties and color of Lake Tohae and Crater Lake. *Limnol.Oceanogr*. **18**:189-199.

Smith, R.C. and Baker, K.S. (1978). The bio-optical state of ocean waters and remote sensing. *Limnol.Oceanogr*.**23**:247-259.

Smith, V.H. (1979). Nutrient dependence of primary productivity in lakes. *Limnol. Oceanog.* **24:**1051-1064.

Smith, V.H. (1986). Light and nutrient effects on the relative biomass of blue-green algae in Lake Phytoplankton. *Can. J. Fish. Aquat. Sci*., **43**:148-153.

Sommer, U. (1988). Growth and survival strategies of planktonic diatoms. In: *Growth and Reproductive Strategies of Fresh water Phytoplankton,*pp. 227-260, (C.D. Sandgren, ed). Cambridge University Press. Cambridge.

Sommer, U. 1989. Nutrient status and nutrient competition of phytoplankton in a shallow, hypertrophic lake. *Limnol. and Oceanogr*. **34**:1162-1173.

Spencer, C.N., and King, D. L. (1987). Regulation of blue green algal buoyancy and bloom formation by light, inorganic nitrogen, Carbon dioxide and trophic level interactions. *Hydrobiologia,* **144:**183-192.

Steinman, A.D. (1996). Effects of grazers on freshwater benthic algae. In: *Algal Ecology: Freshwater Benthic Ecosystems,* pp.341–373 (R.J. Stevenson, M.L. Bothwell & R.L. Lowe, eds). Academic Press, San Diego, CA.

Tadesse Fetahi. (2004). *Trophic analysis of Lake Awassa using mass-balance Ecopath model* .M.Sc. Thesis, School of Graduate Studies, Addis Ababa University, Addis Ababa.98pp.

Takahashi, M., Shimura, S., Yamaguchi, Y. and Fujita, Y. (1971). Photoinhibition of phytoplankton photosynthesis as a function of exposure time. *J. Oceanogr. Soc. Japan* 27: 43-50.

Talling, J.F. (1965). The photosynthetic activity of phytoplankton in East African lakes. *Int.Rev. ges. Hydrobiol*., **50**:1-32.

Talling, J.F. (1973). The application of some electrochemical methods to the measurement of photosynthesis and respiration in fresh waters. *Freshwat.Biol*. **3**:335-362.

Talling, J.F. (1986).The seasonality of phytoplankton in African lake. *Hydrobiologia*, **138**:139- 160.

Talling, J.F. (1992).Environmental regulation in Africa shallow lakes and wetlands. *Rev.Hydrobiol.Trop*. **25(**2):87-144.

Talling, J.F. and Lemoalle, J. (1998). *Ecological dynamics of tropical inland waters*. Cambridge University Press, Cambridge.

Talling, J.F. and Talling, I.B. (1965).The chemical composition of African lake waters. *Int. Rev. ges. Hydrobiology***, 50**:421-463.

Talling, J.F.and Driver, D. (1963). Some problems in estimation of terrestrial algae: The British Physiological Society, Cambridge Taxonomic analysis of the genus *Anabaenopsis. Arch.Hydrobiol* .**51**:3-24.

Talling, J.F., Wood, R.B., Prosser, M.V. and Baxter, R.M. (1973).The upper limit of photosynthetic productivity by phytoplankton: evidence from Ethiopian Soda lakes.*Freshwater. Biol.,* **3**: 53 -76.

Taylor, W.D. and Zinabu Gebre-Mariam (1989). Size-structure and activity of the plankton community of an Ethiopian rift valley lakes. *Freshwat. Biol.21*:353 -363.

Thornton, J. A. (1987). A review of some unique aspects of the limnology of shallow Southern African man-made lakes. *Geo. journal*, **143**:339- 352.

Thornton, J. A., Chochrane, K. L. Jarvis, A. C., Zohary, T. Roberts, R. D. and Chutter, F. M.(1986).An evaluation of management aspects of a hypertrophic African impoundment. *Water.Res.* **20**:413-419.

Toetz, D.W. (1981). Effects of whole lake mixing on water quality and phytoplankton. *Wat. Res*. **15**:1205-1210.

Tsegaye Mihret-Ab. (1988). *A seasonal study on the species composition and phytoplankton biomass in Lake Ziwai, Ethiopia*. M.Sc. Thesis, Addis Ababa University, AddisAbaba.72pp.

US Environmental Protection Agency, USEPA, (1991). *Volunteer lake monitoring: A methods manual*, EPA 440/4-91-002. Office of Water, Washington, DC.

Van liere, L. and Walsby, A.E. (1982). Interactions of cyanobacteria with light. In: *The Biology of Cyanobacteria*, pp.9-45 (N.G. Carr and B.A.Whitton, eds). Blackwell Scientific Publications. Oxford.

Vareschi, E. (1982).The Ecology of Lake Nakuru. III. Abiotic factors and primary production. *Oecologia,* **55**:81-101.

Visser, P.M., Passarge, J., and Mur, L.R. (1997). Modeling the vertical migration of the cyanobacterium, *Microcystis*. *Hydrobiologia* **349**: 99-109.

Von Damm, K.L. and Edmond,J.M. (1984). Reverse weathering in the close-basin lakes of the Ethiopian Rift. *Amer.J.Sci*. **284**:835-862.

Walsby, A.E., and Booker, M. J. (1976). Stratification and bloom formation by planktonic blue-green algae, In: *Photosynthetic prokaryotes*, pp. 13-14, Proc. 2nd Int. Symp., Dundee. Fed. Eur. Micrab. Sot.

Walsby, A.E., and Booker, M.J. (1980). Changes in buoyancy of a planktonic blue-green algae in response to light intensity. *Br. Phycol. J*. **15**: 311-419.

Watson, S. B., McCauley, E. and Downing, J. (1997). Patterns in phytoplankton taxonomic composition across temperate lakes of different nutrient status. *Limnol. Oceanogr*. **42**:487-495.

Wetzel, R.G. (1983).Limnology.2nd ed. Academic Press, London.

Wetzel, R.G. (2001). *Limnology:* Lake and River Ecosystems. 3rd ed. Academic Press. N.Y.1006 pp.

Wetzel, R.G. and Likens, G.E. (2000). *Limnological analyses*. 3rd ed. Verlag, New York, Inc. N.Y. 429pp.

Whitford, L.A.and Schumacher,G.J.(1973).A manual of freshwater algae.Sparks Press, Raleigh, N.C.

Wood, R.B., Prosser, M, V. and Baxter, R.M. (1978).Optical characteristics of the Rift Valley lakes. Ethiopia. *SINET: Ethiopian Journal of Science*, **1:**73-85.

Wood, R.B., Prosser, M.V. and Baxter, R.M. (1976). The seasonal pattern of thermal characteristic of four Bishoftu crater lakes, Ethiopia. *Freshwater. Biol.* **6**: 519-530

Wood, R.B.,Prosser,M.V.and Baxter,R.M.(1984).Seasonal and comparative aspects chemical stratification in some tropical crater lakes, Ethiopia. *Freshwat. Biol*., **14:551**-573.

Wood, R.B. and Talling, J.F. (1988). Chemical and algal relationships in salinity series of Ethiopian inland waters. *Hydrobiologia* **15**: 29– 67.

Yeshiemebet Major. (2006). *Temporal changes in the community structure and Photosynthetic production of phytoplankton in Lake Babogaya , Ethiopia*. M.Sc. Thesis, School of Graduate Studies, Addis Ababa University, Addis Ababa.94pp.

Zinabu Gebre-Mariam. (1994).Long–term changes in indices of chemical and productivity status of a group of tropical Ethiopian lakes, with differing exposure to human influence .*Arch.Hydrobiologia*. **132(**1):115-125.

