PHYTOPLANKTON PRODUCTION IN LAKE ARENGUADE (HORA-HADO), ETHIOPIA.

A Thesis Presented to the School of Graduate Studies
Addis Ababa University

In Partial fulfillment of the requirements for the degree of Masters of Science in Biology

By

Misgina Belachew

June, 2010

Content **Page**

Acknowledgments…….…….. i
List of tables ……..…… ii
List of figures……..iii
List of appendices ……..……iv
Abstract ……..... v
1. Back ground and justification.....…...1
2. Objectives……...……..…….. 3
2.1. General objectives …….…….……....……..3
2.2. Specific Objectives …… …….……..3
3. Description of the study area …….…….4
4. Materials and Methods ……..…..……..6
4.1. Sampling protocol ……...…….……6
4.2. Measurement of physico- chemical parameters in the filed ……...……7
4.3. Analysis of inorganic nutrients.……..….7
4.4. Measurement of Biological parameters ……...……7
4.4.1. Species composition and phytoplankton abundance……....…….7
4.4.2. Biomass as chlorophyll-a concentration……...…8
4.4.3. Primary production …….. 8
4.5. Statistical analysis ……..….8
4.6. Description of symbols ……9
5. Metrological data …….…..….9
6. Results and discussions …….……12
6.1. Physico-chemical features …….……12
6.1.1. Physical features ……12
6.1.2. Thermal regime ……...13
6.2. Chemical features ……...…16
6.2.1. Dissolved oxygen ……16
6.2.2. Alkalinity and pH ……18
6.2.3. Inorganic nutrients....……..……...……..20
6.3. Biological features …….……23

6.3.1. Taxonomic features …….23
6.3.2. Phytoplankton biomass ……...……25
6.3.3. Stratification of phytoplankton biomass.……...……..……26
6.3.4. Photosynthetic primary production.…….…...…….27
6.3.5. Photosynthetic characteristics…… ……..…….30
6.3.6. Production rate per unite area …….34
6.3.7. Models relating daily integral rates of photosynthesis and euphotic zone chlorophyll – a ……35
6.3.8. Zooplankton……37
7. Conclusion and recommendation ……..……38
8. Reference……...……40

Acknowledgment

I would like to express my special gratitude to my research Advisor, Dr. Demeke Kifle for encouragement, adviser and unreserved guidance and help up to the eleventh hour to the completion of this paper. I would also like to thank the Ziway Fishery Research Center for facilitating transportation and field technician. My special thanks also goes to the hard working driver, Tagi and also to Lemma and Dawite, all from Ziway Fishery Research Center.

I would like to thank the Department of Biology for providing me this opportunity to study. Finally, my thanks also goes to my instructors and graduate students in Fisheries and Aquatic Sciences Stream, and also to Menbere (lab technician) and Baye (PhD. Student).

LIST OF TABLES **Page**

Table 1. Chemical features of Lake Arenguade. Units are ppm unless indicated Otherwise……..……6

Table 2. The physical characteristics of Lake Arenguade. …..... ……. 13

Table 3.List of Phytoplankton taxa identified in samples from Lake Arenguade….. ….24

Table 4. Phytoplankton biomass measured as chlorophyll a concentration in different lakes. (Source: Zelalem Dessalegne, 2007). ……..……26

Table5. Light-saturated rates of gross photosynthesis (Amax) and specific-rates of gross photosynthesis at light-saturation (ϕ_{max}, mg O_2 (mg Chl a)$^{-1}$ h^{-1}) for different lakes. ……..…….....33

Table 6. ΣΣA and ΣB computed using measurements made by Talling et al. (1973).....36

Table 7. Measurements of ∑∑A and ∑B of Lake Arenguade……37

Table 8. Zooplankton…….……..…….38

LIST OF FIGURES **Page**

Fig.1. Map showing the location of the study lake ((Arenguade) …….5

Fig.2. Temporal variations in monthly rainfall mean monthly maximum (closed circle) and minimum (open circle) air temperature in the study lake's region. …...……. 11

Fig.3. Some Depth profiles of temperature in Lake Arenguade……...……15

Fig. 4 - Oxygen depth profiles of Lake Arenguade. …….……17

Fig.5.Temporal variations in total alkalinity (TA, closed diamond), phenolphthalein alkalinity (PA, closed circle), DIC (X) in relation to chlorophyll a (closed star) in Lake Arenguade. …….…….19

Fig.6. Temporal variations in the concentrations of inorganic nutrients (closed circle) in relation to phytoplankton biomass (open circle) in Lake Arenguade……...……..21

Fig .7. Temporal variations in the abundance of Spirulina platensis (open circle) and Anabaenopsis elenkinii (closed circle) in Lake Arenguade. ……. 24

Fig. 8- Temporal variations in phytoplankton biomass (closed circle) and Secchi depth (open circle) in Lake Arenguade. …….. 25

Fig. 9. Stratification of phytoplankton in Lake Arenguade on June 1, 2010 ……27

Fig.10. The depth profiles of gross photosynthetic rates in Lake Arenguade. ….....29

Fig.11. Temporal variations in Light-saturated rat of gross photosynthesis ($A_{max,}$ mg O_2 m^{-3} h^{-1}), Hourly integral rates of gross photosynthesis (g O_2 m^{-2} h^{-1}) in relation to chl a biomass (mg m^{-3}) and seccchi depth (m). ……..…… 31

.

LIST OF APPENDICES

APPENDIX I. Formulae used for the estimation of physical, chemical and biological parameters.

APPENDIX II. Collective chemical features of Lake Arenguade: pH, Total Alkalinity (TA), Phenolphthalein Alkalinity (PA) and calculated dissolved inorganic carbon (DIC) of Lake. Arenguade.

APPENDIX III. Statistical relationships among physico-chemical and biological parameters measured in Lake Arenguade.

Abstract.

