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TEMPORAL DYNAMICS OF PHYTOPLANKTON BIOMASS AND PRIMARY PRODUCTION IN RELATION TO SOME PHYSICO-CHEMICAL VARIABLES IN LAKE HORA-ARSEDI, ETHIOPIA.

BY

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Dedication

Thesis work is dedicated to my children:

Beth-el Abebaw, and Yabetse Abebaw

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I praise Jesus Christ my Lord for giving me the strength to withstand all ups and downs.

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ABSTRACT

The temporal dynamics of biomass and photosynthetic production of phytoplankton in relation to some physico-chemical environmental variables were studied at two stations, central (C) and near-shore (Sh) in Lake Hora-Arsed**i** from July 2005 to April 2006. The phytoplankton community Lake Hora-Arsedi was dominated by blue-green algae although green algae and diatoms were also quantitatively important. Blue-green algae were abundant during the period extending from October, 2005 to February, 2006 while diatoms and green algae became more important during periods of precipitation (August-September, 2005 and March-April, 2006). The phytoplankton biomass varied from 19.1 to 47.6 (mean =33.42) and from 21.5 to 53.15 (mean = 37.47) mg m^{-3} at the central and near-shore stations respectively. The vertical distribution of photosynthetic activity was of a typical pattern for phytoplankton with light-inhibition at the surface on all sampling dates. Light-saturated rate of photosynthesis (**A_{max}**) ranged from ≈ 473 to 1230 mg O_2 (≈ 147.6 to 383.8 mg C) m^{-3} h^{-1}) at the central station. Lack of correspondence between phytoplankton biomass and A_{max} was apparent. Biomass-specific rate of photosynthetic production at light-saturation, photosynthetic capacity (**P_{max}**) ranged from 13.6 to 52.8 mg O_2

(mg Chl a)$^{-1}$ h^{-1} at the central station. An inverse relationship between photosynthetic capacity ($\mathbf{P_{max}}$) and phytoplankton biomass (**B**) was also observed. The hourly integral photosynthetic rate (∑**A**) ranged 0.41 to 2.0 g O_2 (≈ 0.128 to 0.62 g C) m^{-2} h^{-1} and the R^2 value shows that biomass explains 0.4% of the variance in ∑A. The daily integral photosynthetic rates ((∑∑**A)** estimated ranged from 3.0 to 18.0 g O_2 (≈ 0.94 to 5.62 g C) m^{-2} d^{-1}.The temporal variations in the taxonomic composition, biomass and primary production of phytoplankton are discussed in relation to some physico-chemical and biological variables.

1. INTRODUCTION

Providing adequate food for a rapidly increasing human population is one of the greatest challenges of the world. The problem is acute in countries like Ethiopia where, besides population explosion, natural and man-made calamities have rendered conventional agriculture incapable of providing adequate food for the ever-increasing human population. It is, therefore, necessary to consider ways of sustainably exploiting our aq.uatic resources as they could offer one of the workable solutions to the problem of food shortage in this country (Shibru Tedla, 1973). Research on aquatic ecosystems, as on terrestrial ecosystems, is increasing in intensity. Aquatic ecosystems have received attention as actual and potential sources of food. It is from this point of view that the study of aquatic productivity at the beginning of food chain becomes a logical starting point.

Primary production by planktonic algae provides the base upon which the aquatic food chains culminating in natural fish production exploited by man are founded, at the same time generating some 70% of the world's atmospheric oxygen supply (Reynolds, 1984). Studies on primary production of phytoplankton and the ecological factors, which control it, form the basis for the studies on energy fluxes within aquatic ecosystems.

Primary production by phytoplankton is also regarded as a better predictor of fish yield in lakes (Melack, 1976a; 1977; Downing *et al.,* 1990).

More importantly, as Zinabu Gebre-Mariam (1994) and Zinabu Gebre-Mariam *et al.* (2002) have noted the Ethiopian Rift Valley and Crater lakes have been undergoing changes in their limnological features during the last two decades or so. The Bishoftu Crater Lakes are inside or in the vicinity of a fast growing city, Debre Zeit, and their shores are currently used for washing clothes, watering livestock and recreation. Shoreline modifications made for various purposes (e.g. for the construction of hotels in the catchments of Lakes Kuriftu and Bishoftu) also introduce enormous amounts of particulate materials, which form suspensions in the water column thereby reducing light penetration at least in the near-shore regions of the lakes. Diversion of the River Mojo into Lake Kilole, another bewildering human interference, has increased the lake volume by ca. X10 and diluted the salinity by ca. X17 (Brook Lemma, 1994).

In recent decades, large inputs of nutrients have accelerated the eutrophication of many freshwater and coastal marine environments, resulting in phytoplankton blooms and disruption of the structure and functioning of some biological communities (Smetacek *et al.*, 1991; Ryding and Rast, 1994; Gowen and Bloomfield, 1996; Millard *et al.*, 1996). The rapid growth of human population and the attendant agricultural development in Ethiopia has demanded the widespread use of fertilizers and pesticides by farmers on agricultural lands. The fertilizers and pesticides applied on the agricultural lands eventually find their ways into nearby water bodies and pollute them. The most common consequence of enrichments of water bodies with nutrients (*eutrophication*) originating from farm plots is results excessive growth of algae in lakes and reservoirs (Vollenweider, 1981; Lampert and Sommer, 1997).This is one of the commonest water quality problems which is beginning to attract public attention in Ethiopia. The development of toxic blooms of the cyanobacterium *Microcystis aeruginosa* in Lakes Chammo (Amha Belay and Wood, 1982) and Koka Reservoir (Demeke Kifle, Pers.comm.) in the Ethiopian Rift Valley, has been responsible for the death of a large number of domestic and wild animals.

Changes in nutrient regimes can have drastic effects. Limiting nutrients, such as nitrogen and phosphorus, play a major role in determining the abundance and composition of the species making up communities (Tilman, 1982; Abrams, 1995; Dodson *et al.*, 2000), productivity of an ecosystem, which in turn can affect the trophic structure and its stability (Oksanen *et al.,* 1981; Abrams, 1993), and ecosystem functioning (Tilman *et al.,* 1997). Most studies of eutrophication in lakes (Reynolds, 1984) and the marine environment (Maestrini *et al*., 1984) have dealt with phytoplankton because of its fundamental role in the food web and in biogeochemical cycles (Falkowski, 1994; Antoine *et al*., 1996; Ignatiades, 1998).

The extent to which our lakes may have changed as a result of the afore-mentioned human activities or natural causes is not known with certainty. These activities apparently lead to the deterioration of the environmental conditions in the lakes, with consequent changes in the species composition and photosynthetic production of phytoplankton, which determine the pelagic food web structure and fish production in the lakes. The assessment of qualitative and/or quantitative changes taking place in these lakes, therefore, necessitates the generation of basic information on the physical, chemical and biological aspects of these water bodies over an extended period of time.

Studies on the production of tropical phytoplankton started about 70 years ago (Talling and Lemoalle, 1998), although the application of the method to evaluate production rates per unit area had to wait until the early 1950s in Africa (Prowse and Talling, 1958). Currently, research articles published on the taxonomic composition and primary production of phytoplankton in relation to physico-chemical environmental variables in African lakes are numerous.

Ethiopia is endowed with a number of Rift Valley lakes and crater lakes, whose range of variations in morphometric, physical and chemical features (Wood and Talling, 1988) offers a wide opportunity for superb comparative ecological and taxonomic studies (Elizabeth Kebede, 1996). Despite the crucial role, which these inland water bodies may play in ameliorating the problem of protein shortage, the limnology of some of these lakes is unexplored. Although a large number of studies have been made on the community structure and primary production of phytoplankton in various East African lakes (Talling and Lemoalle, 1998), very little has been done on this aspect in Ethiopian lakes. Most of the studies conducted on phytoplankton of Ethiopian lakes have not been systematic nor sustained. The sporadic information on the dominant or most common species of planktonic algae reported in various limnological papers is compiled in Wood and Talling (1988). The few systematic studies made on the species composition of phytoplankton in Rift Valley lakes are those of Tsegaye Mihrete-Ab (1988); Elizabeth Kebede and Amha Belay (1994) and Elizabeth Kebede and Willen (1998).

Primary production of phytoplankton in Ethiopian lakes (in two of the Bishoftu crater lakes-Arenguade and Kilole), though on a short-term basis, was studied for the first time by Talling *et al.* (1973). However, the only studies made on the temporal and spatial variations of phytoplankton production in relation to some physical and chemical variables over an extended period of time are those of Girma Tilahun (1988) and Getachew Beneberu (2004) for Lake Ziway, Demeke Kifle and Amha Belay (1990) and Tadesse Fetahi (2004) for Lake Awassa and Eyasu Shumbulo (2004) for Lake Chamo. Despite the fact that the Bishoftu crater Lakes have been the subject of many limnological investigations, some dating as far back to the early 1930s (listed in Prosser *et al.,* 1968), published information on the temporal dynamics of biomass and primary production phytoplankton in Lake Hora-Arsedi (Betemengest), is not available.

The purpose of this research project was, therefore, to study the temporal dynamics of biomass and photosynthetic production of phytoplankton in relation to some physico-chemical factors in Lake Hora-Arsedi.

2. OBJECTIVES

2.1. GENERAL OBJECTIVE

- To investigate temporal dynamics of biomass and primary production of phytoplankton in relation to some environmental variables in Lake Hora-Arsedi;

2. 2. SPECIFIC OBJECTIVES

- To assess changes in the physico-chemical quality of the lake water over the study period;

- To investigate the temporal changes in the biomass and primary production of phytoplankton;

- To identify the environmental factors, which are of over-riding importance in determining the temporal variations in the biomass and photosynthetic production of phytoplankton in the study lake;

- To generate physico-chemical and biological data, which can be used as a base-line information for future research on the lake or other similar ecosystems and to recommend suitable management strategies for Lake Hora-Arsedi.

3. DESCRIPTION OF THE STUDY SITE

Lake Hora-Arsedi (Fig.1), one of the crater lakes at Debre Zeit (Bishoftu), is found at an altitude of 1850 m (Prosser, *et al.,* 1968; Wood*, et al.,* 1984) some 45 Km southeast of Addis Ababa. Mohr (1961), who estimated its age as early Holocene (≈ 7000 years ago), was the first to describe the geology Lake Hora-Arsedi. Some limnological features of the lake are presented in Table 1.

Previous limnological studies on Lake Hora-Arsedi described bathymetry (Prosser *et a*l., 1968), water chemistry (Prosser *et al.,* 1968; Wood *et al*., 1984; Rippey and Wood, 1985; Zinabu Gebre-Mariam *et al*., 2002), thermal stratification and mixing (Baxter and Wood, 1965; Wood *et al.,* 1976), chlorophyll "a" and phytoplankton (Wood and Talling, 1988) and community structure of Rotifera (Green and Seyoum Mengestou, 1991).

Lake Hora-Arsedi is a double crater with a maximum depth (in meters) of 38 (North crater) and 31 (South crater) and a mean depth of 17.5 m. The lake has a surface area of about 1.03 Km^2 and volume of 0.018 Km^3. Like all the other volcanic crater lakes in this area, Lake Hora-Arsedi is a closed system, surrounded by very steep and rocky hills and cliffs. The catchment of the lake is formed from volcanic rocks of basalt, rhyolite and tuff (Mohr, 1961).