Zinabu Gebre-Mariam, Elizabeth Kebede –Westhead and Zerihun Desta .(2002).Long term changes in chemical features of waters of seven Ethiopian Rift Valley lakes. *Hydrobiologia*, **477**: 81-91.

Zinabu Gebre-Mariam and Taylor, W.D. (1997).Bacteria –chlorophyll relationships in Ethiopian lakes of varying salinity: are soda lakes different? *J.P lankt. Res*. **19**: 647- 654.

# 7. APPENDICES

**Appendix 1: Depth profile of temperature ($^{o}C$) and dissolved oxygen (mg $L^{-1}$) at central station of Lake Bishoftu, 2006/07**

| Depth(m) | Date | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25/8/06 | 21-10-06 | | 25-11-06 | | 26-12-06 | | 27-01-07 | | 28-03-07 | | 28-04-07 | | 27/05/07 | |
| | T | $O_2$ | T | $O_2$ | T | $O_2$ | T | $O_2$ | T | $O_2$ | T | $O_2$ | T | $O_2$ | T |
| 0.00 | 25.30 | 13.73 | 22.96 | 13.28 | 22.38 | 8.62 | 22.22 | 13.70 | 23.25 | 11.22 | 23.70 | 7.40 | 23.60 | 149.80 | 25.8 |
| 0.25 | | 11.80 | | 12.80 | 22.00 | 8.88 | 22.18 | 11.84 | 23.16 | 11.03 | 23.40 | 7.30 | 22.90 | 145.30 | 25.1 |
| 0.50 | 24.30 | 10.90 | | 11.90 | 21.80 | 7.49 | 22.00 | 10.40 | 23.11 | 11.06 | 23.10 | 7.20 | 22.30 | 153.60 | 24.6 |
| 0.75 | | 12.30 | | 13.61 | 21.30 | 7.15 | | 11.20 | | 11.19 | 23.00 | 7.66 | 22.10 | 155.40 | 23.8 |
| 1.00 | 23.40 | 14.20 | 22.24 | 10.13 | 21.18 | 6.11 | 21.22 | 13.23 | 23.06 | 11.15 | 22.80 | 7.86 | 22.00 | 143.30 | 23 |
| 1.50 | | 14.32 | | 8.70 | 20.96 | 4.72 | 21.04 | 13.04 | 23.05 | 11.23 | 22.60 | 7.41 | 21.90 | 148.50 | 22.6 |
| 2.00 | 22.90 | 14.41 | 22.15 | 7.75 | | 2.77 | 21.00 | 12.53 | 23.05 | 10.43 | 22.20 | 7.94 | 21.90 | 146.70 | 22.4 |
| 2.50 | | 14.21 | | 6.90 | | 1.89 | 20.84 | 11.30 | | 10.74 | 22.10 | 7.64 | 21.80 | 139.40 | 22.3 |
| 3.00 | 22.50 | 14.12 | 22.13 | 6.06 | 20.95 | 1.40 | 20.63 | 10.96 | 21.70 | 10.53 | 22.10 | 7.38 | 21.70 | 135.40 | 22.1 |
| 4.00 | 22.48 | 13.85 | 22.12 | 4.20 | 20.94 | 0.96 | 20.47 | 8.60 | 21.15 | 8.20 | 21.80 | 7.54 | 21.70 | 91.00 | 21.9 |
| 5.00 | 22.40 | 13.66 | 22.09 | 3.00 | | 0.74 | 20.38 | 1.15 | 20.56 | 2.81 | 21.60 | 7.23 | 21.60 | 39.20 | 21.6 |
| 6.00 | 21.90 | 13.11 | 22.07 | 2.70 | | 0.68 | 20.36 | 0.65 | 20.46 | 0.00 | 21.20 | 7.21 | 21.50 | 0.00 | 21.4 |
| 7.00 | 21.30 | 12.72 | 22.02 | 2.50 | | 0.66 | 20.34 | 0.45 | 20.42 | | 20.90 | 7.15 | 21.50 | | 21.3 |
| 8.00 | 21.10 | 12.24 | 21.99 | 2.20 | 20.89 | 0.60 | 20.33 | 0.41 | 20.39 | | 20.60 | 6.99 | 21.40 | | 21.1 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9.00 | | 1.74 | 21.45 | 1.80 | | 0.50 | | 0.35 | 20.36 | | 20.40 | 5.45 | 21.00 | | 20.9 |
| 10.00 | | 1.21 | 21.15 | 1.30 | 20.86 | 0.42 | 20.32 | 0.00 | 20.34 | | 20.30 | 0.00 | 19.80 | | 20.6 |
| 11.00 | 20.40 | 1.10 | | 1.00 | | 0.37 | | | 20.33 | | 20.20 | | 19.50 | | 20.4 |
| 12.00 | 20.00 | 1.02 | | 0.80 | | 0.30 | 20.32 | | | | 20.00 | | 19.40 | | 20.1 |
| 13.00 | | 0.96 | | | | 0.20 | | | 20.32 | | 19.90 | | 19.30 | | 19.8 |
| 14.00 | | 0.79 | | | 20.85 | | | | | | 19.70 | | 19.30 | | 19.5 |
| 15.00 | | 0.77 | 20.54 | | 20.85 | | 20.31 | | 20.32 | | 19.60 | | 19.20 | | 19.3 |
| 16.00 | | | | | | | | | | | 19.60 | | 19.20 | | 19.2 |
| 17.00 | | | | | | | | | | | 19.60 | | 19.20 | | 18.9 |
| 18.00 | | | | | | | | | | | 19.60 | | 19.20 | | 18.9 |

**Appendix 2**. Measurements of water temperature on Lake Bishoftu and other East African Lakes as reported by various authors

| Lake | Sampling Date | Temperature($^0$C ) | Data Source |
|---|---|---|---|
| Awassa | 1983-85 | 20.5-28.4 | Demeke Kifle (1985) |
| Ziway | 1987-88 | 18.5- 27.5 | Girma Tilahun (1988) |
| Abijata | 1980-1981 | 18-27 | Kassahun Wodajo, (1982) |
| Langano | 1980-1981 | 18-27 | Kassahun Wodajo (1982) |
| Arenguade | Oct., 1966 | 19.7-27 | Wood *et al*. (1976) |
| **Bishoftu** | Oct., 1966 | 19.2 - 24.5 | Wood *et al*. (1976) |
| | **2006/07** | **22.22 - 25.8 0** | **Present study** |
| Babogaya | 2004/05 | 22.3-26.8 | Yeshiemebet Major (2006) |
| Chamo | Mar. 2004 | 23-30 | Eyasu Shumbulo (2004) |
| George | 1974 | 26-36 | Ganf and Horne (1975) |
| Turkana | 1974 | 27.5-32.5 | Ganf and Horne (1975) |

**Appendix 3:** Optical parameters: Integral surface irradiance, PAR (E $m^{-2}$ $h^{-1}$), Instantaneous surface irradiance, $I_o$(µE $m^{-2}s^{-1}$), Vertical Light Extinction Coefficient, $K_d$ ($m^{-1}$), Biomass specific light extinction, $K_s$ (%), light extinction by non algal matter, $K_w$ (%), euphotic, $Z_{eu}$ (m) and Secchi depths, $Z_{SD}$ (m) of Lake Bishoftu.