Dynamics of Chl a biomass, abundance amd photosynthetic production of phytoplankton in relation to some phyico-chemical factors were studied in Lake Arenguade from December, 2008 to October, 2009. Water transparency in Lake Aranguade varied from 0.21 to 0.37 indicating the shallowness of the trophogenic zone owing to high turbidity, which seems to be largely of biological origin. Depth profiles of temperature showed the occurrence of a superficial type of thermal stratification which is created by solar heating and destroyed by nocturnal cooling although oxygen depth profiles determined on two days seem to sugggsest the formation of stable and deep-seated thermal stratification at times. Total Alkalinity of the lake ranged from 33 to 50.6 while pH varied from 9.62 to 9.84. SRP, nitrate and silica varied temporally from about 702 to 2123 µg $L^{-,1}$, 4.1 to 78 µg L^{-1} and 3.5 to 37.3 mg L^{-1}, respectively. The phytoplankton community of Lake Arenguade was co-dominated by two species of blue-green anlgae, Spirulina platensis (Arthospira fusiformsi) and Anabaenopsis elenkinii, chl a biomass of phytoplankton varied temporally ranging from 41.7 to 271 mg L^{-1} and with peaks coinciding with those of phosphate and silicate and low levels of nitrate. The depth-distribution of gross photosynthesis per unite water volume (A, mg C m^{-3} h^{-1}) exhibited the typical pattern for phytoplankton with maximum production rates at depths below the surface on most sampling dates.The light-saturated rate of gross photosynthesis (A_{max}), which ranged from 76.14 to 650 mg C (243.64–2080 mg O_2) m^{-3} $h^{-1.}$ was positively but modestly (r=0.53, r^2=0.28 at p=0.061) correlated with Chl a biomass. Biomass-specific rates at light-saturation (ϕ_{max}, photosynthetic capacity) ranged from 2.3 to 13.2 mg O_2 (mg Chl a)$^{-1}$ h^{-1} with most values between 8 and 11 mg O_2 (mg Chl a)$^{-1}$ h^{-1}. Hourly integral rates of photosynthesis (ΣA) ranged from 0.13 to 1.67 g O_2 m^{-2} h^{-1}. The seasonal peaks of hourly integral rates were associated with peaks of chlorophyll a concentration and light-saturated rate of gross photosynthesis (A_{max}). The correlations between hourly integral rates and chlorophyll a concentration (r=0.53, r2=0.28 at p=0.06 and A_{max} (r = 0.78, r^2=0.62 at p=0.0014), were positive and strong. The causal relationship between biological parameters and physico-chemical variables are examined and discussed.

Background and Justification

Tropical Africa contains the world most productive ecosystems (e.g., Lake Arenguade, $30gO_2m^{-3}h^{-1}$,Talling *et al*., 1973; Lake Nakure, $36g\ O_2m^{-2}\ d^{-1}$, Melack, 1981) favored not only by high solar irradiance and high temperature, but also by the high efficiency of nutrient use, which allows primary production of alga to reflect the favorable irradiance and temperature (Lewis, 2000).

Alkaline saline lakes have tremendous potential as a source of harvestable and cultivable algal resources (e.g. *Spirulina/Arthrospira*) and unique thermophilic microbial communities (Seyoum Mengistou, 2006). The blue-green alga *Spirulina,* which was recommended as a suitable protein source to combat malnutrition and protein deficiency in developing countries (Fox, 1996; Henrikson, 1989), grows abundantly forming an almost uni-algal phytoplankton community in some alkaline lakes of East Africa including such Ethiopian lakes as the present study lake, Arenguade (Talling *et al*., 1973; Talling and Lemoalle, 1988; Elzabeth Kebede, 2002; Demeke Kifle *et. al*., manuscript in preparation) and Lake Chitu.

Human population is increasing in the world where food production is not meeting demands, indicating the indispensability of productivity studies at all levels of the food chain (Henderson *et al*., 1973). Phytoplankton primary production transforms solar energy and inorganic substances into organic material, with significant implications not only for phytoplankton biomass, but also for the cycling of oxygen, carbon dioxide, nutrients, trace elements and suspended mater (Chan *et. al*., 2002). Melack (1976) and Oglesby (1977) have also concluded that primary productivity is, theoretically and empirically, a better predictor of fish yield in lakes than other suggested indices. Both authors provided linear regression equations relating fish yield and primary productivity. Other methods of relating fish yield to nutrient concentration and primary productivity (Henderson *et al*., 1973; Ryder, 1974, cit. Zelalem, 2007) reinforced the concept of the dependence of potential fish yield on lake's primary productivity.

Primary production by phytoplankton is affected by a number of physico-chemical factors and their interaction. Light and thermal regimes are among the physical factors that can directly influence physiology and species composition of phytoplankton (Franks and Anderson, 1992). For example, blooms of blue-green algae are favored by high

temperature of the warmer months of the year and prefer stable water conditions with low flows, long retention times, light wind and minimum turbulence as buoyancy regulation and vertical positioning work best under stable conditions (Bartram and Chorus, 1999).

Primary production is influenced not only by solar irradiance and temperature, but also by the availability of nutrients. In fact, persistent nutrient depletion could nullify the favorable effects of temperature and irradiance; a nutrient-limited tropical lake would sustain no more net primary production than a temperate lake with a similar degree of nutrient limitation. Tropical lakes are favored not only by high solar irradiance and high temperature, but also by high efficiency of nutrient use. Under nutrient-limiting conditions, the ability of a lake to sustain primary production is determined by recycling mechanisms. Recycling mechanisms within the mixed layer occur more rapidly at low latitude because of sustained high temperature. Furthermore, nutrients lost from the upper mixed layer are much more likely to be returned to the euphotic zone of a tropical lake within a given stratification season because of the dynamic nature of the mixed layer (Lewis, 2000). Cyanobacterial dominance in tropical lakes is attributed to low CO_2 under high pH conditions, low nitrate concentration and low N **:** P ratio (Elizabeth Kebede *et. al*., 2002).

Biomass (the mass or weight of all living material in a unit area at a given instant in time) evaluations are essential in any analysis of aquatic population or of production dynamics (Wetzel, 2001). Phytoplankton biomass and succession are of particular interest due to their position in the food web, and the adverse effects phytoplankton blooms may have on water quality and aquatic biota. An understanding of the process affecting phytoplankton biomass and succession is required to predict and manage the occurrence of potentially harmful blooms (Chanu *et.al*, 2002).

The absence of marked variation in the duration of light and temperature does not rule out the existence of distinct seasonal cycles in tropical lakes (Talling, 1986), as these water bodies are remarkably affected by the wind regime and seasonal pattern of rainfall in their basins. In addition to this, tropical lakes may also exhibit marked diurnal fluctuations governed by a combination of local and sometimes short-term environmental changes, as demonstrated by Talling *et. al* (1973) and Wood *et. al*.(1976) for Lake Arenguade. Seasonal mixing of tropical lakes is relatively brief (typically not more than 2

months) and is often interrupted by periods of water column stability during which phytoplankton biomass may be regenerated through rapid photosynthesis near surface (Lewis, 1990). Thus, seasonal mixing and intermittent stability that is favored by high rate of density change with heat uptake at the warm temperatures of low land tropical lakes together ameliorate the most severe suppression of biomass in temperate lakes. This effect contributes to the tendency of tropical lakes to have a higher minimum biomass in tropical lakes (Lewis, 1990).