The lake has no surface outflows and receives water primarily from rainfall falling directly on its surface and run-off from its small catchment. The annual variation in depth of this lake is less than a meter, which suggests the maintenance of water level by seepage to and from the water table (Baxter and Wood, 1965). According to Lamb (2001), groundwater inflow represents about forty per cent of the total water inflow to Lake Hora-Arsedi , but only about three percent of its water loss, the remainder being lost by evaporation**.**

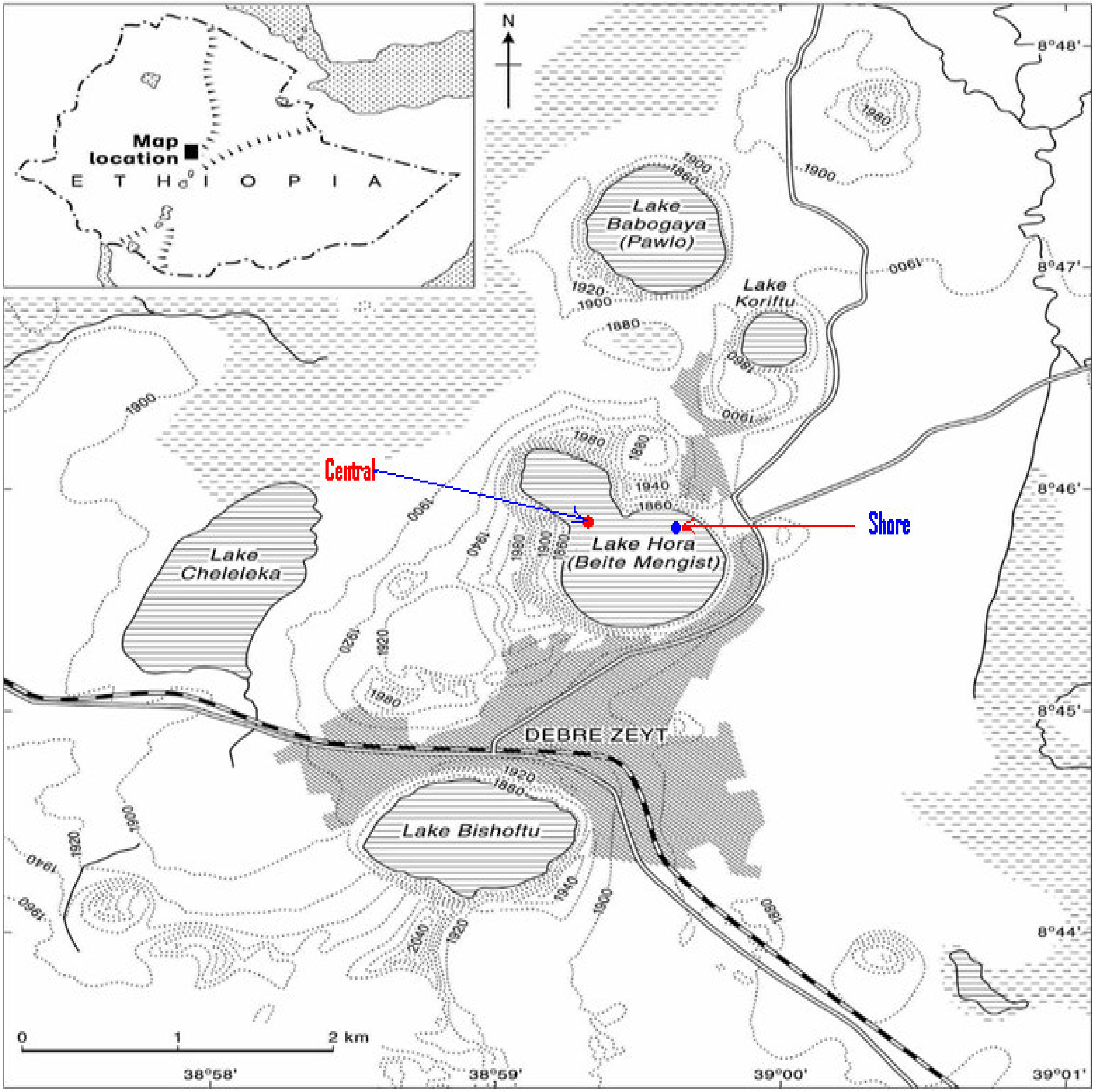

Fig. 1. Location of Lake Hora-Arsedi in, Bishoftu Ethiopia

Table 1. Some limnological features of Lake Hora-Arsedi [Source: Chemical data from Baxter (2002) and morphometric data from Prosser, *et al.* (1968)].

Surface area (Km^2)	1.03
Maximum depth (m)	38
Mean depth (m)	17.5
Volume (km^3)	0.018
Conductivity (µS cm^{-1})	2350
Salinity (g l^{-1})	2.57
Alkalinity (meq l^{-1})	26.5
$_{P}$H	9.2
PO_4–P (µg l^{-1})	<5
NO_3-N (µg l^{-1})	<5
SiO_2 (mg l^{-1})	<0.1
Sum of cations (meq l^{-1})	29.5
Sum of anions (meq l^{-1})	32.9
Na^+ (meq l^{-1})	23.9
Cl^- (meq l^{-1})	5.7
Chlorophyll ” *a*”(µg l^{-1})	36

The immediate surroundings of the lake are semi-urban in character, with many planted and invasive exotic species (e.g. *Eucalyptus, Casuarina, Schinus and Opuntia spp).*

The region around the lake is characterized by moderate rainfall, varying around about 850 mm per annum (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 ^{0}C and 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). Its seasonal cycle of stratification and mixing is probably similar to that of the nearby Lake Babogaya (Pawlo), which mostly resembles hydrochemically (Lamb, 2001). The lake stratifies during the February-October wet season, and mixes as a result of heat loss to clear night skies during the dry season (Lamb, 2001). Through their studies over extended periods, Baxter *and Wood (*1965) and Wood *et al.* (1976) have shown the frequent occurrence of pronounced and deep-seated thermal stratification with a consequent stratification of various chemical species in Lake Hora-Arsedi (Wood *et al.,* 1984).

Lake Hora-Arsedi is a dilute lake with Na^+ as the dominant cation and carbonate-bicarbonate as the dominant anion. The water is alkaline, 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).

The phytoplankton community is dominated by the colonial cyanobacterium *Microcystis aeruginosa* (Kütz,) Kütz. (Wood and Tallinig, 1988), which is known to form blooms in some Rift valley and crater lakes of Ethiopia. The zooplankton community of Lake Hora-Arsedi includes the rotifers *Asplanchna sieboldi* Leydig*, Brachionus calyciflorus* Pallas*, and B. dimidiatus* Bryce*, B. urceolaris* Müller and *Hexarthra jenkinae* de Beauchamp (Green and Seyoum Mengestou, 1991) and copepoda and cladocera (Tamiru Gebre unpublished thesis, 2006). The Lake supports a piscifauna, which is exclusively composed of Tilapia (*Oreocromis niloticus* Linnaeus) although not much fishing is done.

METEOROLOGICAL DATA

The temporal changes in mean maximum and minimum air temperature, wind speed (of the sampling dates), and monthly rainfall of the study lake area obtained from the National Meteorological Agency is shown in Fig. 2.

Mean maximum monthly air temperature (in ^{o}C) varied from 24 of July, 2005 to 28.3 of February, 2006 with most values above 25.5, while the mean minimum monthly temperature ranged from 3.5 of December, 2005 to 13.6 of August, 2005.

Monthly rainfall (in mm) was high (> 150 mm) during the period extending from July to September, with the largest peak in August (186.7) and smaller peaks in February and April, 2006.

Wind speed (m s^{-1}) of the sampling dates varied from 1 of September to 1.9 of November, with high values (> 16) during the period extending from October 2005 to February 2006.

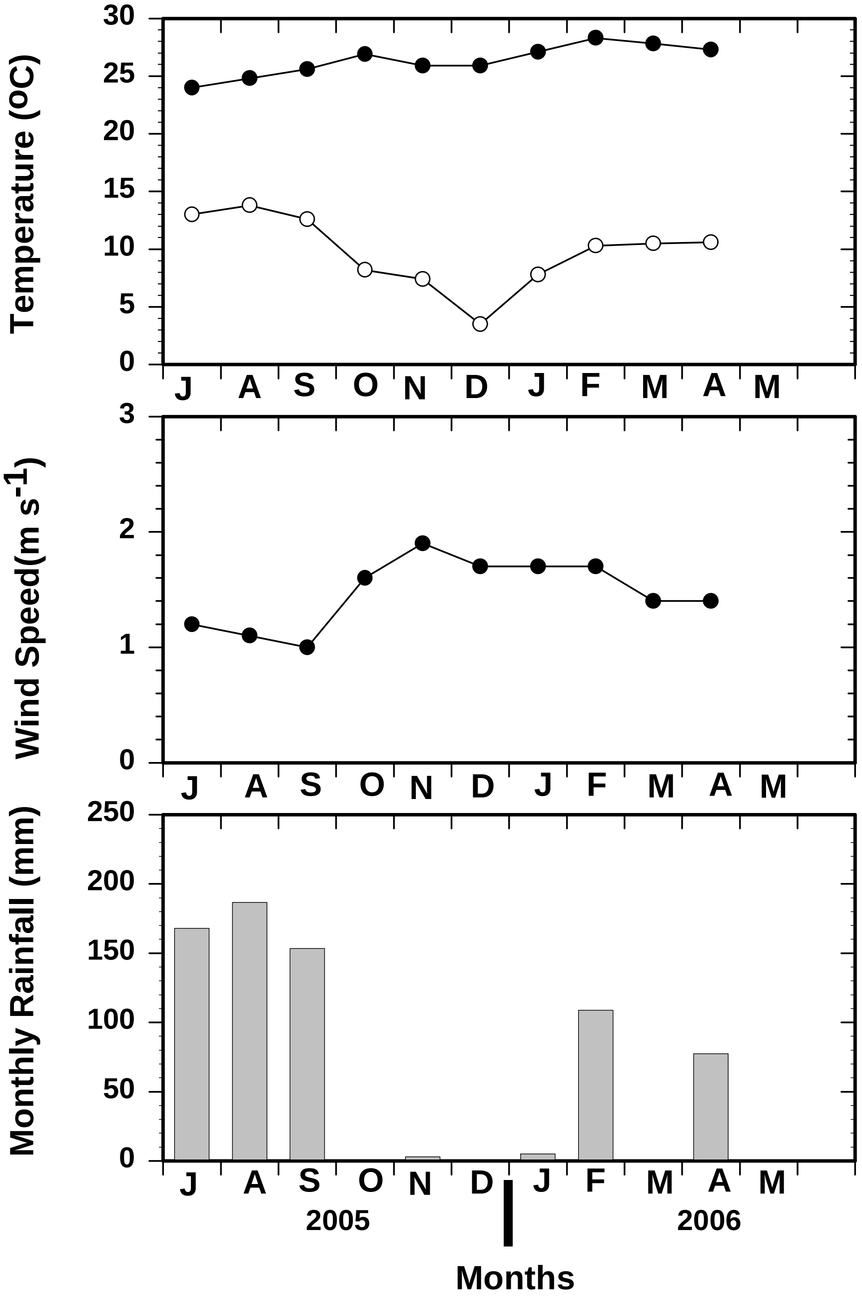

Fig. 2. Meteorological data of Lake Hora- Monthly rainfall (mm), mean monthly wind speed (m s^{-1}) and mean monthly maximum (closed circle) and minimum (open circle) air temperature.