| Sampling date | PAR | $I_o$ | $K_d$ | Ks (%) | $K_w$ (%) | $Z_{eu}$ (m) | $Z_{SD}$ (m) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | C | NS |
| 25/08/06 | | | | | | 1.88 | 0.68 | 0.64 |
| 19/09/06 | 3.43 | 993.9 | 2.53 | 8.70 | 91.30 | 1.82 | 0.58 | 0.56 |
| 21-10-06 | 4.61 | 1004 | 1.62 | **20.10** | 79.90 | 2.84 | 0.75 | 0.72 |
| 25/11/06 | 3.32 | 804.7 | 1.92 | 18.10 | 81.90 | 2.40 | 0.64 | 0.62 |
| 26/12/06 | 5.64 | 1029.3 | 2.90 | 7.30 | **92.70** | 1.59 | **0.50** | **0.46** |
| 27/01/07 | 4.65 | 1207 | 2.56 | 13.60 | 86.40 | 1.80 | 0.78 | 0.75 |
| 28/03/07 | 2.07 | 1228.9 | 1.29 | 13.30 | 86.70 | 3.57 | 0.88 | 0.80 |
| 28/04/07 | 5.55 | 1115.3 | 1.30 | 8.70 | 91.30 | 3.54 | **1.05** | **1.00** |
| 27/5/07 | 3.58 | 1052.3 | 1.26 | 13.13 | 86.87 | **3.65** | 0.92 | 0.88 |

**Appendix 4**. Measurements of Secchi depth ($Z_{SD}$) on Lake Bishoftu and other East African Lakes as reported by various authors

| **Lake** | **Sampling date** | | **$Z_{SD}$ (cm)** | **Data Source** |
|---|---|---|---|---|
| Babogaya | 2004/05 | | 50-150 | Yeshiemebet Major (2006) |
| Abaya | | | 43 | Elizabeth Kebede *et al*., (1994) |
| Hayq | | | 124 | Baxter and Golabitsch (1970) |
| Koka | | | 28 | Elizabeth Kebede *et al*., (1994) |
| Ziway | | | 35 | Elizabeth Kebede *et al*., (1994) |
| Awassa | Mar., 1985 | | 65-95 | Demeke Kifle and Amha Belay (1990) |
| **Bishoftu** | 2006/07 | C | **50 - 105** | **Present study** |
| | | NS | **46 - 100** | |
| Chamo | 2004 | | 3.8-10.86 | Eyasu Shumbulo,2004 |
| George | 1972 | | 0.4 | Ganf and Viner (1973) |
| Naivasha | 1973/1974 | | 1 - 1.5 | Melack(1979a) |
| Baringo | 10 Mar., 1989 | | 0.15 | Patterson and Wilson (1995) |

**Appendix 5**. Measurements of Euphotic Depth ($Z_{eu}$) on Lake Bishoftu and other East African Lakes as reported by various authors

| Lake | Sampling date | $Z_{eu}$(m) | Data Source |
|---|---|---|---|
| Arenguade | Jan./Jul.'66 | 0.15-0.27 | Talling *et al*.(1973) |
| Kilole | Jan./Jul.'66 | 0.24-0.38 | Talling *et al*.(1973) |
| Nakuru | 1972 | 0.22-0.41 | Vareschi (1982) |
| George | 167-68 | 0.7 | Ganf (1975) |
| Ziway | 1987/88 | 0.4-1.06 | Girma Tilahun (1988) |
| Chamo | Mar., 2004 | 0.67-1.25 | Eyasu Shumbulo (2004) |
| Awassa | Mar., 1985 | 1.59-2.7 | Demeke Kifle and Amha Belay (990) |
| Shalla | Apr., 1981 | 4.93 | Amha Belay and Wood (1984) |
| **Bishoftu** | **2006/07** | **1.59 - 3.65** | **Present study** |
| Babogaya | 2004/05 | 4 -15 | Yeshiemebet Major (2006). |

**Appendix 6**. Measurements of alkalinity on Lake Bishoftu and other East African Lakes as reported by various authors

| Lake | Sampling Date | $HCO_3+CO_3$ (meq $L^{-1}$) | Data Source |
|---|---|---|---|
| Kilole | Apr., 1992 | 2.4 | Zinabu G.- Mariam (1994) |
| Koka | Mar., 1964 | 3.22 | Wood and Talling (1988) |
| Ziway | 1987/88 | 3.5-4.4 | Girma Tilahun (1988) |
| Naivasha | 5 Jun.'61 | 3.31 | Talling and Talling (1965) |
| Babogaya | Apr., 1992 | 9.5 | Zinabu G.- Mariam (1994) |
| | 2004-2005 | 6.4-12.1 | Yeshiemebet Major(2006) |
| Awassa | 1983-85 | 7.7-9.1 | Demeke Kifle (1985) |
| Chamo | Mar. 2004 | 9.2 | Eyasu Shumbulo (2004) |
| Hora | Apr., 1963 | 26.8 | Prosser *et al*. (1968) |
| | Apr., 1992 | 16.8 | Zinabu G.- Mariam (1994) |
| **Bishoftu** | Apr., 1963 | 20 | Prosser *et al.* (1968) |
| | 2006/07 | **13.70 – 16.8 (15.4)** | **Present study** |
| Metehara | May, 1991 | 44 | Elizabeth Kebede *et al*. (1994) |
| Arenguade | Apr., 1963 | 51.4 | Prosser *et al.* (1968) |
| | Apr., 1992 | 54 | Zinabu G.- Mariam (1994) |
| Shalla | Mar, 1991 | 218 | Elizabeth Kebede *et al.* (1994) |
| Abijata | Mar, 1991 | 325 | Elizabeth Kebede *et al.* (1994) |
| Chitu | Mar, 1991 | 573 | Elizabeth Kebede *et al.* (1994) |
| Nakuru | 24 Feb., '61 | 1440 | Talling and Talling, 1965 |

Mean value is given in ( )

**Appendix 7**: Water column concentration of inorganic nutrients, phytoplankton biomass as Chl-a and total nitrogen to total phosphorus ratio of Lake Bishoftu at two stations in 2006/07.

| 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) | | B(mg Chl a $m^{-3}$) | | ∑B (mg Chl a $m^{-2}$) | TN : TP ratio | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | NS | C | NS | C | NS | C | NS | C | NS | C | NS | C | C | NS | M |
| 25/8/06 | 50 | 30 | 70 | 70 | 5.52 | 10.53 | 21 | 12 | 88 | 70 | 41.70 | 18.24 | 78.40 | 5:1 | 6:1 | 6:1 |
| 19/9/06 | 50 | 30 | 70 | 70 | 4.81 | 11.54 | 20 | 10 | 80 | 60 | 34.75 | 24.33 | 63.25 | 6:1 | 7:1 | 6:1 |
| 21-10-06 | 110 | 90 | 160 | 150 | 7.64 | 8.11 | 20 | 14 | 90 | 80 | 33.01 | 34.75 | 93.75 | 12:1 | 12:1 | 12:1 |
| 25/11/06 | 50 | 50 | 90 | 80 | 13.31 | 14.25 | 20 | 10 | 40 | 30 | 41.70 | 19.70 | 100.08 | 14:1 | 17:1 | 15:1 |
| 26/12/06 | 40 | 80 | 40 | 10 | 20.86 | 19.45 | 40 | 20 | 60 | 40 | 38.23 | 27.80 | 60.79 | 5:1 | 5:1 | 5:1 |
| 27/1/07 | 20 | 40 | 217 | 170 | 17.56 | 21.81 | 21 | 46 | 77 | 81 | 55.60 | 57.34 | 100.08 | 15:1 | 12:1 | 14:1 |
| 28/3/07 | 60 | 47 | 226 | 179 | 19.45 | 27.95 | 45 | 34 | 98 | 86 | 13.90 | 19.11 | 49.62 | 13:1 | 12:1 | 13:1 |
| 28/4/07 | 13 | 20 | 406 | 406 | 28 | 22 | 17 | 21 | 52 | 53 | 13.90 | 12.16 | 49.21 | 41:1 | 41:1 | 41:1 |
| 27/5/07 | 6 | 6.7 | 75.5 | 94.3 | 33.15 | 30.31 | 19 | 4 | 77 | 31 | 13.03 | 13.90 | 47.56 | 5:1 | 16:1 | 9:1 |