Although Limnology in the tropics has only recently developed past the age of exploration (Melack, 1996 Talling and Lemoalle, 1998), many studies have been conducted on the composition, distribution and production of phytoplankton in various Eastern African lakes (Talling and Lemoalle, 1998) . Very little has, however, been done on this aspect in Ethiopian lakes (Wood and Talling, 1988; Tudorancea *et. al*., 1999). Lake Arenguade is no exception. Although phytoplankton biomass and primary productivity in this lake were investigated over an extended period (Demeke Kifle *et al*., unpublished data), the study did not include measurements of environmental factors of overriding importance to the ecophysiology of phytoplankton- nutrients and underwater irradiance-owing to lack of facilities.

In this study, results of abundance, biomass and primary productivity of phytoplankton of Lake Arenguade in relation to some physico-chemical variables are presented.

2. Objectives.

2.1. General Objective

- To investigate the ecological status of Lake Arenguade.

2.2. Specific objectives

- To estimate temporal changes in phytoplankton primary productivity.
- To asses temporal changes in phytoplankton biomass.
- To estimate the abundance of major phytoplankton taxa.
- To asses changes in the physico-chemical quality of the lake water over the study period.

3. DESCRIPTION OF THE STUDY AREA

Lake Arenguade (Fig. 1) is a member of an extensive series of volcanic explosion crater lakes –Bishoftu crater lakes– situated some 47 kms South East of Addis Ababa at a latitude of 8^{o}41.856' N and 038^{o}58.796' E and an altitude of about 1900 m, above sea level. The lake is without an obvious outlet and inlet, is well protected by a crater wall rising steeply from the lake shore and forming an almost continuous rim some 200 m from the water level (Prosser *et al*., 1968; Tenalem Ayenew, 2009). Lake Arenguade is an alkaline soda lake with a diameter of approximately 800m (Klemperer and Cash, 2007) and maximum and mean depth of 32 and 18 m respectively (Prosser *et al*., 1968).

Lake Arenguade was so named (Arenguade means green in Amharic language) after the green coloration of surface waters by the filamentous blue-green alga *Spirulina platensis*, which in some years sustains a large breeding population of lesser flamingoes. Local people use the lake for laundry and ablutions, watering their cattle at the fresh water springs feeding the lake (Seyoum Mengistou *et al*., 2003, cit. in Klemperer and Cash, 2007), and even encourage their cattle to drink the lake water believing that the *Spirulina* water has some therapeutic effects and compensates for some lack in the diet of their cows (Elizabeth Kebede, 1997).

Limnological investigations made on Lake Arenguade include those on bathymetry and/or water chemistry (Prosser *et al*., 1968; Rippey and Wood,1985; Zinabu Gebre-Mariam,1994), thermal regime (Baxter *et. al*., 1965: Wood et al., 1976), phytoplankton biomass (Zinabu Gebre-mariam,1994) and, zooplankton community structure and dynamics (Afeworki Gebrai, 1992) and grazing rates of zooplankton (Habte Jebessa,1994).The only study for an extended period on phytoplankton biomass and primary production in Lake Arenguade, which was conducted by Demeke Kifle *et al*.(unpublished), did not include measurements of nutrients and light. The purpose of the present study was, therefore, to investigate the biomass and primary production of phytoplankton in relation to some environmental factors including nutrients in Lake Arenguade. Some data on the chemical conditions of Lake Arenguade are presented in Table 1

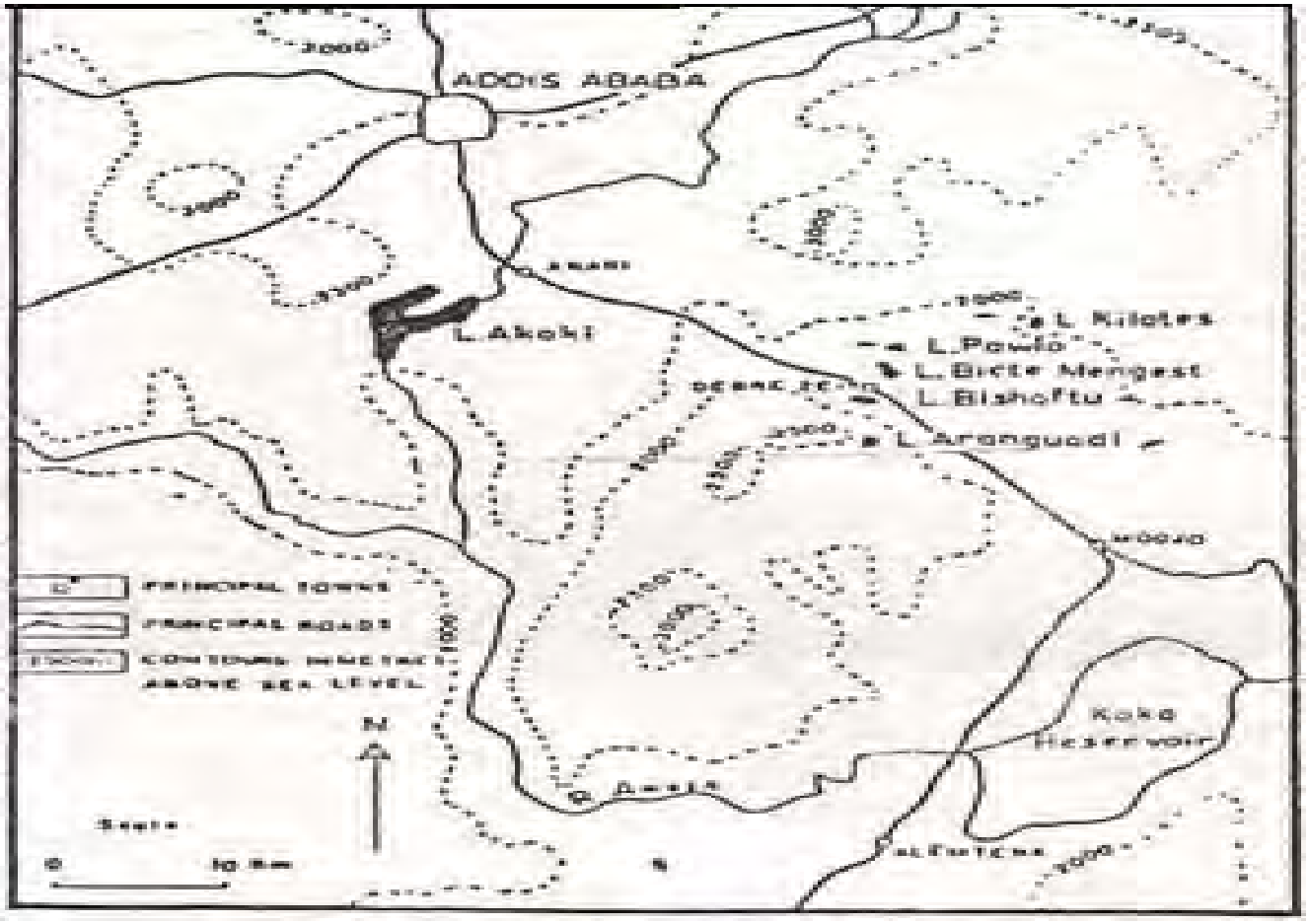


Fig.1. Map showing the location of Lake Arenguade in relation to other Bishoftu crater lakes.