4. MATERIALS AND METHODS

4.1. SAMPLING PROTOCOL

Samples were collected about every two weeks, from central and near-shore stations with approximate depths of 33 and 3.5 meters respectively, from July 2005 to April 2006. Water samples were taken with a bottle sampler (Ruttner) from discrete depths distributed within the euphotic zone, the lower limit of which was approximated as being equal to Z_{SD} x 3. The collected samples were mixed in equal proportions to produce composite samples. The composite samples were used for the estimation of phytoplankton biomass as chlorophyll *"a"* concentration and photosynthetic production and for the analyses of inorganic nutrients.

4.2. MEASUREMENTS OF PHYSICO-CHEMICAL PARAMETERS

Shortly before sample collection, water temperature and dissolved oxygen concentration were measured *in situ* with portable digital oxygen meter (Hanna 9024) connected to an oxygen-temperature combination probe.

Secchi depth (transparency) of the Lake was estimated with a standard Secchi disc of 20 cm diameter.

Electrical conductivity and salinity were measured with a combined conductivity-salinity meter (YSI model 30), while pH was determined with a portable digital pH meter (Jenway 3200). Total alkalinity was determined within a few hours of sample collection by titration with 0.1N HCl to a pH of 4.5 using a mixed Bromocresol green-methyl red indicator (Wetzel and Likens, 2000). Composite water samples filtered through glass fiber filters (GF/C) were used for the analyses of inorganic algal nutrients. Nitrate-nitrogen (NO_3-N) was analyzed by the Cadmium Reduction Method, using a Hach Kit (DR/2400 spectrophotometer) according to the procedures outlined in the Instructions' manual of the manufacturer. The Ascorbic Acid and Molybdosilicate methods were used to estimate Soluble Reactive Phosphate-phosphorus (SRP, PO_4-P) and dissolved molybdate-reactive silica (SiO_2) colorimetrically (APHA *et al.*, 1999).

4.3. *BIOLOGICAL PARAMETERS*

4.3.1. Species composition of phytoplankton

Composite water samples preserved with Lugol's iodine were used for the identification of phytoplankton taxa. The phytoplankton samples were examined with an inverted microscope ((Nikon) and their identification to genus or species level was made on the basis of various taxonomic literature available on phytoplankton (e.g. Whitford and Schumacher, 1973; Jeeji-Bai, 1977; Durand and Leveque, 1980; Gasse, 1986; and John *et al.*, 2002).

4.3.2. Estimation of phytoplankton biomass

Phytoplankton biomass was estimated as chlorophyll “a” concentration spectrophotometrically from 90% acetone extracts of the particulate material retained on Whatman glass fiber filters (GF/C). The filters were manually ground with a glass rod in a small volume of 90% acetone, placed in a parafilm-covered tube, and centrifuged at 3000 rpm for ten minutes. The extract was then decanted into a 25 ml volumetric flask and made up to the mark with 90% acetone. The absorbance of the centrifuged pigment extracts was measured at 665nm (the red absorption maximum) spectrophotometrically (Model SP6-350) and corrected for turbidity by subtracting the corresponding readings at 750 nm. The corrected values were used to calculate the concentration of chlorophyll a using the approximate relations of Talling and Driver (1963). No corrections for phaeopigments (degradation products of chlorophyll a) were made. **(Appendix 2).**

4.3.3. Estimation of Primary production of phytoplankton

Photosynthetic production of phytoplankton was measured *in situ* at the central station by the Light and Dark bottle technique and the Winkler method of oxygen determination (Mackereth, *et al*., 1978; Wetzel and Likens, 2000). The composite samples were siphoned into duplicate 250 ml pyrex light (clear) and dark (covered with a cloth tape) glass bottles under dim light conditions. Pairs of light bottles were attached to a metal suspension rod marked at 0, 0.25, 0.50, 0.75, and 1.25, 1.75 and 2.25 m). Two dark bottles were also

included, one near the surface and another near the bottom of the series of bottles. To avoid shading, the arms of the suspension line, intended for the different depths of incubation, were made in such a way that they project out in different directions thereby avoiding overlap of bottles of successive depths of exposure. The suspension rod was attached to a buoy (float). A pair of initial bottles was fixed with Winkler reagents immediately after lowering the suspension rod into the water column. The incubation period usually lasted for three hours around mid-day (between 10:00 a.m. and 1:00 p.m.). At the end of the incubation period, the sample bottles were covered with a black cloth and fixed with Winkler reagents.

Oxygen concentration was determined by titration with sodium thiosulphate using starch as indicator (Wetzel and Likens, 2000). Gross and net photosynthesis were estimated from changes in oxygen concentration in the dark, initial, and light bottles.

Explanations of the symbols used throughout this thesis and in previous similar studies (Talling, 1965; Talling *et al*., 1973) are given below.

Z_{SD} – Secchi depth in meter

Z_{eu} – Depth of euphotic zone in meter

K_d – mean vertical extinction coefficient in ln units m^{-1}.

B – standing crop or biomass of phytoplankton per unit volume in mg Chl a m^{-3}.

A – Gross photosynthesis per unit water volume in mg O_2 m^{-3} h^{-1}

A_{max-} – Light-saturated rate of gross photosynthesis per unit water volume, in mg O_2 m^{-3} h^{-1}

ΣA – Hourly rate of gross photosynthesis per unit area, in g O_2 m^{-2} h^{-1}

ΣΣA -	Daily rate of gross photosynthesis per unit area, in g O_2 m^{-2} d^{-1}.
Φ(A/B)-	Specific rate of gross photosynthesis per unit biomass, in mg O_2 (mg Chl a)$^{-1}$ h^{-1}
Φ_{max} (P_{max}) -	Light-saturated rate of gross photosynthesis per unit biomass, in mg O_2 (mg Chl a)$^{-1}$ h^{-1}.
Ph.A.R.-	Photosynthetically Active Radiation, in µE m^{-2} S^{-1} or E m^{-2} h^{-1}.

5. RESULTS AND DISCUSSION

5.1. Physical features of **Lake Hora-Arsedi**

Surface water temperature, **Z_{SD}, K_d** and **Z_{eu}** of the present sampling stations in Lake Hora-Arsedi are presented in Table 2. During the study period, surface water temperatures varied from 23.1 to 30.0 ^{0}C at both central and near-shore stations, with a difference between the seasonal minimum and maximum temperature of only 6.9 ^{0}C. The observed relatively small seasonal variation is consistent with Beadle's (1981) finding that the temperature of the equatorial region of the world does not show pronounced temporal variation although diurnal changes very near the surface may be great. The maximum surface water temperature (30 ^{0}C) occurred in September, 2005 and March, 2006 at both stations and in February, 2006 at the central station and in April, 2006 in the near-shore station, while the minimum (23.1^{0}C) was observed in November, 2005 at both stations. Since the majority of temperature measurements were made during the morning. Afternoon temperature measurements could thus give higher maximum temperature.

Table. 2. Surface water temperature, Z_{SD}, $EV_{tot,}$ and Zeu at the central (C) and near-shore (Sh) stations of Lake Hora-Arsedi.

Sampling Date	Sampling Stations	Surface water Temp. (^oC)	Z_{SD} (m)	K_d (ln units m^{-1})	Z_{eu} (m)
20/7/ '05	C	27.0	1.0	1.44	3.20
	Sh	27.0	0.65	2.40	1.92
27/8/ '05	C	29.0	0.90	1.60	2.88
	Sh	29.0	0.63	2.29	2.01
7/9/ '05	C	30.0	1.0	1.44	3.20
	Sh	30.0	0.75	1.92	2.40
14/10/ '05	C	29.0	0.95	1.52	3.03
	sh	29.0	0.73	1.97	2.34
28 /10/ '05	C	27.0	1.0	1.44	3.20
	Sh	27.0	0.75	1.92	2.40
18/11/'05	C	23.1	0.90	1.60	2.90
	Sh	23.1	0.80	1.80	2.56
14/12/'05	C	23.4	0.75	1.92	2.40

	Sh	26.3	0.65	2.40	1.92
08/01/06	C	25.4	0.75	1.92	2.40
	Sh	24.4	0.65	2.40	1.92
19/01/06	C	24.4	0.74	1.94	2.37
	Sh	24.5	0.69	2.09	2.00
4/02/06	C	30.0	0.74	1.94	2.37
	Sh	29.1	0.72	2.0	2.30
22/02/06	C	29.0	0.76	1.89	2.40
	Sh	29.5	0.74	1.94	2.37
2/3/06	C	30.0	0.79	1.82	2.53
	Sh	27.9	0.76	2.53	1.82
26/03/06	C	30.0	0.80	1.8	2.56
	Sh	30.0	0.70	2.06	2.23
29/04/06	C	29.5	0.75	1.92	2.40
	Sh	30.0	0.65	2.22	2.07

The surface water temperature values of Lake Hora-Aresdi (23.1 ^{0}C to 30 ^{0}C) are broadly similar to those reported for most Ethiopian Rift Valley lakes including Lakes Awassa (20.5 - 28.4 ^{0}C, Demeke Kifle, 1985), Chamo, (23-30^{0}C, Eyasu Shumbulo, 2004), Abijata and Langano (25.5 - 29.4 ^{0}C; Kassahun Wedajo, 1982) despite the considerable differences in altitude (1580-1680 m). Wood *et al.* (1976) reported surface water temperature levels ranging from 18.8 to 22.5 ^{0}C and 19.7 to 27 ^{0}C for the other Bishoftu Crater Lakes of more or less similar altitudes (2000 and 1900 m)- Hora-Kilole and Arenguade respectively, probably indicating the greater importance of local meteorological conditions to the surface water temperature of a body of water. Considerably higher surface water temperature values are, however, known for such East African lakes as Lake George, Uganda and Lake Turkana, Kenya (26 - 36 and 27.5 - 32.5 ^{0}C respectively; Ganf and Horne, 1975). Depth-profiles of temperature (Appendix 3) show more or less even vertical distribution.

The transparency of Lake Hora-Arsedi, as measured by a Secchi disc, varied from 0.74 to 1.0 m (mean = 0.85) and 0.63 to 0.80 m (mean = 0.71) in the central and near-shore stations respectively, with consistently lower values at the near-shore station. The Secchi depths of Lake Hora-Arsedi are similar to those of Lake Awassa 0.(65-0.95 m; Demeke Kifle, 1985) whose phytoplankton biomass values (in mg Chl a m^{-3}) are broadly similar (15-58, Demeke Kifle and Amha Bealy, 1990; Elizabeth Kebede *et al.,* 1994) to those recorded for Lake Hora-Arsedi in the present study (19.1-53.2). The observed temporal variations in the transparency of Lake Hora-Arsedi is attributable to changes in the extent of loading of particulate materials through run-off and fluctuations in phytoplankton biomass although the correlation between biomass measured as chlorophyll ***"a"*** concentration and Secchi depth was negative but poor (Pearson correlation, r = - 0.16) **(Appendix 8**).