M= Mean

**Appendix 8**. Measurements of Silica on Lake Bishoftu and other East African Lakes

| Lake | Sampling Date | | $SiO_2$ (mg $L^{-1}$) | | Data Source |
|---|---|---|---|---|---|
| Tanganyika | 3o Jan. '61 | | 0.38 | | Talling and Talling (1965) |
| Tana | 2003/04 | | 6.13 | | Ayalew Wondie *et a*l. (unpublished) |
| Victoria | 4 May '61 | | 8.7 | | Talling and Talling (1965) |
| Babogaya | 2004/05 | | 10 - 58 | | Yeshiemebet Major (2006) |
| | Apr., 1963 | | 25 | | Prosser *et al* (1968) |
| | Apr., 1992 | | 45 | | Zinabu Gebre-Mariam (1994) |
| Kilole | Apr., 1963 | | 32 | | Prosser *et al*. (1968) |
| Hora | Apr., 1963 | | 55 | | Prosser *et a*l. (1968) |
| Arenguade | Apr., 1963 | | 50 | | Prosser *et a*l. (1968 |
| **Bishoftu** | Apr., 1963 | | **38** | | Prosser *et a*l. (1968) |
| | Apr., 1992 | | **15** | | Zinabu Gebre-Mariam (1994) |
| | 2006/07 | C | **5 - 28** | **(18)** | **Present study** |
| | | NS | **8 - 28** | | |
| Koka | Mar., 1964 | | 32 | | Wood and Talling (1988) |
| Ziway | Mar., 1964 | | 45 | | Wood and Talling (1988) |
| Abaya | Mar., 1964 | | 40 | | Wood and Talling (1988) |
| Langano | Mar., 1964 | | 48 | | Wood and Talling (1988) |
| Chamo | Mar., 1980 | | 38 | | Amha Belay and Wood (1982) |
| Naivasha | 5 Jun.'61 | | 32.5 | | Talling and Talling (1965) |
| Awassa | 1983-85 | | 50-90 | | Demeke Kifle(1985) |
| Oloidien | Mar., 1964 | | 96 | | Wood and Talling (1988) |
| Chitu | Mar., 1964 | | 320 | | Wood and Talling (1988) |
| Nakuru | 1972-1974 | | 125-180 | | Vareschi (1982) |

Mean ( )

**Appendix 9**. Measurements of Phosphate in Lake Bishoftu and other East African Lakes

| Lake | Sampling Date | | $PO_4$-P ( µg $L^{-1}$) | | Data Source |
|---|---|---|---|---|---|
| Babogaya | 2004/05 | | 1 - 18 | | Yeshiemebet Major (2006) |
| | Apr., 1963 | | < 5 | | Prosser *et al*. (1968) |
| | Apr., 1992 | | 81 | | Zinabu G.- Mariam (1994) |
| Hora | Apr., 1963 | | < 5 | | Prosser *et al*. (1968) |
| **Bishoftu** | Apr., 1963 | | < 5 | | Prosser *et al*. (1968) |
| | Apr., 1992 | | 28 | | Zinabu G.- Mariam (1994) |
| | 2006/07 | C | **17 - 45** | **(22)** | **Present study** |
| | | NS | **10 - 46** | | |
| Awassa | 1983-85 | | 5-42 | | Demeke Kifle (1985) |
| Chamo | Mar. 2004 | | 44 | | Eyasu Shubulo (2004) |
| Ziway | 1987-88 | | 40-170 | | Getachew Beneberu (2005) |
| Abijata | Mar, 1991 | | 98 | | Elizabeth Kebede *et al*. (1994) |
| Metehara | May, 1991 | | 1302 | | Elizabeth Kebede *et al*. (1994) |
| Arenguade | Apr., 1992 | | 3200 | | Zinabu G.- Mariam (1994) |
| Kilole | Apr., 1963 | | 6500 | | Prosser, *et al*. (1968) |
| Chitu | Mar, 1991 | | 1985 | | Elizabeth Kebede *et al*. (1994) |
| Bogoria | 3 Feb., '80 | | 149-202 | | Vareschi (1982) |
| Nakuru | 24 Feb., '61 | | 114 | | Talling and Talling, 1965 |
| Simbi | Nov. 1976 | | 760 | | Melack (1979**b**) |

**Appendix 10**. Percent Contribution of phytoplankton and Zooplankton

| Sampling date | Blue greens | | Diatoms | | Others | | Copepods | | Rotifers | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C | NS | C | NS | C | NS | C | NS | C | NS |
| 25/8/06 | 94.50 | 94.63 | 5.00 | 5.13 | 0.50 | 0.49 | - | - | - | - |
| 19/9/06 | 93.62 | 93.21 | 5.29 | 6.27 | 0.30 | 0.50 | - | - | - | - |
| 21-10-06 | 99.00 | 98.00 | 0.67 | 1.40 | 0.14 | 0.13 | - | - | - | - |
| 25/11/06 | 93.66 | 90.66 | 5.56 | 8.62 | 0.53 | 0.55 | - | - | - | - |
| 26/12/06 | 99.53 | **99.53** | 0.43 | 0.67 | 0.10 | 0.12 | - | - | - | - |
| 27/1/07 | **99.85** | **99.09** | 0.13 | 0.21 | 0.01 | 0.09 | 8.33 | 9.37 | 91.67 | 90.63 |
| 28/3/07 | **58.00** | **61.32** | 41.16 | 38.31 | 0.12 | 0.06 | 83.26 | 70.47 | 16.74 | 29.53 |
| 28/4/07 | 83.30 | 78.97 | 15.58 | 20.30 | 0.54 | 0.52 | 100.00 | 100.00 | 0.00 | 0.00 |
| 27/5/07 | 78.79 | 94.63 | 20.56 | 20.46 | 0.35 | 0.32 | 100.00 | 100.00 | 0.00 | 0.00 |

Others – the sum of three other groups, Dinophyceae, Chlorophyceae and Haptophyceae