A Photo of Lake Arenguade by Baye Sitotawe, Jan. 2010.

Table1. Chemical features of Lake Arenguade. Units are ppm unless indicated otherwise.

Chemical parameters	Quantity	Sampling date	Sources
Total dissolved solids (g L^{-1})*	5.82	April 1963	Prosser *et al*. (1968)
Ca^{2+}	13.43	April 1963	Prosser *et al*. (1968)
	14.03	Feb.1964	Wood and Talling (1998).
	16.0	April 1992	Zinabu Gebre-mariam (1994)
	6.96	Jan. 2003	Klemperer and Cash (2007).
Li^{+}	0.01	Jan. 2003	Klemperer and Cash (2007).
Mg^{+}	< 7	April 1963	Prosser *et al*. (1968)
	6.08	Feb.1964	Wood and Talling (1998).
	4.86	April 1992	Zenabu Gebre-mariam(1994)
	7.67	Jan. 2003	Klemperer and Cash (2007).
Na^{+}	1540	April 1963	Prosser *et al*.(1968)
	1500	Feb.1964	Wood and Talling (1998).
	1360	April 1992	Zinabu Gebre-mariam (1994).
	1350	Jan. 2003	Klemperer and Cash (2007).
K^{+}	317	April 1963	Prosser *et al*. (1968)
	375	Feb.1964	Wood and Talling (1998).
	450	April 1992	Zenabu Gebre-mariam (1994)
	190.67	Jan. 2003	Klemperer and Cash (2007).
Cl^{-})	780	April 1963	Prosser *et al*. (1968)
	606	Feb.1964	Wood and Talling (1998).
	780	April 1992	Zenabu Gebre-mariam (1994)
	388	Jan. 2003	Klemperer and Cash(2007)
SO_4^{2-}(	34	April 1963	Prosser *et al*. (1968)
	269	Feb.1964	Wood and Talling (1998).
	2	April 1992	Zinabu Gebre-mariam (1994)
	15	Jan. 2 003	Klemperer and Cash (2007).
Alkalinity (CO_3^{2-} + HCO_3^{-}) (meq L^{-1})	51.4	April 1963	Prosser *et al*. (1968)
SiO_2	50	April 1963	Prosser *et al*. (1968)
pH	10.3	April 1963	Prosser *et al*. (1968)
	10.0	April 1992	Zinabu Gebre-mariam (1994)
	9.6	Jan 2003	Klemperer and Cash(2007)
PO_4-P	3.2	April 1963	Prosser *et al*. (1968).
NO_3 +NO_2-N	< 0.005	April 1963	Prosser *et al*.(1968)

4. MATERIALS AND METHODS

4.1. Sampling protocol

To study temporal changes in the biomass and photosynthetic production of phytoplankton and abundance of major species of the phytoplankton community in relation to some chemical and physical factors in Lake Arenguade, samples were collected at least monthly from December, 2008 to October, 2009 from one offshore station (located at about the

center of the lake). Samples were taken from 0, 0.25, 0.50, 0.75 and 1m depths. Composite samples were prepared by mixing samples collected from these depths in equal proportions and used for the estimation of photosynthetic production, biomass and abundance of phytoplankton, and analysis of inorganic nutrients.

4.2. Measurement of Physico-Chemical Parameters in the Field

In the field, some physical and chemical parameters were measured on each sampling day. Water transparency was determined using a standard Secchi disc of 20cm diameter quartered alternately black and white. Depth profiles of oxygen were determined up to a depth of 20-30 m by the Winkler method, and temperature readings were taken from 0-30m depth by using a thermometer attached to a water sampler. Within two hours after sample collection, carbonate-bicarbonate alkalinity was determined by titration with 0.1N HCl using Phenolphthalein and Bromocresol green-Methyl Red indicators at the lake shore.

4.3. Analysis of Inorganic Nutrients

Nutrients were analyzed following the standard methods described in Wetzel and Likens (2000) using samples previously filtered through Whatman Glass Fibre Filters (GF/F). Orthophosphate (PO_4- P) was determined by the Ascorbic Acid method while soluble reactive silica (SiO_2) was determined by the Molybdosilicate method. The determination of Nitrate (NO_3-N) was carried out by the salicylic acid method (APHA, et al., 1999).

4.4. Measurement of Biological Parameters

4.4.1. Species composition and abundance of phytoplankton

Aliquots of composite samples were used to identify species of phytoplankton dominant on each sampling date using keys available on tropical phytoplankton (Whitford and Schumacher, 1973; Gasse, 1986; Hindak, 1992; Jeji-Bai et al., 2002; Komarek and Anagnostidis, 2005). Samples used for the identification and enumeration of phytoplankton were preserved with Lugol's iodine. 50 ml of the samples were sedimented in a graduated cylinder over five days. The supernatant was removed by a syringe leaving 20ml of the sample in the graduated cylinder. From the concentrated sample, 1 ml sub-sample was taken with an automatic pipette and transferred into a Sedgewick-Rafter cell. Algal units (filaments) within up to 70 random squares were counted with a Richart Neovar binocular microscope at a magnification of x100. The

number of algal units per ml of water sample was calculated according to Hotzel and Croome (1999).

4.4.2. Biomass as Chlorophyll-a concentration

Chlorophyll *a* (Chl *a*) concentration was estimated spectrophotometrically from samples (200ml) previously filtered using Whatman Glass Fiber filter (GF/F,). Filters containing seston were manually ground in a small volume of 90% acetone with a glass rod to enhance the extraction of chlorophyll *a*. The extracts were transferred into a centrifuge tube and centrifuged at 3000 rpm for 10 minutes. The absorbance of pigment extracts was measured against a blank at 665 and 750 nm and the concentration of chlorophyll a was calculated according to Talling and Driver (1963).