Vertical extinction coefficients for total underwater light (mean vertical extinction coefficient) (K_d**)** can be determined from Secchi depths according to Holmes (1970) (**Appendix 5**). The K_d in Lake Hora-Arsedi ranged from

1.44 to 1.96 and from 2.06 to 2.53 at the central and near- shore stations respectively. The consistently higher mean vertical extinction coefficients of the near-shore station are attributable to the greater introduction of particulate materials into the water column through run-off and resuspension of sedimented materials resulting from wind-induced mixing of its much shallower water column. The lower limit of the trophogenic zone, Euphotic depth (**Z_{eu}**), in Lake Hora-Arsedi was approximated using the mathematical relationship **Z_{eu}** and K_d **(**Kalff, 2002) (**Appendix 5).** The calculated euphotic depths ranged from 2.34 to 3.20 m and from 1.64 to 2.4 at the central and near- shore stations respectively. The euphotic depths of Lake Hora-Arsedi are broadly similar to those of Lake Awassa (1.59 - 2.7 m, Demeke Kifle and Amha Belay, 1990) whose phytoplankton biomass values have already been shown to be comparable to those of Lake Hora-Arsedi . Compared to those of other Bishoftu Crater lakes, Z_{eu} values of Lake Hora-Arsedi are intermediate between those for the former Kilole (0.24-0.45m) and Arenguade (0.15-0.27 m) (Talling *et al.*, 1973) in which turbidity of the water column is almost exclusively of biological origin and the mesotrophic and deep Crater Lake, Babogaya (5-15 m, Yeshiemebet Major unpublished thesis, 2006).

5. 2. CHEMICAL FEATURES OF LAKE HORA-ARSEDI

5.2.1. Dissolved Oxygen (DO) and collective chemical parameters.

Depth profiles of dissolved oxygen (DO) concentration are given in Appendix 4**. Dissolved oxygen concentration in the surface water of the central station in Lake Hora-Arsedi ranged from 6.5 to 11.5 mg l^{-1}, with much higher values below the surface (17-20.3 mg l^{-1}) in July 2005. DO concentrations were generally lower in the near-shore station, with surface concentrations ranging from 6.1.to 8.0 mg l^{-1}. Vertical distribution of dissolved oxygen was fairly uniform in the near-shore station, unlike that in the central station where large differences in DO concentration were observed between successive depths of measurement. The more or less even distribution of DO down the water column in the near-shore station is obviously related to deep-mixing favored by its shallow depth.**

Salinity, Conductivity (K_{25}), Total Dissolved Solids (TDS), Total Alkalinity, and pH of Lake Hora-Arsedi measured over the study period are shown in Table 3. Lake Hora-Arsedi is a sub saline lake with its salinity (ppt) varying from 2.3 to 2.56. The highest salinity level (2.56) recorded for Lake Hora-Arsedi in the present study is similar to that reported (2.6 ppt) by Zinabu Gebre-Mariam (1994) for the same lake. The highest salinity was recorded in mid-January, 2006, when the seasonally maximum conductivity was also observed. Lake Hora-Arsedi is more saline than all the Main Ethiopian Rift

Valley Lakes (with salinity in the range 0.2-1.9, Prosser *et al.,* 1968; Brook Lemma, 1994; Elizabeth Kebede and Amha Belay, 1994; Elizabeth Kebede *et al*., 1994) except Lake Langano, whose salinity (2.4 ppt, Elizabeth Kebede et al., 1994) is similar to that of Lake Hora-Arsedi. The higher salinity of Lake Hora-Arsedi is to be expected in light of the fact that it is a closed-basin crater lake.

Table 3. Conductivity (K_{25}), Salinity, Total Dissolved Solids (TDS), Total Alkalinity (TA) and pH at the central (C) and near- shore (Sh) stations of Lake Hora-Arsedi.

Sampling date	Station	pH	TA	K_{25} (µS cm^{-1})	TDS(mg l^{-1})	Salinity ppt
20/7/ '05	C	8.69	22.3	-	-	-
	Sh	8.82	24.5	-	-	-
27/8/ '05	C	8.70	26.0	-	-	-
	Sh	8.90	25.0	-	-	-
7/9/ '05	C	9.16	16.5	2221	1080	2.4
	Sh	9.16	18.9	2231	1100	2.3
14/10/ '05	C	9.32	17.0	2230	1150	2.5
	sh	9.35	19.7	2220	1120	2.3
28 /10/ '05	C	9.29	14.5	-	-	-
	Sh	8.67	16.5	-	-	-
18/11/'05	C	9.67	15.6	-	-	-
	Sh	8.52	13.6	-	-	-
14/12/'05	C	8.22	14.5	-	-	-
	Sh	8.20	13.5	-	-	-
08/01/06	C	9.31	24.0	2200	1090	2.5
	Sh	8.26	24.0	2230	1110	2.3
19/01/06	C	9.38	24.0	2260	1120	2.56
	Sh	8.25	24.0	2270	1130	2.4

4/02/06	C	9.30	25.0	2221	1090	2.46
	Sh	8.46	26.2	2231	1300	2.3
22/02/06	C	9.5	24.0	2260	1110	2.4
	Sh	8.4	24.1	2270	1130	2.3
2/3/06	C	8.77	24.0	2230	1120	2.4
	Sh	9.2	25.0	2220	1230	2.3
26/03/06	C	8.54	26.0	2230	1110	2.5
	Sh	8.64	26.0	2231	1090	2.3
29/04/06	C	8.5	26.0	2200	1120	2.5
	Sh	8.46	26.0	2230	1130	2.5

Conductivity (in μS cm^{-1}), which is regarded as a surrogate of salinity, varied from 2200 to 2270 (values of both stations combined), with most recorded values close to that reported for the same lake (2200) by Zinabu Gebre-Mariam (1994).

Total Dissolved Solids (TDS) ranged from 1080 to 1120 mg l^{-1} at the central station and from 1110 to 1230 mg l^{-1} at the near - shore station, with almost consistently higher values in the near-shore station. This seems to be associated with the higher input of solids to the water column of the near-shore station resulting from the more frequent wind-induced mixing (favoured by its sallow depth) and greater exposure to anthropogenic impacts owing to its position.

Total alkalinity (in meq l^{-1}) showed marked temporal fluctuations, varying from 14.5 to 26-meq l^{-1} in the central station and from 13.5 to 26 meq l^{-1} in the near-shore station, with most high values (> 24 meq l^{-1}) during the period extending from July to August, 2005 and from January to April, 2006. Input of inorganic carbon through runoff from the catchments area seems to be considerable. The total alkalinity values recorded in the present study are comparable to those reported for Lake Hora-Arsedi by Prosser *et al.* (1968) and Zinabu Gebre Mariam (1994). The low alkalinity values were recorded during the dry period.

pH values ranged from 8.1 to 9.32 in the central station and from 8.2 to 9.35 in the near- shore station, with most higher values at the central station. The pH values of Lake Hora-Arsedi are broadly similar to those of the Ethiopian Rift Valley and Crater lakes with salinities less than 3 ppt. (Elizabeth Kebede and Willen, 1998). Much higher values of pH are known from other Crater lakes in Ethiopia including Lakes Arenguade (10.3) (Prosser *et al.*, 1968) and Chitu (10.2) (Elizabeth Kebede *et al.*, 1994) in which the CO_2-demand by photosynthesis is intense due to the superabundant phytoplankton populations they support (Talling, 1965; Talling *et al.,* 1973). The high positive correlation between pH and alkalinity reported for the combined data of Ethiopian lakes (Wood and Talling, 1988) and saline lakes worldwide (Hammer, 1986) was not observed in the present study for Lake Hora-Arsedi. The correlation between pH and alkalinity for Lake Hora-

Arsedi was also negative and poor (r = - 0.06), probably only TA and PA (phenolphthalein alkalinity) were measured in this study.

Maberly (1996) noted that high rates of primary production allow large daytime CO_2 and HCO_3^- withdrawal (depletion) resulting in a large rise in pH. No apparent relationship between pH and phytoplankton biomass /photosynthetic rates was, however, observed for Lake Hora-Arsedi although a few high pH values coincided with high phytoplankton biomass or photosynthetic activity (e.g. September and October, 2005 and mid-January, 2006). It has been shown that despite the high photosynthetic removal of $CO_{2,}$, the pH may remain lower due to pH depression by organic acids (e.g. humic acids) of plant origin (Hydersen, 1998).

4.2.2 INORGANIC NUTRIENTS

The temporal variations in the concentration of inorganic nutrients in relation to phytoplankton biomass at the central and near - shore stations in Lake Hora-Arsedi are shown in Fig. 3 (**and Appendix 6).** In the present study, nitrate concentrations were low, varying between 10 and 20 μg l^{-1} at the central station and between 9.0 and 20.5 μg l^{-1} at the near- shore station. The nitrate levels detected in the present study for Lake Hora-Arsedi are much higher than the values reported for Bishoftu crater lakes including the present study lake (< 5 μg l^{-1}, Prosser *et al.,* 1968; Wood *et al.,* 1984) in which nitrate was seldom detectable in the surface waters during a long-term study conducted over several years.

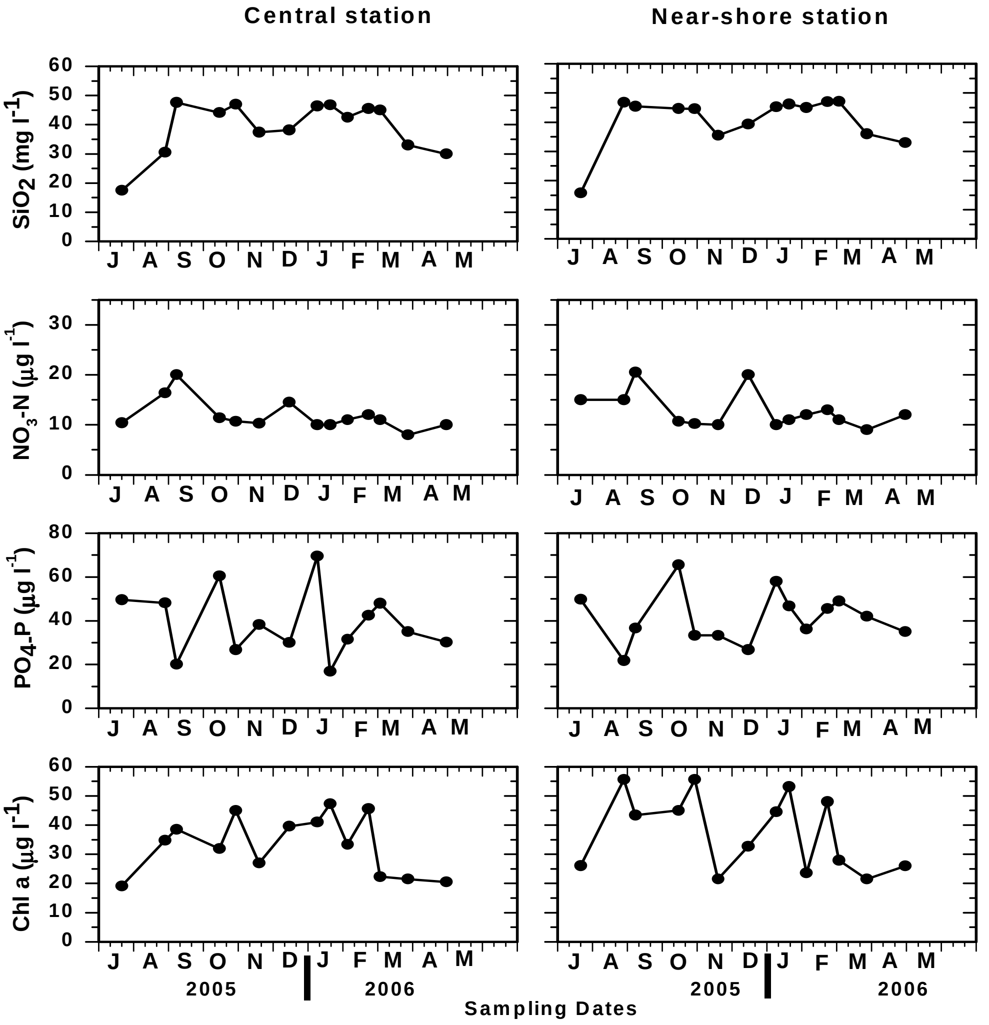

Fig. 3. Temporal variations in the concnetration of inorganic nutrients in relation to phytoplankton biomass measured as chl a at the central and near-shore stations in Lake Hora.