**Appendix 11**: phytoplankton abundance (cell count/ml) at two stations

| Sampling date | *Microcycstis spp.* X $10^4$ | | *Coelosphaerium sp.*$10^4$ | | *Nitschia spp. spp.*x$10^3$ | | *Peridinium Sp.*x$10^2$ | | *Quadrigula lac.*x$10^2$ | | *Merismopedia* x$10^2$ | | *Chrysochromulina sp.* X$10^2$ | | Total phyt.x$10^4$ | | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | NS | C | NS | C | NS | C | NS | C | NS | C | NS | C | NS | C | NS | |
| 25/8/06 | 49 | 31 | 8 | 6 | 30 | 20 | 8 | 7 | 0 | 0 | 0 | 0 | 0.8 | 0.5 | 60 | 39 | 22 |
| 19/9/06 | 27 | 25 | 5 | 2 | 18 | 15 | 6 | 5 | 0 | 0 | 0 | 0 | 0.6 | 0.5 | 34 | 29 | 14 |
| 21-10-06 | 27 | 33 | 3 | 16 | 2 | 5 | 4 | 6 | 0 | 0 | 0 | 0 | 0.4 | 0.3 | 30 | 50 | 18 |
| 25/11/06 | 26 | 20 | 7 | 5 | 20 | 25 | 0 | 0 | 0 | 0 | 72 | 100 | 0.2 | 0.2 | 36 | 29 | 14 |
| 26/12/06 | 41 | 26 | 6 | 4 | 2 | 2 | 0 | 0 | 4.4 | 3.2 | 25 | 16 | 0.3 | 0.4 | 47 | 30 | 18 |
| 27/1/07 | 16 | 11 | 3 | 2 | 0.24 | 0.27 | 0 | 0 | 0 | 1 | 0 | 1.2 | 0.1 | 0.2 | 19 | 13 | 7 |
| 28/3/07 | 0 | 0 | 0 | 0 | 7 | 7 | 0.13 | 0.06 | 0 | 0 | 0.8 | 1.2 | 0 | 0 | 1 | 1 | 1 |
| 28/4/07 | 3 | 2 | 0 | 0 | 5.83 | 5.79 | 0.5 | 0.3 | 0.8 | 0.4 | 25.2 | 16.8 | 0 | 0 | 4 | 3 | 2 |
| 27/5/07 | 7 | 7 | 0.35 | 0.23 | 21 | 19.5 | 2.3 | 10 | 0.2 | 0.2 | 0.9 | 0.6 | 0 | 0 | 10 | 9 | 4 |
| Total | 197 | 155 | 32 | 35 | 106 | 100 | 21 | 28 | 5 | 5 | 124 | 136 | 2 | 2 | 241 | 202 | 100 |
| % | 44.00 | 35.00 | 7.00 | 8.00 | 2.39 | 2.25 | 0.05 | 0.06 | 0.01 | 0.01 | 0.28 | 0.31 | 0.00 | 0.00 | 54.00 | 45.00 | |

**Appendix 12**. Relative Abundance of zooplankton (No/$m^3$) in four months

| Sampling date | Copepods | | *Brachionus spp.* | | *Asplanchna sp.* | | *Hexarthra sp.* | | *Keratella sp* | | Total | | Total % | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | NS | C | NS | C | NS | C | NS | C | NS | C | NS | C | NS |
| 27/1/07 | 7144 | 8334 | 28574 | 33380 | 21430 | 19446 | 23811 | 22224 | 4762 | 5556 | 85721 | 88940 | 41.1 | 42.7 |
| 28/3/07 | 20705 | 1265 | 1667 | 250 | 1661 | 113 | 0 | 0 | 834 | 167 | 24867 | 1795 | 11.9 | 0.9 |
| 28/4/07 | 5084 | 917 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5084 | 917 | 2.4 | 0.4 |
| 27/5/07 | 600 | 500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 600 | 500 | 0.3 | 0.2 |
| Total | 33533 | 11016 | 30241 | 33630 | 23091 | 19559 | 23811 | 22224 | 5596 | 5723 | 116272 | 92152 | 55.8 | 44.2 |

**Appendix 13**.Statistical Relationship among Physico-chemical and Biological Variables, predictors (X) and Response (y) variables at 95% confidence interval.

| Predictors (Independent Variable)-x | Response (dependent variable)-y | Relationships | $R^2$ | r | P | t |
|---|---|---|---|---|---|---|
| $NO_3$ + $NO_2$-N | Chl a | y=28.3+0.078 x | 0.03 | 0.16 | 0.68 | 0.43 |
| $NH_4^+$+$NH_3$ – N | Chl a | y=39.0-0.0479 x | 0.14 | -0.37 | 0.32 | -1.07 |
| $SiO_2$ | Chl a | y=46.7-0.897 x | 0.35 | -0.59 | 0.09 | -1.94 |
| SRP | Chl a | y=38.0 - 0.254x | 0.03 | -0.17 | 0.66 | -0.46 |
| TP | Chl a | y=38.6-0.093 x | 0.01 | -0.12 | 0.76 | -0.32 |
| Chl a | $A_{max}$ | y =623 + 18.2 x | **0.38** | 0.62 | 0.08 | 2.07 |
| $NO_3$ + $NO_2$-N | $A_{max}$ | y =1461 - 75 x | 0.04 | -0.2 | 0.63 | -0.51 |
| Φ | $A_{max}$ | y = 465 + 248 Φ | **0.61** | 0.78 | **0.02** | 3.06 |
| $NH_4^+$+$NH_3$ – N | $A_{max}$ | y =1436 -1.57 x | 0.17 | -0.41 | 0.27 | -1.21 |
| SRP | $A_{max}$ | y =441 + 28.2 x | **0.46** | 0.68 | 0.07 | 2.25 |
| $Z_{SD}$ | $A_{max}$ | y = 2306 - 1469 x | **0.34** | -0.58 | 0.10 | -1.89 |
| $Z_{eu}$ | $A_{max}$ | y= 2004 - 313 x | **0.36** | 0.60 | 0.09 | -2.00 |
| SRP | $P_{max}$ | y =-7.0+2.06 x | **0.59** | 0.77 | **0.02** | 3.15 |
| TP | $P_{max}$ | y =-8.7+0.718 x | **0.25** | 0.50 | 0.17 | 1.53 |
| $NO_3$ + $NO_2$-N | $P_{max}$ | y=41.5+0.059 x | 0.01 | 0.07 | 0.86 | 0.18 |
| $NH_4^+$+$NH_3$ – N | $P_{max}$ | y =40.8+0.0221x | 0.01 | 0.09 | 0.81 | 0.25 |
| $SiO_2$ | $P_{max}$ | y =31.4 +0.76 x | 0.08 | 0.27 | 0.48 | 0.75 |
| $CO_2$ | $P_{max}$ | y = 6.4 + 13.9 x | **0.45** | 0.67 | 0.07 | 2.22 |
| Temperature | $P_{max}$ | Y =-153 + 7.39x | **0.31** | 0.55 | 0.12 | 1.76 |
| PAR | $P_{max}$ | Y =109 - 15.7x | **0.43** | -0.66 | 0.08 | -2.13 |
| $NO_3$ + $NO_2$-N | ∑A | y = 1856 + 9.3x | 0.10 | 0.32 | 0.41 | 0.88 |

| | | | | | | |
|---|---|---|---|---|---|---|
| $NH_4^+$+$NH_3$ – N | ∑A | y = 2371-0.69 x | 0.01 | -0.09 | 0.82 | -0.24 |
| $SiO_2$ | ∑A | y =2741 -28.4 x | 0.10 | -0.31 | 0.42 | -0.86 |
| SRP | ∑A | y = 1291 +39.4x | **0.20** | 0.44 | 0.23 | 1.3 |
| TP | ∑A | y = 522 + 23.7x | **0.25** | 0.50 | 0.17 | 1.52 |
| Chl a | ∑A | y= 1204 + 33.5 x | **0.31** | 0.55 | 0.12 | 1.76 |
| ∑B | ∑A | y = 865 + 19.6 x | 0.23 | | 0.19 | 1.44 |
| $A_{max}$ | ∑A | y = 253 + 1.68x | **0.67** | 0.82 | **0.01** | 3.78 |
| $P_{max}$ | ∑A | y = 1870 + 9.0 x | 0.07 | 0.27 | 0.48 | 0.75 |
| $K_w$ | ∑A | y = 7231 - 57.0 x | 0.07 | -0.27 | 0.52 | -0.68 |
| Chl a | Kd | y=1.20+0.0103x | 0.13 | 0.36 | 0.38 | 0.96 |
| ∑B | Kd | y=0.883+ 0.034y | **0.65** | 0.80 | **0.02** | 3.3 |
| ∑B | Ks | y = 5.93 + 0.106 x | 0.34 | 0.59 | 0.13 | 1.77 |
| $P_{max}$ | ∑∑A | y=16832 + 81x | 0.07 | 0.27 | 0.48 | 0.75 |
| $A_{max}$ | ∑∑A | y = 2277+15.1x | **0.67** | 0.82 | **0.01** | 3.78 |
| Chl a | ∑∑A | y = 10837 + 301 x | 0.31 | 0.55 | 0.12 | 1.76 |
| $Z_{eu}$ | ∑∑A | y = 29856 - 3684 x | 0.15 | -0.38 | 0.31 | -1.10 |
| $K_d$ | ∑∑A | y = 10510 + 5120 x | 0.15 | 0.39 | 0.34 | 1.03 |
| PAR | Φ | y= 5.97-0.777x | 0.45 | -0.67 | 0.07 | -2.22 |
| $P_{max}$ | Φ | y = 1.32 + 0.0326 x | 0.45 | 0.67 | 0.07 | 2.22 |
| SRP | Φ | y = 0.74 + 0.0806 x | 0.38 | 0.61 | 0.11 | 1.91 |