4.4.3. Primary production

Primary productivity of phytoplankton was determined by the Light and Dark Bottle Technique and the Winkler method of oxygen determination (Mackereth *et al*., 1978). Composite water samples were siphoned into light (clear) and dark (covered with black cloth) bottles. Duplicate light bottles were incubated at surface, 0.25, 0.5, 0.75 and 1m depths distributed within the euphotic zone for a period of 1.5-2 hours around mid-day (10.00 am-2.00 pm). Dark bottles were also incubated at the surface and 1.25 m depths. The bottles were attached to a suspension line prepared for this purpose. Samples in a pair of bottles were fixed with Winkler reagents immediately after incubating the light and dark bottles and used as initial bottles. At the end of the incubation period, the bottles were rapidly withdrawn along the shaded part of the boat and dissolved oxygen fixed immediately with the Winkler reagents. Treatment of bottles before and after incubation was made under a cover of dark cloth. On returning to the laboratory, samples were titrated with a standard solution of sodium thiosulphate using starch as an indicator. The concentration of dissolved oxygen in the incubation bottles was calculated according to Mackereth *et al*. (1978).

4.5. Statistical analyses

The different sets of data were analyzed statistically using Microsoft excel and Sigmaplot 10.0 softwares.

4.6. Description of symbols

Descriptions of Symbols used throughout this thesis are given below:

Z_{SD} …… Secchi depth (m)

Z_{eu} ……Depth of euphotic zone (m)

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

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

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 water volume, (mg O_2 m-3 $_h$-1).

ϕ - (A/B)……Biomass-specific rate of gross photosynthesis, [mg O_2 (mg Chl *a*)$^{-1}$ h^{-1}]

ϕ_{max} ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,Biomass-specific rate of gross photosynthesis at light-saturation or photosynthetic capacity; in mg O_2 (mg Chl a) $^{-1}$ h^{-1}

∑A……Hourly integral photosynthetic production (g O_2 m^{-2} h^{-1}).

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

5. Meteorological data of Lake Arenguade

All metrological data were obtained from National Metrological Agency of Ethiopia.Temporal variations in total monthly rainfall, monthly mean minimum and maximum air temperature are shown in Figure 2. The monthly mean minimum air temperature ranged from 7.8 ^{O}C of November, 2008 to 13.8 ^{O}C of August, 2009, while the monthly mean maximum air temperature varied from 24.5 of August 2008 to 30.2 of May, 2009.

The present lowest value of the mean monthly minimum air temperature of Lake Arenguade is considerably higher than that reported for Lake Hora (3.5 ^{O}C) by Abebaw Wondie (2006) and which occurred in December, 2005 although the lowest mean monthly maximum and the highest mean monthly minimum are remarkably similar to those recorded by Abebaw Wondie (2006) (13.6 and 24.0 respectively). The lowest

monthly mean maximum air temperature level occurred during the month with the present largest peak of precipitation, August, 2009, while the lowest monthly mean minimum was observed during the part of the year described as the dry period, indicating that the period extending from November to January is also the coldest period of the year in this lake region.

Total monthly rainfall over the study period ranged from 0.6 mm of November to 243.9 mm of August, 2009. After its abrupt decline to one of its low values in March, the monthly rainfall increased almost consistently to its seasonal maximum in August, 2009 before it declined to a lower value in October, 2009. Although the lake region was described by Baxter *et al*. (1965) as having two rainy periods, the minor one extending roughly from February to April and the major one beginning in June and ending in September, the months which were known to constitute the dry period of the study lake region (November–January) had considerable levels of precipitation (above 40 mm), which were much higher than those of months of the minor rainy period (March-May). Rippey and Wood (1985) documented that this lake area has moderate rainfall, varying around about 850 mm per annum. The present meteorological data for Lake Arenguade, however, show an 11-month period rainfall of about 618 mm.