The present higher values of nitrate are obviously indicative of increased input of inorganic nutrients as a result of intensified human activities in the lake's area.

The low concentrations of nitrate-nitrogen observed in the present study are similar to those reported from a seasonal study on Lake Awassa by Elizabeth Kebede and Amha Belay (1994). Nitrate concentrations are generally low in tropical lakes (Moss, 1969; Talling and Talling, 165; Njuguna, 1988; Wood and Talling, 1988). The low levels of nitrate in tropical lakes have been attributed to nitrogen-poor soils of the region (Kalff, 2002) and internal loss of nitrogen through denitrification (Lewis, 2002). The correlation between nitrate and phytoplankton biomass measured as chlorophyll *"a"* concentration was positive but low (r = 0.31) and low concentrations of nitrate seem to follow previous periods of relatively high phytoplankton biomass at least on some sampling dates. Some of the high nitrate levels were associated with the period of heavy precipitation although there appears to be no explanation for the nitrate peak observed in December at both stations.

The concentration ranges of SRP were 16.86 to 69.5 and 21.79 to 57.99 µg l-^{1} for the central and near-shore stations respectively, with large peaks occurring in October, 2005 and January, 2006 at both stations. Comparable levels of SRP have been reported for other Ethiopian lakes including, Awassa and Langano (Wood and Talling, 1988). Exceptionally high levels of phosphate are also known from alkaline saline crater lakes of the same area, Lakes Arenguade (3200 µg l-^{1}) and Chitu (1700 µg l-^{1}) (Wood and Talling, 1988).

There was no obvious association of SRP with phytoplankton biomass and wet/dry periods although the January peak of SRP concentration coincided with high Chl a values of the same month at both stations. The remarkably high SRP levels of the present study reflect the impact of human activities on the nutrient chemistry of Lake Hora-Arsedi as the concentrations reported earlier were much lower (< 5 µg l-^{1}, Prosser *et al.*, 1968).

Although the excretion of nutrients by animals has not been studied in any detail in African lake ecosystems (Thornton, 1986) the contribution of zooplankton in Lake Hora-Arsedi should not be overlooked. Daily phosphate release by Cladoceran zooplankton has been shown (Lehman, 1980) to be in the order of 35 – 60 % of their total body phosphorus. The contribution of rotifers, whose year-round dominance in Lake Hora-Arsedi has been demonstrated by Tamiru Gebre unpublished thesis (2006), is expected to be 3-4 times higher ((Lehman, 1980).

Molybdate reactive silica varied from 17.48 to 46.96 mg l^{-1} at the central station and 15.76 to 46.77 mg l^{-1} at the near-shore station. Silica levels were high at both stations, as they usually are in East African lakes including those found in Ethiopia (Talling and Talling, 1965; Prosser *et al.*, 1968; Wood and Talling, 1988; Elizabeth Kebede and Amha Belay, 1994; Elizabeth Kebede et al., 1994). Unusually high silica concentrations (exceeding 100 mg l^{-1}), like those of SRP, have been reported (Wood and Talling, 1988) for the more saline and alkaline lakes of Ethiopian Rift valley. The consistently high levels of silica in tropical lakes including Lake Hora-Arsedi are attributable to the importance of groundwater inputs and enhanced dissolution of solid silicates in saline waters of high alkalinity and pH (Talling and Talling, 1965; Talling, 1992). Unlike the other two inorganic nutrients, silica levels were maintained at more or less similarly high levels apart from the abrupt drop in November-December and March-April at both stations. The sharp decline in silica concentration in March-April coincided with the abundance of diatoms (Tamiru Gebre unpublished thesis, 2006). Temporal changes in silica concentrations exhibited a pattern, which was more or less similar to that of phytoplankton biomass measured as Chl a. The correlation between silica levels and phytoplankton biomass was also positive and strong (r = 0.69).

5.3. Biological features of Lake Hora-Arsedi

5.3.1. Temporal changes in the taxonomic composition and relative abundance of phytoplankton in Lake Hora-Arsedi

A total of 19 species of phytoplankton belonging to five algal classes and 15 genera were identified (Table 4) in composite samples collected from Lake Hora-Arsedi. The species diversity of phytoplankton was found to be low in comparison with those of the Ethiopian Rift Valley Lakes like Awassa (Elizabeth Kebede and Amha Belay, 1994) and Ziway (Tsegaye Mihrete-ab, 1988) although the major species of phytoplankton were considered for Lake Hora-Arsedi. Five algal groups (classes) primarily constituted the phytoplankton community of Lake Hora-Arsedi. It was, however, blue-green algae, green algae and diatoms, which were most common and quantitatively important (Tamiru Gebre unpublished thesis, 2006). The qualitative composition of the phytoplankton community in Lake Hora-Arsedi, which was dominated by blue-greens, greens and diatoms, is similar to the composition of most other tropical lakes including those in Ethiopia (Lewis, 1978; Hecky and Kling, 1981; Kalff and Watson, 1986; Talling, 1987; Tsegaye Mihrete-Ab, 1988; Elizabeth Kebede, 1996).

Table 4. List of major phytoplankton taxa identified in samples collected from **Lake Hora-Arsedi** *during the study period.*
Plus (+) signs denote the relative abundance of species of phytoplankton
++++ _ abundant, +++_ common, ++_ sparse +_ rare

Phytoplankton Group (Class)	Genera or species
***Cyanophyceae* (Blue green algae)**	*Microcystis aeruginosa (*Kütz.) Kütz **++++** *Anabaena raciborskii* (Wolosz.) Seenyyaa et Subba Raju **+++** *Cylindrospermopsis africana(*Kom. *et* Kling +

	Cylindrospermopsis sp.	+
	Planktolyngbya sp.	+
***Bacillariophyceae* (Diatoms)**	*Fragilaria crotonensis* Kitton	+++
	Synedra nana Meist.	+++
	Nitzschia kützingiana Hilse	+
	Cyclotella sp.	+
***Chlorophyceae* (green algae)**	*Pediastrum simplex* (Meyen) Lemm.	+++
	Scenedesmus diamoiphus (Turp.) Breb.	++
	Scenedesmus quadricauda (Turp.) Breb.	++
	Scenedesmus obliqus (Turp.) Breb.	+
	Chlaydomonas pisiformis Dill	++
	Phacotus lenticularis (Ehr.) Stein.	++
	Staurastrum chaetoceros (Shrod) Smith	+
***Euglenophyceae* (euglenoids)**	*Phacus longicauda* (Ehr.) Dujardin	++
	Phacus orbicularis (Hubner)	+
***Cryptophyceae* (cryptomonads)**	*Cryptomonas ovata* Ehr.	++

The discussion on the quantitative aspect of the phytoplankton community in Lake Hora-Arsedi is based on the information generated by Tamiru Gebre unpublished thesis (2006) through a study conducted in the same lake concurrently with this work. The blue-green algae persisted with appreciable numbers throughout the period extending from October 2005 to February 2006 although the relative abundance of the constituent species was variable (Tamiru Gebre unpublished thesis, 2006). Among the blue-green algae, *Microcystis aeruginosa* (Kütz) Kütz, was the most abundant species, consistently making

up a large proportion of the total phytoplankton abundance. Although lack of adequate facility did not allow the determination of depth-profiles of temperature and oxygen in Lake Hora-Arside, the physical regime of the period of cyanobacterial dominance and persistence in the same lake must have been conducive to the growth and maintenance of cyanobacteria. Cyanobacteria prefer stable water conditions with low flows, light winds and minimum turbulence as buoyancy regulation and vertical positioning work best under stable water column conditions (Reynolds, 1984).

Compared to blue-green algae, diatoms and green algae became more important during periods of precipitation (August-September, 2005 and March-April, 2006) owing to the turbulent water column condition. During March- April, there was complete replacement of *Microcystis aeruginosa* and other blue-green algae by diatoms and green algae at both stations, which coincided with low algal biomass. Diatoms are non-motile algae incapable of regulating their vertical position in the water column during calm periods and are hence liable to rapid sedimentation (Graham and Wilcox, 2002). Furthermore, they are opportunistic phytoplankton capable of exploiting temporary pulses of nutrients that result from runoff and mixing-associated vertical nutrient transfer (Harris, 1986) and rapidly building up their populations owing to their high growth rates (Paasche, 1975). The present timing of diatom dominance in Lake Hora-Arsedi is, however, bewildering in light of the physical regime described in a previous study (Wood ***et al***., 1976). According to Wood ***et al***. (1976) Lake Hora-Arsedi became almost completely de-stratified during November-February as a result of low minimum temperature and evaporative cooling and then thermal stratification was gradually restored from about March 2006 and persisted through the minor and major rainy seasons. In lakes like Lake Hora-Arsedi which are sufficiently deep to stratify, the period of low surface temperature is likely to be that in which vertical mixing, partial or complete, is most readily induced (Wetzel, 2001). The sequence of thermal events described by Wood ***et al.*** (1976) are not, however, expected to occur every year since the weather pattern may vary considerably from one year to another (Baxter, 2002) and consequently the stratification pattern in Lake Hora-Arsedi may have changed.

5.3.2. Phytoplankton biomass

The phytoplankton biomass measure as chlorophyll “a” concentrations exhibited temporal fluctuations at both the central (C) and near - shore (Sh) stations (Fig 3 and **Appendix 7**). Phytoplankton biomass measured as Chlorophyll a concentration ranged from 19.1-to 47.6 (mean =33.42) mg m-^{3} and from 21.5-to 53.15 (mean = 37.47) mg m-^{3} at the central and near-shore stations respectively. The present phytoplankton biomass values are comparable to those recorded for the same lake in 1980 (29) by Wood and Talling (1988) and in 1992 (30) by Zinabu Gebre-Mariam (1994) and for the other two Crater lakes in Ethiopia, Kilole (30) and Babogaya (33,37) by Zinabu Gebre Mariam, 1994).

Phytoplankton biomass peaked in October 2005 and in January and February 2006 at both stations with an additional peak in August 2005 at the near-shore station. Although the major peaks of chlorophyll ”a” occurred at times of high silica concentrations, they generally coincided with low levels of nitrate and phosphate. The correlation with biomass was also positive and strong (r = 0.69) for silica in spite of the fact that diatoms were quantitatively important only in August-September and March-April. Phytoplankton biomass correlated positively but weakly (r = 0.31) with nitrate. Despite the remarkably general dependence of phytoplankton biomass on phosphorus (Dillon and Rigler, 1974; Schindler, 1977; Kalff, 1983; Prairie *et al.*, 1989), a negative and weak correlation (r = - 0.22) was found between phosphate and chl a concentration. However, circumstances under which biomass concentrations are inversely correlated with ambient nutrient concentrations are not uncommon since biomass is a sign of past nutrient uptake (Talling and Lemoalle, 1998). The observed greater correlation of phytoplankton biomass with nitrate and not phosphate, is consistent with the observations made in such tropical water bodies as Lake Victoria (Talling, 1966), Lake Lano (Lewis, 1974) and some reservoirs of the Nile River (Talling and Rzoska, 1967), in which reduced algal productivity was connected with nitrate depletion. Talling and Talling (1965) also gave nitrogen the role of a limiting nutrient in tropical African lakes since nitrate levels were often very low, whereas phosphate levels were relatively high.