**Appendix 14**. Measurements of phytoplankton biomass on Lake Bishoftu and other East African Lakes as reported by various authors

| Lake | Sampling Date | | B (mg Chl a $m^{-3}$ ) | Data Source |
|---|---|---|---|---|
| Shalla | Oct., 1966 | | 5 | Wood *et al.* (1978) |
| | Apr., 1981 | | 6 | Amha Belay and Wood (1984) |
| Langano | Oct., 1966 | | 7 | Wood *et al.* (1978) |
| | Mar, 1980 | | 7 | Amha Belay and Wood (1984) |
| | 1980-1981 | | 3-12 | Kasahun Wedajo (1982) |
| Tana | 2003/04 | | 0.2-13 | Ayalew Wondie *et al.* (unpublished) |
| | 1960-61 | | 1 - 6 | Talling (1965) |
| Tanganyika | Oct.-Nov.,'75 | | 1 - 5 | Hecky *et al*.(1978) |
| | Feb.-Nov.'75 | | 0.2 - 20 | Hecky and Kling (1981) |
| Babogaya | 2004/05 | | 4 - 24 | Yeshiemebet Major (2006) |
| | 1992 | | 33 | Zinabu G. Mariam and Taylor (1997) |
| **Bishoftu** | **2006/07** | **C** | **14 – 56** | **Present study** |
| | | **NS** | **12 - 57** | |
| | | **M** | **30** | |
| | Apr,1992 | | **60** | Zinabu Gebre-Mariam (1994) |
| | 1986 | | **34** | Wood and Talling (1988) |
| Koka | Feb., 1985 | | 22 | Melaku Mesfin *et al.* (1988) |
| | Mar-May,'91 | | 16 | Elizabeth and Willen (1998) |
| Metehara | May, 1991 | | 27 | Elizabeth Kebede *et al.(*1994) |
| Awassa | 2004 | | 10 - 25 | Tadesse Fetahi (2004) |
| Hora | Feb/Nov.'90 | | 29 | Zinabu G. Mariam and Taylor (1997) |
| Arenguade | Feb., 1964 | | 2170 | Talling *et al*. (1973) |
| | 1995 | | 195-880 | Demeke Kifle *et al.* (unpublished) |
| Chitu | Aug., 1966 | | 2600 | Wood and Talling (1988) |
| Nakuru | 1972 | | 1160 | Vareschi (1982) |
| Simbi | Nov. 1976 | | 200 | Melack(1979**b**) |

M= mean

**Appendix 15.** Depth profile of gross photosynthesis-A (mg $O_2$ $m^{-3}$ $h^{-1}$), Net photosynthesis-Net (mg $O_2$ $m^{-3}$ $h^{-1}$), Biomass specific rate of gross photosynthesis-P (mg $O_2$ (Chl a) $h^{-1}$), Respiration rate (mg $O_2$ $m^{-3}$ $h^{-1}$) and Specific rate of Respiration (mg $O_2$ (Chl a) $h^{-1}$).

| Sampling date | Depth(m) | A | NP | P | % Reduction | Respiration |
|---|---|---|---|---|---|---|
| 25/8/06 | 0.00 | 1520 | 1030 | 36.5 | 3.2 | 493 |
| | 0.25 | | | | | |
| | 0.50 | 1570 | 1080 | 37.6 | | |
| | 1.00 | 1434 | 940 | 34.4 | | |
| | 1.50 | 810 | 313 | 19.4 | | |
| | 2.00 | 140 | -359 | 3.4 | | |
| | 2.50 | | | | | |
| | 2.75 | | | | | |
| 19/9/06 | 0.00 | 806 | 353 | 23.2 | 20 | 454 |
| | 0.25 | 1008 | 555 | 29.0 | | |
| | 0.50 | 907 | 454 | 26.1 | | |
| | 1.00 | 806 | 353 | 23.2 | | |
| | 1.50 | 706 | 252 | 20.3 | | |
| | 2.00 | 605 | 151 | 17.4 | | |
| | 2.50 | 504 | 51 | 14.5 | | |
| | 2.75 | 101 | -353 | 2.9 | | |
| | 3.00 | | | | | |
| 21/10/06 | 0.00 | 420 | -370 | 12.7 | 59 | 790 |
| | 0.25 | 655 | -135 | 19.8 | | |
| | 0.50 | 890 | 101 | 27.0 | | |
| | 1.00 | 974 | 185 | 29.5 | | |
| | 1.50 | 1025 | 235 | 31.1 | | |
| | 2.00 | 941 | 151 | 28.5 | | |
| | 2.50 | 924 | 134 | 28.0 | | |
| | 2.75 | 739 | -51 | 22.4 | | |
| | 3.00 | 605 | -185 | 18.3 | | |
| | 3.25 | 454 | -336 | 13.8 | | |
| 25/11/06 | 0.00 | 347 | 274 | 8.3 | 72 | 80 |
| | 0.25 | 629 | 548 | 15.1 | | |
| | 0.50 | 895 | 823 | 21.5 | | |
| | 1.00 | 1250 | 1169 | 30.0 | | |
| | 1.50 | 468 | 387 | 11.2 | | |
| | 2.00 | 411 | 331 | 9.9 | | |
| | 2.50 | 371 | 290 | 8.9 | | |
| | 2.75 | 234 | 153 | 5.6 | | |
| | 3.00 | 137 | 56 | 3.3 | | |
| | 3.25 | 40 | -40 | 1.0 | | |
| 26/12/06 | 0.0 | 1363 | 855 | 35.7 | 15.5 | 508 |
| | 0.25 | 1613 | 1110 | 42.2 | | |
| | 0.50 | 1161 | 653 | 30.4 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 1.00 | 855 | 355 | 22.4 | | |
| | 1.50 | 710 | 202 | 18.6 | | |
| | 2.00 | 653 | 153 | 17.1 | | |
| | 2.50 | 605 | 105 | 15.8 | | |
| | 2.75 | 556 | 48 | 14.5 | | |
| | 3.00 | 452 | -56 | 11.8 | | |
| | 3.25 | 403 | -105 | 10.5 | | |
| 27/1/07 | 0.00 | 1270 | 490 | 22.8 | 28 | 780 |
| | 0.25 | **1630** | 840 | 29.3 | | |
| | 0.50 | 1510 | 720 | 27.2 | | |
| | 1.00 | 1390 | 600 | 25.0 | | |
| | 1.50 | 1330 | 540 | 23.9 | | |
| | 2.00 | 1140 | 360 | 20.5 | | |
| | 2.50 | 1080 | 300 | 19.4 | | |
| | 2.75 | 720 | -60 | 12.9 | | |
| | 3.00 | 300 | -490 | 5.4 | | |
| | 3.25 | 300 | -490 | 7.8 | | |
| 28/3/07 | 0.00 | 1090 | 180 | 78.4 | 31 | 910 |
| | 0.25 | **1280** | **455** | 91.4 | | |
| | 0.50 | 1180 | 340 | 84.3 | | |
| | 1.00 | 970 | 60 | 69.8 | | |
| | 1.50 | 910 | 0 | 65.5 | | |
| | 2.00 | 910 | 0 | 65.5 | | |
| | 2.50 | 870 | -40 | 62.6 | | |
| | 2.75 | 850 | -60 | 61.2 | | |
| | 3.00 | 590 | -320 | 42.4 | | |
| | 3.25 | 590 | -320 | 42.4 | | |
| 28/4/07 | 0.00 | 30 | -170 | 2.2 | 92.7 | 200 |
| | 0.25 | 50 | -140 | 3.6 | | |
| | 0.50 | 200 | 0 | 14.4 | | |
| | 1.00 | 280 | 80 | 20.1 | | |
| | 1.50 | 330 | 140 | 23.7 | | |
| | 2.00 | 360 | 160 | 25.9 | | |
| | 2.50 | 410 | 220 | 29.5 | | |
| | 2.75 | 360 | 160 | 25.9 | | |
| | 3.00 | 220 | 30 | 15.8 | | |
| | 3.25 | 80 | -110 | 5.8 | | |
| 27/5/07 | 0.00 | 180 | -180 | 13.8 | 75 | 360 |
| | 0.25 | 350 | 0 | 26.9 | | |
| | 0.50 | 680 | 330 | 52.2 | | |
| | 1.00 | 710 | 350 | 54.5 | | |
| | 1.50 | 630 | 280 | 48.3 | | |
| | 2.00 | 430 | 80 | 33.0 | | |
| | 2.50 | 280 | -80 | 21.5 | | |
| | 2.75 | 230 | -130 | 17.7 | | |
| | 3.00 | 100 | -250 | 7.7 | | |
| | 3.25 | 80 | -280 | 6.1 | | |