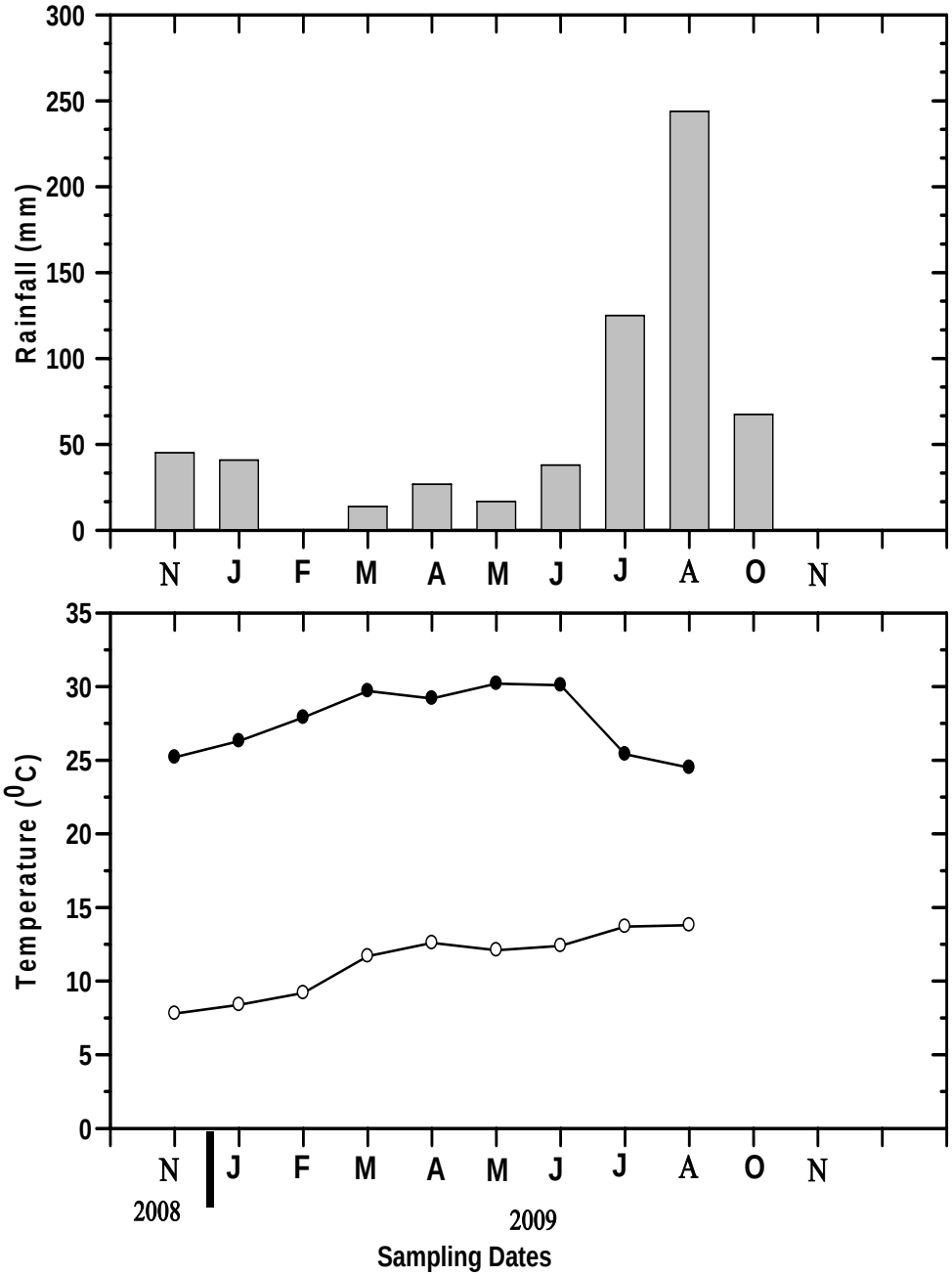


Fig. 2.Temporlal variations in monthly rainfall, mean monthly maximum (closed circle) and minimum (open circle) air temperature in the study lake's region.

6. RESULTS AND DISCUSSION

6.1. PHYSICO-CHEMICAL FEATURES

6.1.1. Physical features

The physical characteristics of Lake Arenguade recorded during the study period are given in Table 1. Lake's transparency (vertical visibility) varied between 0.21 m in June, 2009 at the beginning of the major rainy season to 0.37 m in late December, 2008 of the dry season.

Although the high Secchi depth values of Lake Arenguade are much smaller than those recorded for other lakes of the same area including Lakes Bishoftu (1.05 m, Tadesse Ogato, 2007), Hora-Kilole (0.78m, Rediat Abate, 2008) and Koriftu (0.6 m, Zelalem Desalegne, 2007), they are comparable to those recorded for water bodies of Ethiopia in which abiogenic turbidity seems to be more important in determining their underwater climate (see, for example, Adane Sirage, 2006; Hadgembes Tesfay, 2007; Amha Belay and Wood, 1984).

The temporal variations observed in the transparency of Lake Arenguade seem to be related more to changes in the extent of biomass accumulated than to the amount of suspended inorganic particles in the light of its deep water column and the protection afforded by its crater wall that may preclude the frequent occurrence of wind-driven mixing although the correlation between Secchi depth readings and phytoplankton biomass was negative but poor($r = -0.19$, $r^2 = 0.0361$ at $p=0.5349$) .

The mean vertical light extinction coefficients ($K_{d,}$ in ln units m^{-1}) estimated from secchi depths (see Appendix 1) using the widely used equation of Holmes (1970) ranged from a minimum of 4.6 to a maximum of 8.10 corresponding to euphotic depths (Z_{eu}), approximated as $Z_{eu} = 4.6/ K_d$ (Kalff, 2002), of 1 and 0.57. Euphotic depths estimated using vertical extinction coefficients calculated from Secchi depths seem to indicate that the vertical extent of the euphotic zone was almost always shallower than 1 m corroborating the previous data recorded on the optical features of the same lake by Talling *et al*.(1973) and Demeke Kifle *et al*.(unpublished).

Table 2. The physical characteristics of Lake Arenguade.

Sampling date	**Surface water temperature(^{o}C)**	**Z_{SD} (m)**	**Kd (m)**	**Zeu (m)**
1/12/08	ND	0.25	6.80	0.68
21/12/08	21.50	0.37	4.60	1.00
5/01/09	21.60	0.30	5.70	0.81
2/02/09	22.60	0.32	5.30	0.87
23/02/09	20.20	0.31	5.50	0.84
16/03/09	23.80	0.21	8.10	0.57
30/03/09	24.50	0.22	7.70	0.60
26/04/09	22.30	0.25	6.80	0.68
28/05/09	24.40	0.25	6.80	0.68
14/06/09	ND	0.21	8.10	0.57
18/07/09	ND	0.29	5.70	0.81
09/08/09	21.90	0.26	6.50	0.71
12/10/09	ND	0.27	6.30	0.73

ND = Not determined

6.1.2. Thermal regime

The surface water temperatures at the centre of Lake Arenguade ranged from a minimum of 20.2 ^{0}C in late February, 2009 to a maximum of 24.5 ^{o}C in March, 2009 with most values between 21.5 and 22 ^{o}C. The maximum surface water temperatures of Lake Arenguade were generally lower than those of the Ethiopian Rift Valley Lakes including Lakes Chamo (26-30 0C; Eyasu Shumbulo, 2004), Ziway (18.5-27.5 ^{o}C; Girma Tilahun, 1988), Abijata and Langano (18-27 ^{o}C ; Elizabeth Kebede *et al.,* 1994) and Awassa (23.8-28.4 ^{o}C) (Demeke Kifle, 1985) and other lakes of the same region as the present study lake, Lakes Babogaya (20.5-28.4 ^{o}C; Yeshiemebet Major, 2006) and Bishoftu (22.2- 25.8. Tadesse Ogato, 2007). Fig. 3 presents the vertical distribution of temperature in Lake Arenguade. The vertical distribution of temperature in Lake Arenguade shows the occurrence of differences between successive depths of the water column down to ~3.5 m.

Limnologist agree that the depth in the water column where the drop in temperature with increasing depth from the surface is less than 1^{o}C, is still within the epiliminion. But, the depth where the temperature decline becomes 1 ^{o}C per meter of depth, marks the upper limit of metaliminion. Finally, the lower limit of the metalimnion is similarly determined but in the reverse order, where the drop in temperature with increasing depth first becomes less than 1 ^{o}C per meter (Brook Lemma, 2008). Thus, Lake Arenguade had mean thickness values of 1m, 2.3m, and 28.5m of its epiliminion, metaliminion, and hypoliminion, respectively. The hypoliminion of Lake Arenguade was, thus, very thick with measured temperatures being never less than 19.6 ^{o}C on all the sampling dates. This is not surprising for a totally closed lake with sufficient protection from wind.