The temporal variations in phytoplankton biomass are also known to be controlled by loss processes including grazing by rotifers, crustaceans and fish. The significance of phytoplankton loss due to grazing is indicated by a clear water phase, in late spring and early summer in lakes (Lampert *et al.,* 1986) whose generation is primarily the impact of cladocerans (Kalff, 2002). A study conducted by Tamiru Gebre unpublished thesis (2006) concomitantly with this work has shown the almost year-round dominance of rotifers with peaks in November, 2005-January, 2006. The abundance of rotifers declined in March 2006 with the emergence of copepods and dominance of the phytoplankton community by diatoms, green algae and cryptomonads-, which are susceptible to zooplankton grazing. The relatively low phytoplankton biomass in August 2005 and March-April is probably the result of loss due to grazing by the efficient grazers, calanoid copepods, which were abundant at this time of the year (Tamiru Gebre unpublished thesis, 2006). The abrupt drop in phytoplankton biomass in November 2005 at both stations seems to be associated with the peak abundance of rotifers. The generally high levels of chlorophyll a observed between October 2005 and February 2006 are associated with blue-green algal abundance, whose major proportion was constituted by colonial and filamentous forms. These algae are less susceptible to grazing by zooplankton owing to their ability to interfere with the feeding apparatus of the grazers through their morphology and physiology (toxin-production) (Schoenberg and Carlson, 1984; Elser and Mackay, 1989).

Considering the differences in phytoplankton biomass values observed between the central and near-shore stations, a t-test was conducted according to Fowler (1998) to determine if the inter-station differences were significant. A t-test conducted at $p = 0.05$ (**Appendix 7**) indicated that the spatial variations in Lake Hora-Arsedi were significant. These spatial variations are attributable to the external loading of particulate and dissolved substances through runoff and complete wind-induced mixing of the near-shore station, which led to the horizontal variations of nutrients reflected in the generally higher levels of phosphate and nitrate at the near-shore station.

5.3.3. Photosynthetic production of phytoplankton

5.3.3.1. Depth profiles of gross photosynthesis

In situ experimental measurements of rates of gross photosynthesis per unit water volume (**A**, mg O_2 m^{-3} h^{-1}) are shown in Fig 4. The depth profiles of gross photosynthetic activity of phytoplankton in Lake Hora-Areside showed lower rates at the lake's surface throughout the study period. The maximum (light-saturated) rates of phytoplankton photosynthesis occurred at a depth of 0.75 m on all sampling dates except in February 2006 when the maximum rate was observed at a depth of 1.25 m.

Lower rate of photosynthesis at a lake's surface is commonly observed in tropical as well as temperate lakes and has been reported for phytoplankton communities in East African Lakes including those in Ethiopia (Talling *et al.*, 1973; Amha Belay and Wood, 1984; Girma Tilahun, 1988; Demeke Kifle and Amha Belay, 1990; Eyasu Shumbulo, 2004), Chad (Lemoalle, 1983), Kenya (Talling, 1965; Melack, 1979b, 1981) and Tanzania (Melack and Kilham, 1974).

The reduction in photosynthetic rates, known as photo-inhibition, is linked to the disruption of pigment systems by photo-oxidation (Amha Belay and Fogg, 1978), increased photorespiration (Harris and Lott, 1973) and inactivation of photosynthetic enzymes (Steemann-Nielsen, 1962) and results from excess photons, which are not dissipated by photosynthetic carbon fixation (Long *et al*, 1994) when light exceeds physiological saturation.

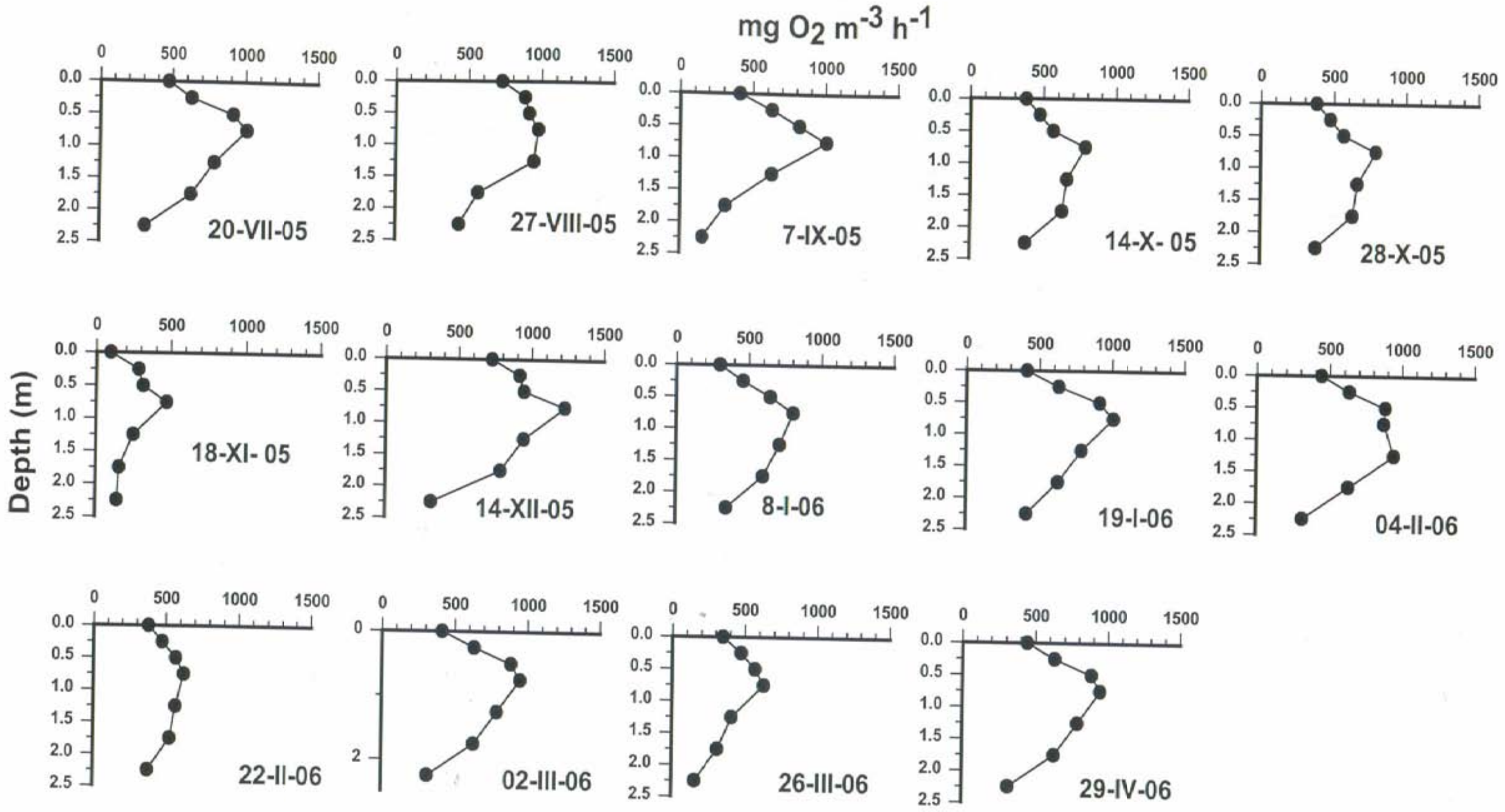

Fig. 4. Depth profiles of gross photosynthesis per unit water volume (mg O_2 m^{-3} h^{-1}) at a central station in Lake Hora.

Below the depth of $A_{max,}$ an almost exponential decline in rates of gross photosynthesis with increasing depth was observed reflecting the corresponding exponential decline in underwater irradiance. The depth at which community respiration equals photosynthetic production (compensation depth) was not clearly located for all the depth profiles owing probably to inadequate spacing of the depths of exposure of experimental bottles.

5.3.3.2. Photosynthetic Parameters

The temporal variations in specific rates of gross photosynthesis at light-saturation (A_{max}), photosynthetic capacity **[**P_{max}, mg O_2 (mg Chl a)$^{-1}$ h^{-1}**]** and hourly integrals of gross photosynthetic rates ($\sum A$, g O_2 m^{-2} h^{-1}) in relation to phytoplankton biomass (B, mg Chl a m^{-3}) are shown in Fig. 5. $\mathbf{A_{max}}$ of the phytoplankton community in Lake Hora-Areside ranged from ≈ 473 to 1230 mg O_2 (≈ 147.6 to 383.8 mg C m^{-3} h^{-1}). The conversion of the amount of oxygen evolved to the amount of carbon fixed assumes a photosynthetic quotient of 1.2 (Laws, 1991). Most of the present $\mathbf{A_{max}}$ values (mg O_2 m^{-3} h^{-1}) are higher than those reported for such East African lakes as Naivasha (150-240; Melack, 1979b) and Sonachi (130-850;

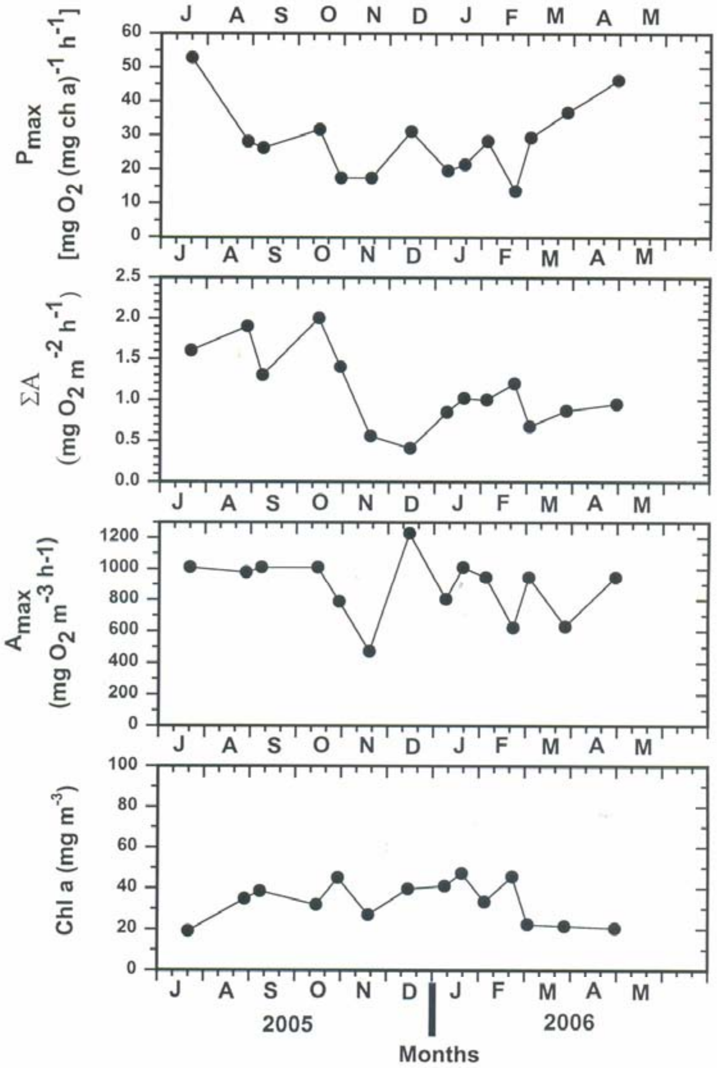

Fig. 5. Temporal changes in photosynthetic parameters in relation to biomass at the central station in lake Hora.