**Appendix 16.** Light-saturated rates ($A_{max}$, mg $O_2$ $m^{-3}$ $h^{-1}$) and Photosynthetic capacity [$P_{max}$, mg $O_2$ (mg Chl a)$^{-1}$ $h^{-1}$] of phytoplankton in Lake Bishoftu and other East African Lakes as reported by various authors

| Lake | $A_{max}$ | $P_{max}$ | Data Source |
|---|---|---|---|
| Naivasha | 150-240 | - | Melack (1979a) |
| Awassa | 217-425 | 4-19 | Demeke Kifle and Amha Belay(1990) |
| Sonachi | 130-850 | 8-14 | Mealck (1976) |
| Babogaya | 106-407 | 19-29 | Yeshiemebet Major (2006) |
| Abijata | 960 | 14.8 | Amha Belay and Wood (1984) |
| Oloidein | 260-710 | - | Melack (1979a) |
| Chamo | 716-1789 | 10-34 | Eyasu Shumbulo (2004) |
| Ziway | 1640-4670 | 9.6-22.5 | Amha Belay and Wood (1984), Girma Tilahun (1988) |
| **Bishoftu** | **410 -1630** | 29 -91 (42) | **Present study** |
| Elementeita | 270-5540 | - | Melack (1976), Melack (1979a) |
| Victoria, | 400-910 | 14-35 | Talling (1965), Melack (1979a) |
| George | 1900-6000 | - | Ganf (1975) |
| Bogoria | 640-6000 | - | Melack (1976), Melack (1979c) |
| Simbi | 950-12900 | 15-17 | Melack (1979c) |
| Nakuru | 1100-2300 | - | Melack and Kilham (1974), Melack (1976, 1979a) |
| Kilole | 4000-10000 | 16.3-33.7 | Talling *et al*. (1973) |
| Arenguade | 10000-30000 | 11-18 | Talling *et al*. (1973) |

Mean values in parentheses, ( ).

**Appendix 17**. Measurements of hourly (∑A, g $O_2$ $m^{-2}$ $h^{-1}$) and daily (∑∑A, g $O_2$ $m^{-2}$ $d^{-1}$) production rates per unit area on Lake Bishoftu and other East African Lakes as reported by various authors

| Lake | Sampling Date | ∑A (g $O_2$ $m^{-2}h^{-1}$) | ∑∑A (g $O_2$ $m^{-2}d^{-1}$) | Data Source |
|---|---|---|---|---|
| Babogaya | | 0.47-1.8 | 1.01 to 5.98 | Yeshiemebet Major (2006) |
| Ziway | 1987/88 | 0.3 - 1.6 | 3.1 - 17.6 | Girma Tilahun 1988 |
| Awassa | Mar., 1985 | | 3.3 to 7.8 | Demeke Kifle and Amha Belay (990) |
| Chamo | Mar., 2004 | | 3.8-10.86 | Eyasu Shumbulo (2004) |
| Naivasha | 1973/1974 | | 3.7-6.2 | Melack (1979a) |
| Kilole | Feb.-Mar.'64 | | 1.49-2.4 | Talling *et al*.(1973) |
| **Bishoftu** | 2006/07 | **0.89 - 3.88** | **8.03 – 34.88** | **Present study** |
| Arenguade | 1995 | 1.25 - 4.96 | 11.25-44.83 | Demeke Kifle *et al.* (unpublished) |
| George | 167-68 | | 14.4 | Ganf (1975) |
| | 1974 | | 15.56 | Ganf and Horne (1975) |
| Baringo | 10 Mar., 1989 | | 3.8 | Patterson and Wilson (1995) |
| Simbi | Nov. 1976 | 0.62 - 5.22 | 19.2 | Melack (1979c) |
| Bogoria | | 0.28 - 3.00 | 280-3000 [a] | Melack (1976) |
| Nakuru | 1972 | | 15.2-21.2 | Vareschi (1982) |
| Oloidien | Jan.1971 | | 11.7 | Melack(1979a) |

## Appendix 18. Equations used in estimating different parameters

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

   Where, $K_d$, mean extinction coefficient; $I_o$, surface irradiance; $I_z$, irradiance at depth Z,

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

3. $Ks = \frac{K_c \times [Chl\ a]}{K_{d\ PAR}} = \frac{K_c \times [Chl\ a]}{K_c \times [Chl\ a] + K_w}$ (Kirk, 1983)

   Where, extinction coefficient of chl a ($K_c$) = 0.016 & $K_w$ = the attenuation coefficient due to non-chlorophyll components of the water, $K_{d\ PAR}$ = mean extinction coefficient of PAR.

4. PAR (E $m^{-2}$ $h^{-1}$) = $\frac{T_c \times 0.0377042}{H}$ (Kalff, 2002)

   Where, $T_c$ = total of the integrator readings during the time of incubation for photosynthesis, H = period of incubation in hours.