The study conducted on the thermal characteristics of nine East African lakes including the present study lake by Baxter *et al*. (1965) indicated that the type of thermal stratification observed in Lake Arenguade was of a superficial type, which is generated daily by solar heating and destroyed by nocturnal cooling and mixing which chiefly affects the 0-3m stratum. Detailed observations of the diurnal cycle of the thermal regime in Lake Arenguade by Baxter *et al*.(1965) between 30 October and 1 November, 1964 showed nocturnal destruction of thermal stratification coincident with rapid surface cooling that resulted in a slight degree of unstable inverse stratification. The present study seems to conform to the findings of Baxter et al. (1965) as steep thermal gradients were observed only in the 0 ~3.3m stratum. Temperature readings taken in February, 2009 indicated the existence of only a 0.6 ^{o}C temperature difference between the surface water and the water at a depth of 14m, probably indicating the occurrence of mixing the night before the measurements were taken. Baxter *et al*. (1965), in their studies on African lakes, have noted that complete mixing is normally frequent in lakes with maximum depth (Z_{max}) of less than 15-30 m and thermal stratification is largely diurnal.

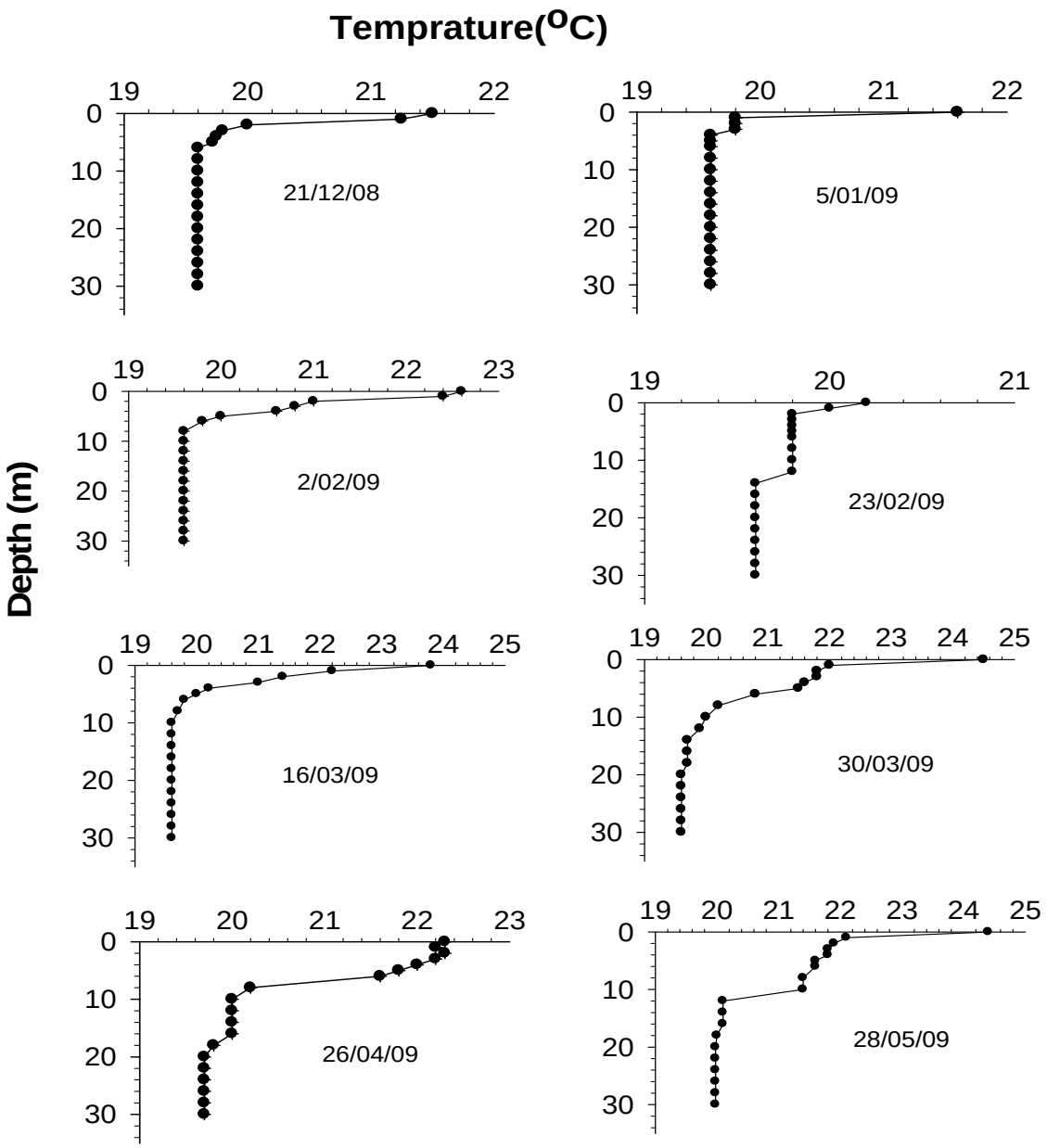


Fig.3. Some Depth profiles of temperature in Lake Arenguade.

6.2. Chemical features

6.2.1. Dissolved Oxygen

Dissolved oxygen concentration showed both spatial (vertical) and temporal variations which were presumably associated with the fluctuations in phytoplankton photosynthetic activity (related to light and photosynthetic biomass), thermal regime and changes in the weather conditions of the lake region.

Depth profiles of dissolved oxygen determined at the center of Lake Arenguade during the study period are shown in Fig 4. All depth profiles (determined by the Winkler Method) showed oxygen maximum in the upper 0-1 m layer of the water column, with a minimum of 0.40 mg O_2 L^{-1} at the surface recorded in December, 2008 and a maximum of 13.1 mg O_2 L^{-1} observed in October, 2009. The oxygen concentrations at the surface water of Lake Arenguade were generally similar to those recorded for the nearby lakes, Lake Kilole (3.4 to 10.6 mg O_2 L^{-1}; Brook Lemma, 1994), and Babogaya (2.75-15.8 mgO_2 L^{-1}; Yeshiemebet Major, 2006). Oxygen depth profiles showed maximum values at the surface of the water column on all sampling dates except on February 2 and March 30, 2009, the depth profiles of which had sub-surface maxima probably associated with high surface temperature (the seasonal maximum surface temperature was observed on 30 March, 2009) that resulted in reduced oxygen solubility and/or subsurface photosynthetic maxima due to light inhibition of photosynthesis at the lake's surface. Dissolved oxygen determinations made by a probe on August 9, 2009 and June 1, 2010 gave zero oxygen concentrations at 4 and 2.32m, respectively, indicating complete deoxygenation of the water column in the study lake below these depths.