Melack, 1976a) both in Kenya, Lake Awassa, Ethiopia (217- 408; Demeke Kifle, 1985) and several irrigation reservoirs in Sri Lanka (110 to 640; Silva *et al.,* 2002). Much higher values are, however, known from crater and Rift Valley lakes including Lakes Ziway (1640-4670; Girma Tilahun, 1988), Arenguade (10000- 30000) and Kilole (4000-10000) all in Ethiopia (Talling *et al*., 1973), Lake George, Uganda (1900-6000; Ganf, 1975) and Lake Simbi (950-12900; Melack, 1979c) in Kenya. The lakes with A_{max} values higher than 10000 mg O_2 m^{-3} h^{-1} supported phytoplankton communities dominated by the cyanobacterium *Spirulina platensis.*

Although the temporal variations in the saturation rate parameter, is chiefly due to variable biomass concentration (Talling and Lemoalle, 1998), there is apparently no correlation (r = 0.08) between the A_{max} and biomass values of Lake Hora-Areside. However, weak but positive correlations between phytoplankton biomass and A_{max} have been reported for the Ethiopian Rift Valley Lakes Chamo (r=0.3; Eyasu Shumbulo, 2004) and Ziway (r=0.36; Girma Tilahun, 1988). Lack of correspondence between A_{max} **and phytoplankton biomass is prominent for phytoplankton of Lake Hora-Arsedi as it has been for many lakes of the tropical region (Talling and Lemoallle, 1998). In Lake Hora-Arsedi, the smallest biomass (19.11 mg Chl a m^{-3}) was associated with one of the very high values of** A_{max} (≈**1009 mg O_2 m^{-3} h^{-1}**), **while one of the peak biomass values (45.6 mg Chl a m^{-3}) yielded the relatively low A_{max} (622 mg O_2 m^{-3} h^{-1}). Lack of correspondence between** A_{max} **and biomass has also**

been reported for phytoplankton of reservoirs (Silva *et al.*, 2002) and other lakes (Talling *et al.*, 1973; Demeke Kifle and Amha Belay, 1990; Eyasu Shumbulo, 2004) of the tropical region. According to Talling (1965) and Hammer (1981), high maximum rates associated with low algal biomass levels are the result of high biomass-specific activity [**(P_{max}, mg O_2 (mg chl a)$^{-1}$ h^{-1}**]. **The positive and fairly strong correlation (r = 0.43) between A_{max} and P_{max} may also provide partial explanation for the association of high light-saturated rates with low algal biomass observed in the present study lake. The fact that the association of low algal biomass with high A_{max} in July, 2005 was observed at the time of the seasonal maximum in P_{max} further corroborates the influence of P_{max} on $A_{max.}$ Much higher correlation (r = 0.71) between these two photosynthetic parameters was reported by Eyasu Shumbulo (2004) for phytoplankton of lake Chamo.**

When comparing the photosynthetic capacity of phytoplankton communities, consideration of the magnitude of the light-saturated rate of gross photosynthesis per unit biomass measured as chlorophyll a, photosynthetic capacity, **[**(P_{max}, mg O_2 (mg chl a)$^{-1}$ h^{-1}**],** has become a common practice. Biomass-specific rates at light-saturation varied from 13.6 to 52.8 for Lake Hora-Arsedi. The upper values of the range of $\mathbf{P_{max}}$ for Lake Hora-Arsedi are considerably higher than those reported for some Rift Valley and Crater lakes of Ethiopia such as Kilole (16.3 - 33.7; Talling *et al.*, 1973), Ziway (9.6 - 22.5; Amha Belay and Wood, 1984; Girma Tilahun, 1988), Awassa (4-19; Demeke Kifle and Amha Belay, 1990), Abijata (14.8; Amha Belay and Wood, 1984); Chamo (14-39; Eyasu Shumbulo, 2004) and Arenguade (11-18; Talling *et al.*; 1973), Kenyan lakes such as Lakes Simbi and Sonachi (15-17 and 8-14 respectively; Mealck, 1981) and in the Ugandan part of Lake Victoria, (14 - 35; Talling, 1965).

Physical factors like Light (Falkowski, 1981) and temperature (Eppley, 1972), chemical factors like nutrient regimes (Falkowski and Stone, 1975) as well as such biological factors as algal type including cell size (Malone, 1971) are known to determine the temporal variations in P_{max}. As the marked seasonality of light and temperature observed in the temperate latitudes is absent in the tropics, chemical and biological factors may be of greater importance as determinants of P_{max}. High values of P_{max} were generally associated with low algal biomass. The strong but negative correlation (r= -0.77) between biomass and P_{max} seems to reflect the same trend. The inverse correlation between phytoplankton biomass and photosynthetic capacity is encountered in all geographical regions (Talling and Lemoalle, 1998) and the trend has been shown for African lakes including Lakes George, Uganda (Ganf, 1972), Ibrie, Ivory Coast (Dufour, 1982), Macllwaine, Rhodesia (Robarts, 1979), Chamo (Eyasu Shumbulo, 2004) and Awassa (Demeke Kifle and Amha Belay, 1990) both in Ethiopia. There appears to be no apparent relation between concentration of inorganic nutrients and photosynthetic capacity as the seasonal maxima of the latter were observed when inorganic nutrients were very low.

5.3.3.3. Production rates per unit area

The area enclosed by each depth profile of gross photosynthesis is a measure of the hourly rate of integral photosynthesis ($\sum$**A,** g O_2 m^{-2} h^{-1}). Values determined by Grid Enumeration Analysis (Olson, 1960) are shown in Fig. 5, above and **Appendix 9**. Hourly integral rates of gross photosynthesis of Lake Hora-Areside ranged from 0.41 to 2.0 g O_2 (≈ 0.128 to 0.62 g C) m^{-2} h^{-1}. The seasonal peak of hourly integral was associated with one of the high values of A_{max} while the highest observed A_{max} corresponded to the seasonal minimum hourly integral of gross photosynthesis.

Hourly integral rates (g O_2 m^{-2} h^{-1}) of more or less similar extent were recorded for Lakes Ziway (0.3 - 1.6, Girma Tilahun, 1988) and Chamo (0.36 -1.72; Eyasu Shumbulo, 2004) in Ethiopia. All the hourly integrals estimated for Lake Hora-Arsedi are within the range for most African lakes (0.1-3.0 g O_2 m^{-2} h^{-1}, Vareschi, 1982). A much higher value was, however, reported for the other Bishoftu crater lake with a much larger photosynthetic biomass, Lake Arenguade ((1.43 - 2.56; 917-2170 mg Chl a m^{-3}, Talling *et al.*, 1973).

The daily integral rates of gross photosynthesis (**ΣΣA**; g O_2 m^{-2} d^{-1} **)** were also estimated for Lake Hora-Arsedi from the hourly-integrals. The hourly integrals were multiplied by the number of hours of sunshine commonly used for tropical lakes (10) and then the product was multiplied by the empirically derived factor of 0.9 used by Talling (1965) for other East African Lakes. The daily integral photosynthetic rates estimated accordingly ranged from 3.0 to 18.0 g O_2 (≈ 0.94 to 5.62 g C) m^{-2} d^{-1} (Fig.5 and **Appendix 9**).

Daily integral rates (in g O_2 m^{-2} d^{-1}) of similar magnitude have been reported for the productive shallow lakes, Lakes Ziway (3.1-17.8; Girma Tilahun, 1988) and Chamo (3.8 to 18.58; Eyasu Shumbulo, 2004) in Ethiopia and Lake Naivasha (18.58; Ganf and Viner, 1973) and other freshwater lakes (3.2 to 20.0; Melack and Kilham, 1974) in Kenya.

1. GENERAL DISCUSSION

Lake Hora-Areside is a subsaline and fairly deep eutrophic lake with moderate transparency, which supports a phytoplankton community dominated primarily by blue-green algae although diatoms and green algae are quantitatively important during the minor and major rainy seasons. The dominance of blue-green algae in Lake Hora-Arsedi seems to be favored by the deep-seated and stable thermal stratification, which was reported to persist for a major portion of the growing season phytoplankton.

Lake Hora-Areside has obviously been affected by anthropogenic impacts in the last few decades as the increase in Chl *"a"* concentration (mg m^{-3}) from 5 (Habte Jebessa, 1994) to over 50 of the present study seem to suggest. The lake is in the middle of a fast-growing city and its shores are being used continuously for washing clothes, watering animals and swimming. Furthermore, there are farm plots in the immediate surroundings of the lake on which fertilizers are applied. These human activities obviously constitute some of the major sources of nutrients for the lake.

Even though the extent and patterns of temporal dynamics of biological parameters have not generally been documented, it is normally assumed that there is a tendency towards limited variability in the equatorial region (Talling and Lemoalle, 1998). With a view to determine the extent of monthly variability in the rates of phytoplankton production per unit area in Lake Hora-Arsedi, the coefficient of variation (CV = standard deviation/mean: Melack, 1979a) was used as an index. The calculated CV (42 %) places Lake Hora-Arsedi, under patter **A** of Mealck (1979a) with

Lake Chamo from Ethiopia and lakes Naivasha Crater Lake and Oloiden in Kenya, in which production rates varied in approximate correlation with dry and rainy seasons. Phytoplankton biomass and production varied spatially and temporally in Lake Hora-Arsedi. The temporal variations in phytoplankton biomass and production are the result of the interplay of physico-chemical and biological factors. Physical stratification/mixing seem to determine the temporal variations in phytoplankton biomass through their effect on species composition as related to the susceptibility of algae to grazing. Although molybdate reactive silica and phosphate are fairly high, nitrate may be limiting to algal growth at least during periods of high phytoplankton density and prolonged physical stratification. Zooplankton grazing also seems to regulate the phytoplankton biomass during the minor and major rainy seasons.

7. RECOMMENDATIONS

The filamentous and colonial blue-green algae seem to be responsible for the generally high algal biomass observed in the lake. The persistence and dominance of blue-green algae are signs of cultural eutrophication of water bodies. Since the luxurious growth of these algae can lead to unpredictable consequences, efforts should be made to prevent further degradation of the aquatic ecosystem. Based on the results obtained during the study period, the following recommendations are made:

- **Public education is one of the most effective preventive methods regarding water quality problems. The public should be educated about the importance of aquatic ecosystems and the need to protect them for our very existence. The public should be advised not to produce wastewater without safe and sanitary means for their disposal as the runoff that comes from private holdings picks up nutrients and toxic chemicals on its way to the lake.**
- **The data on water column stratification/mixing and its importance to phytoplankton dynamics is far from being adequate. Future investigations on Lake Hora-Arsedi should, therefore, include measurements of temperature, dissolved oxygen, and concentration of inorganic nutrients down to the deeper parts of the water column.**

- **Future investigations on the water chemistry of Lake Hora-Arsedi should consider a look into the importance of the exchange of nutrients between the sediment and the overlying water so as to complement the existing chemical data and provide a better picture of the significance of inorganic nutrients in controlling the dynamics, of biomass and production of phytoplankton in the lake.**

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APPENDICES

Appendix 1. Mean monthly air temperature, monthly rainfall and Monthly wind speed in Lake Hora-Arsedi.