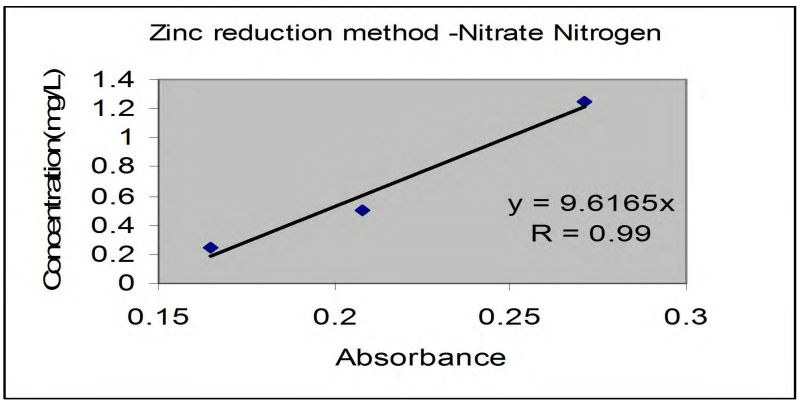
5. Alkalinity (meq $L^{-1}$) = $\frac{(N_{\text{of acid}} \times 1000) \times V_{acid}}{V_{\text{sample titrated}}}$ (Wetzel and Likens, 2000)

6. $CO_2$ (mg /L) =1.589 x $10^6$ [H] x mg/L alkalinity as $HCO_3$ (Rainwater and Thatcher, 1960 cited in Lind, 1979)

## Calibration Curves for the Estimation of Inorganic Nutrients

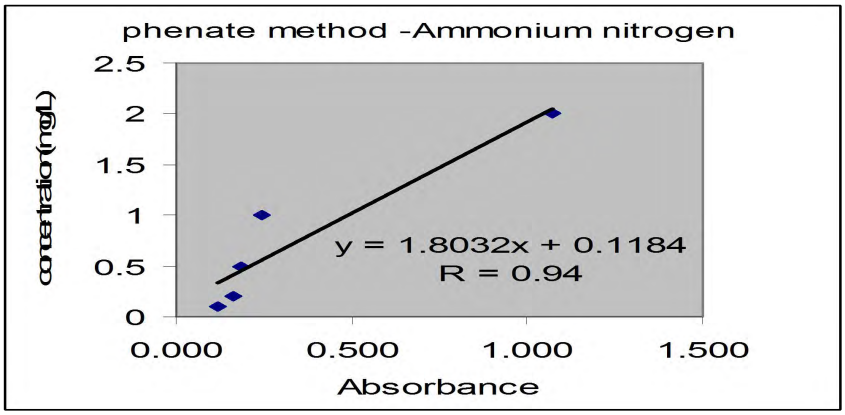
7. $NO_3$-N (Zinc Réduction Method) (Nelson *et al*. 1954)

Conc.(mg $L^{-1}$) = 9.62 x Absorbance + 0

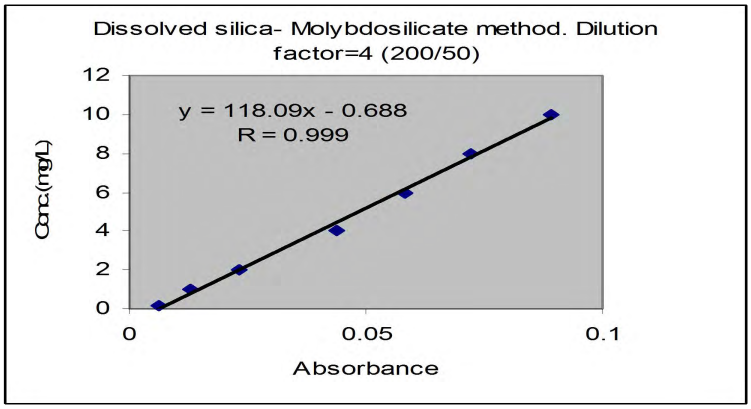



**8. $NH_4^+$ -N**

Conc. (mg $L^{-1}$) =1.80 x Absorbance + 0.12

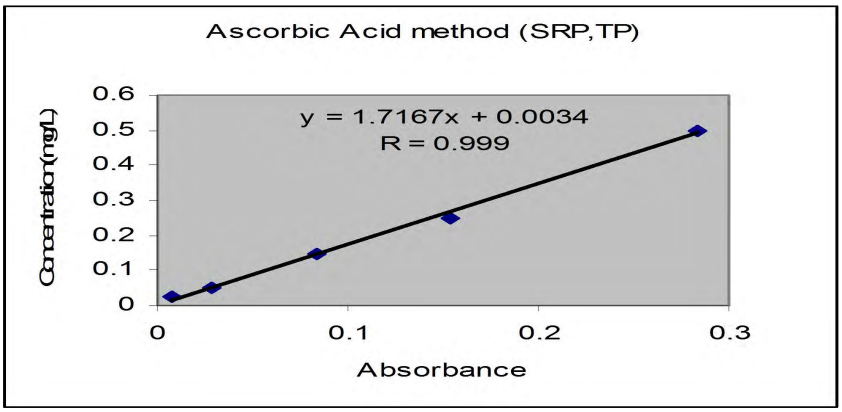


9. Dissolved $SiO_2$ = Conc. (mg $L^{-1}$) = 118.08 x Absorbance - 0 .688




10. $PO_4$-P (SRP) and TP

Conc. (mg $L^{-1}$) = 1.72 x Absorbance + 0.00341




11. Phytoplankton Cell count (Hotzel and. Croome, 1999; Wetzel and Likens, 2000).

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

Where, N = number of cells or units counted

A = area of field ($1mm^2$)

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

F= number of fields counted

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

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

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

Where, C= counted zooplankton, TG= total grid (15), F= factor of sub sample, CG= counted grids, $V_{net}$= Volume of net (0.3 $m^3$), r= radius of the net (15cm), d = the length of the course of the net through the water (depth of sampling, 4m), $\pi$ = 3.14.

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

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

Where, E665 = extinction at 665 nm

E750 = extinction at 750 nm

Ve = volume of extract (in ml)

Vs = volume of sample filtered (in Litres)

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

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

14. mg $O_2\ L^{-1}$ = $\frac{(\text{ml titrant})\ (\text{N of thiosulfate})\ (8000)}{(\text{ml sample})\ (\text{ml bottle} - 2)}$

(ml of bottle)

15. Gross photosynthesis (mg C/$m^3$/h) = $\frac{[(O_2, LB) - (O_2, DB)]\ (1000)\ (0.375)}{(PQ)\ (t)}$

OR: GP (mg $O_2$/$m^3$/h) = $\frac{[(O_2, LB) - (O_2, DB)]\ (1000)}{(t)}$

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/32mg$O_2$), PQ= photosynthetic quotient, assumed to be 1.2.

16. Net photosynthesis (mg C/$m^3$/h) = $\frac{[(O_2, LB) - (O_2, IB)]\ (1000)\ (0.375)}{(PQ)\ (t)}$

Or: NP (mg $O_2$/$m^3$/h) = $\frac{[(O_2, LB) - (O_2, IB)]\ (1000)}{(t)}$

Where, IB = Initial bottle

Factor of conversion to Oxygen to C = 0.375/1.2=0.3125

17. Respiration (mg C/$m^3$/h) = $\frac{[(O_2, IB) - (O_2, DB)]\ (RQ)\ (1000)\ (0.375)}{(t)}$

Or: R (mg $O_2$/$m^3$/h) = $\frac{[(O_2, IB) - (O_2, DB)]\ (1000)}{(t)}$

Where, RQ= respiratory quotient, assumed to be 1.

Daily Integral Photosynthesis, ΣΣA (mg $O_2$ $m^{-2}$ $d^{-1}$) =ΣA x 10 x 0.9 (Talling, 1965)

18. Biomass Specific hourly rate of gross photosynthesis, P (mg $O_2$ (mg Chl-a)$^{-1}$ $h^{-1}$)

= $\frac{A\ (mg\ O_2\ m^{-3}\ h^{-1})}{mg\ Chl\text{-}a\ m^{-3}}$

19. Photosynthetic efficiency (Φ) in % = $\frac{9.33\ calorie\ x\ mg\ C\ m^{-2}\ (day)^{-1}\ x\ 100}{PAR\ (cal\ m^{-2}\ (day)^{-1}}$

Where 1mg C = 9.33 calorie (Morel, 1978)