Months	Mean monthly air temperature (^{0}C)		Monthly total rainfall (mm)	Monthly wind speed (m/s)
	Minimum	**Maximum**		
July 2005	13.0	24	168	1.2
August 2005	**13.6**	**24.8**	**186.7**	**1.1**
September 2005	**12.6**	**25.6**	**153.3**	**1.0**
October 2005	**8.2**	**26.9**	**-**	**1.6**
November 2005	**7.4**	**25.9**	**2.9**	**1.9**
December 2005	**3.5**	**25.9**	**-**	**1.7**
January 2006	**7.8**	**27.1**	**5**	**1.7**
February 2006	**10.3**	**28.3**	**108.8**	**1.7**
March 2006	**10.5**	**27.8**	**0**	**1.4**
April 2006	**10.6**	**27.3**	**77**	**1.7**

Appendix 2. Equation of Talling and driver (1963) used to estimate Chl “a” in Lake Hora-Arsedi.

$$\text{Chl “a” } \mu g/L = \underline{13.9 \text{ x } (E665- E750) \text{ X } Ve}$$

Vsf x PL

Where E_{665} =Extinction at 665 nm

E_{750} = Extinction at 750 nm

Ve = Volume of extract

Vsf = Volume of sample filtered (in liters)

PL = Path length of the cuvette (1cm)

Appendix 3. Depth profiles of temperature in Lake Hora-Arsedi.

	Depth (m)	Date of Record							
		20/7/'05	27/8/'05	7/9/'05	14/10/'05	28/10/'05	18/11/'05	14/12/05	08/01/06
Station (C)	0.0	29.2	30.0	30.0	28.7	23.1	23.1	23.1	25.
	0.25	30.0	30.0	28.8	28.7	25.5	23.3	23.6	23.9
	0.5	30.5	30.0	28.8	28.8	25.5	23.4	23.6	23.4
	0.75	30.6	30.0	28.8	28.8	24.6	23.4	23.6	22.70
	1.25	29.0	29.3	28.7	28.7	24.2	23.5	23.5	22.3
	1.75	28.8	28.9	27.5	28.6	23.8	23.5	23.1	22.1
	2.25	27.0	28.9	27.5	28.6	23.7	23.5	22.8	21.0
Station.(Sh)	0.0	30.1	28.7	28.7	28.7	25.5	23.1	26.3	24.4
	0.25	30.0	28.8	28.7	28.7	25.4	23.5	25.2	23.8
	0.5	30.0	28.8	28.8	28.8	25.3	23.6	24.6	23.3
	0.75	30.6	28.8	28.8	28.8	25.3	23.6	24.0	23.0
	1.25	29.3	28.7	28.7	28.7	25.0	23	23.1	22.4
	1.75	29.3	28.7	28.0	28.7	23.0	23	22.7	22.2
	2.25	28.0	28.7	28.0	28.7	23.0	22.0	22.7	21.9

Appendix 4. Depth-profiles of dissolve oxygen in Lake Hora-Arsedi.

	Depth (m)	Date of Record							
		20/7/ '05	27/8/ '05	7/9/ '05	14/10/ '05	28/10/ '05	18/11/' 05	14/12/ 05	08/01/ 06
Station (C)	0.0	10.93	11.5	7.0	11.36	11.6	7.23	6.5	8.2
	0.25	17.15	11.43	7.1	11.23	11.2	7.93	9.9	8.6
	0.5	17.34	11.5	7.3	10.8	10.8	9.9	9.7	10.0
	0.75	20.34	11.42	7.3	10.6	10.6	9.7	11.8	20.7
	1.25	17.0	11.26	7.3	10.5	10.5	11.8	12.7	19.0
	1.75	17.0	10.96	7.2	10.1	10.1	12.7	9.3	10.5
	2.25	7.6	10.63	7.2	9.8	9.8	9.3	3.4	9.0
Station.(Sh)	0.0	6.6	7.0	7.2	8.0	6.1	7.2	8.0	7.4
	0.25	8.3	9.1	9.0	8.1	6.2	9.0	8.1	12.4
	0.5	8.3	8.3	9.1	8.3	6.2	9.1	8.3	12.7
	0.75	8.4	7.3	9.2	7.3	6.7	9.2	7.3	6.7
	1.25	8.5	7.3	9.0	7.3	6.5	9.0	7.3	5.6
	1.75	7.3	7.3	9.0	6.5	6.5	9.0	6.5	4.5
	2.25	7.3	7.0	8.0	5.5	6.4	8.0	5.5	4.0

Appendix 5. Equations used to estimate mean vertical extinction

Coefficient (K_d) and euphotic depths (Z_{eu}) in Lake Hora-Arsedi.

According to Holmes (1970)

$$K_d = \frac{1.44}{Z_{SD}}$$

where Z_{SD} is Secchi depth (m)

According to Kalff (2002)

$$Z_{eu} = \frac{4.6}{K_d}$$

Appendix 6. Concentration of inorganic nutrients at the Central (C) and near -shore (Sh) stations in Lake Hora-Arsedi.

Sampling Date	NO_3N (µg/L)		PO_4-P (µg/L)		SiO_2 (mg/L)	
	C	Sh	C	Sh	C	Sh
20/7/'05	10.4	15.0	49.6	49.76	17.48	15.76
27/8/ '05	16.4	15.0	48.12	21.79	30.5	46.77
7/9/ '05	20.0	20.5	20.15	36.6	47.57	45.43
14/10/ '05	11.4	10.7	60.5	65.5	44.09	44.66
28/10/ '05	10.7	10.2	26.73	33.31	46.96	44.6
18/11/'05	10.3	10.0	38.25	33.31	37.39	35.48
14/12/'05	14.5	20.0	30.02	26.73	38.16	39.3
08/01/06	10.0	10.0	69.5	57.99	46.39	45.24
19/01/06	10.0	11.0	16.86	46.77	46.77	46.2
4/2/2006	11.0	12.0	31.5	36.2	42.5	45.0
22/2/2006	12.0	13.0	42.5	45.5	45.5	47.0
2/3/2006	11.0	11.0	48.0	49.0	45.0	47.1
26/03/06	8.0	9.0	35	42.0	33.0	36.0
29/04/06	10.0	12.0	30.2	35.0	30.0	33.0

Appendix 7. Phytoplankton biomass as chl “a” at the Central(C) and near-shore (Sh) Stations.

Sampling Date	B (Chl a) [µg l^{-1} (mg m^{-3})	
	Stations	
	C	Sh
20/7/05	19.11	26.06
27/8/05	34.76	55.6
7/9/2005	38.5	43.4
14/10/05	31.92	45
28/10/05	45	55.6
18/11/05	27	21.5
14/12/05	39.6	32.7
8/1/2006	41	44.5
19/01/06	47.26	53.15
4/2/2006	33.36	23.6
22/2/06	45.6	48
2/03/06	22.32	27.90
26/03/06	21.5	21.5
29/04/06	20.5	26.0

Appendix 8. Statistical relations among physico-chemcial and Biological parameters.

X (dependent Variable)	Y (independent variable)	r	R^2	Regression equation	P
Z_{SD}	B	-0 .16			
pH	TA	0.06	0.038	TA = 39.8 - 2.04 pH	0.50
B	NO_3-N	0.31	0.094	B=21.9+0.974 NO_3-N	0.56
B	PO_4-P	- 0.22	0.05	B= 39.2 - 0.148 - PO4-P	0.426
B	SiO_2	0.69	0.482	B = 2.80 + 0.777 SiO_2	0.65
A_{max}	B	0.074	0.005	Amax = 836 + 1.49B	0.202
A_{max}	P_{max}	0.43	0.185	Amax = 663 + 7.79 Pmax	0.145
∑A	Biomass	0.063	0.004	∑A =1.02+ 0.0030 B	0.84
Biomass	P_{max}	- 0.77		-	

Appendix 9. Phytoplankton biomass, photosynthetic parameters

and integral rates of gross photosynthesis of phytoplankton at the Central (C) and near-shore Stations in Lake Hora-Arsedi.

Sampling Date	B (mg Chl a m^{-3})	A_{max} (mg O_2 m^{-3} h^{-1})	P_{max} mg O_2 (mg Chl $a)^{-1}$ h^{-1}	ΣA (g O_2 m^{-2} h^{-1}	ΣΣA (g O_2 m^{-2} d^{-1})
20/7/'05	19.11	1009.	52.8	1.6	14.4
27/8/ '05	34.76	977.9	28.1	1.9	17.1
7/9/ '05	38.5	1009.5	26.2	1.3	11.7
14/10/ '05	31.92	1009.5	31.6	2.0	18.0
28/10/ '05	45	788.6	17.5	1.4	12.6
18/11/'05	27	473.2	17.5	0.56	5.0
14/12/'05	39.6	1230.2	31.1	0.41	3.7
08/01/06	41	804.4	19.6	0.85	7.9
19/01/06	47.26	1009.5	21..4	1.02	9.18
4/2/2006	33.36	946.4	28.3	1.0	9.0
22/2/2006	45.6	622.4	13.6	1.2	10.8
2/3/2006	22.32	946.4	29.3	0.68	6.12
26/03/06	21.5	630.9	36.7	0.87	7.8
29/04/06	20.5	946.9	46.2	0.95	3.0

Appendix 10. pH, Conductivity, Alkalinity and Concentration of inorganic nutrients for Lake Hora from the present study and Prosser et al. (1968).

Chemical Parameter / Water body	pH	(K$_{25}$ (μScm^{-1})	TA (meq l^{-1})	NO$_3$-N (μg l^{-1})	PO$_4$-P (μg l^{-1})	SiO$_2$ mg l^{-1}	Source
Lake Hora	**9.2**	**2350**	**26.8**	**5**	**5**	**55**	**Prosser *et al.* (1968)**
Lake Hora **Central station** **Near-shore station**	 **9.02** **9.41**	 **2. 22** **28** **2237**	 **21.4** **21.9**	 **11.8** **12.8**	 **39.07** **41.39**	 **39.38** **40.8**	 **This study** **This study**

Table 11. Measurements of chemical and biological parameters on Lake Hora as reported by various authors.

Parameter	**Date of sampling**	**Depth sample was collected (m)**	**Value**	**References**
K_{25} (µS cm^{-1})	**July-66** **Feb.-64** **March-May, 1991,**	**0** **0** **0**	**2309** **2401** **2166**	**Wood and Prosser (1968)** **Wood and Talling (1988)** **Zinabu Gebre-Mariam *et al*., (2002)**
Soluble Reactive-P (mg l^{-1})	**July-66** **March-May, 1968,** **1999-2000**	**0** **0** **0**	**<0.005** **<0.005** **<0.005**	**Wood and Prosser (1968)** **Prosser *et al.* (1968)** **Zinabu Gebre-Mariam (1994)**
Nitrate-N (mg l^{-1})	**Feb.90.** **March-May, 1983**	**0** **0**	**<0.005** **<0.005**	**Wood and Prosser (1968)** **Zinabu Gebre-Mariam (1994)**
Chlorophyll "a"(µg l^{-1})	**April, 1992** **July, 91**	**0** **0**	**30** **49**	**Zinabu Gebre-Mariam and Taylor(1997)** **Zinabu Gebre-Mariam(1994)**
Silica (mg l^{-1})	**Dec, 68** **July, 91**	**0** **0**	**55** **55**	**Wood and Prosser (1968)** **Zinabu Gebre-Mariam (1994)**