Percentage saturation of dissolved oxygen at the surface also showed temporal variations, with values ranging from 4.42 to 181.53 % from December 21, 2008 to June 1, 2010, respectively.

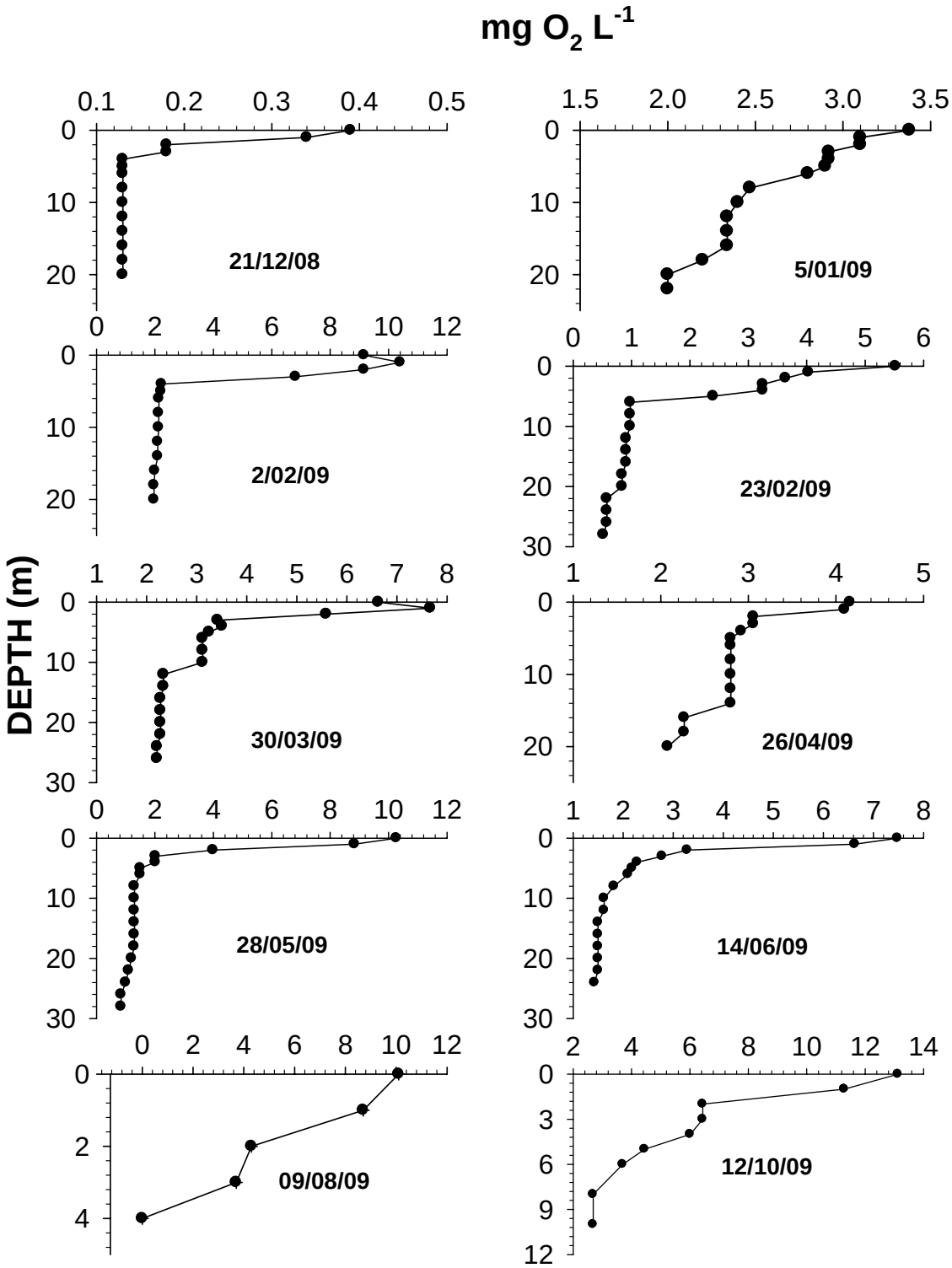


Fig. 4 - Oxygen depth profiles of Lake Arenguade.

6.2.2. Alkalinity and pH

Temporal changes in aggregate chemical parameters in relation to Chl a biomass of phytoplankton measured over the study period in Lake Arenguade are shown in Fig. 5. Total alkalinity varied temporally ranging from 33 to 50.6 meq L^{-1}, with a temporal pattern of variations similar to that of dissolved inorganic carbon (DIC, in meq L^{-1}). On most of the sampling dates, pH was not measured due to lack of facilities. pH measurements made on few sampling different days gave values that ranged from 9.62 in July, 2009 to 9.84 in August, 2009. The pH values recorded for this lake in the present study are lower than those reported in earlier investigations (10.5, Prosser *et al.*, 1968; 10, Zinabu Gebre-Mariam, 1994; 10.85, Demeke Kifle *et a*l., 1995, unpublished). The present pH values of Lake Arenguade are, however, considerably higher than those of the nearby crater lakes, Lake Bishoftu (9.2; Zinabu Gebre-Mariam, 1994) and Babogaya (8.84-9.09; Yeshiemebet Najor, 2006), Koriftu (8.2-8.8; Zelalem Dessalegne, 2007) and the Rift Valley Lake Chamo (8.53-9.44; Eyasu Shumbulo, 2004). pH values similar to those of Lake Arenguade are known from Lake Mariut in Egypt (Aleem and Samaan, 1969), and Red Rock Tarn in Australia (Hammer, 1981). High rates of primary productivity allow large daytime CO_2 and HCO_3- withdrawal leading to an increase in pH (Maberly, 1996). The high pH values of Lake Arenguade are attributed to the high alkalinity of the lake while the temporal fluctuations may be related to biological removal of inorganic carbon (Talling *et al.*, 1973; Talling and Lemoalle, 1998) considering the unusually high photosynthetic biomass supported by lake.

The level of dissolved inorganic carbon (meq L^{-1}) which was calculated using pH-alkalinity relationship (Saunders *et al.*, 1962), ranged from 8.01 in December, 2008 to 9.48 in March, 2009. The concentration of carbon dioxide in a water body is a chemical factor that plays an important role in determining phytoplankton groups that may grow and flourish. When blue-green algae dominate in lakes, carbon dioxide is taken much more efficiently than when the phytoplankton community is composed of non-blue greens (Shapiro, 1997). Thus, unusually low levels of carbon dioxide give a competitive advantage for blue-green algae over other algal groups owing to their physiological adaptation (Shapiro, 1997).

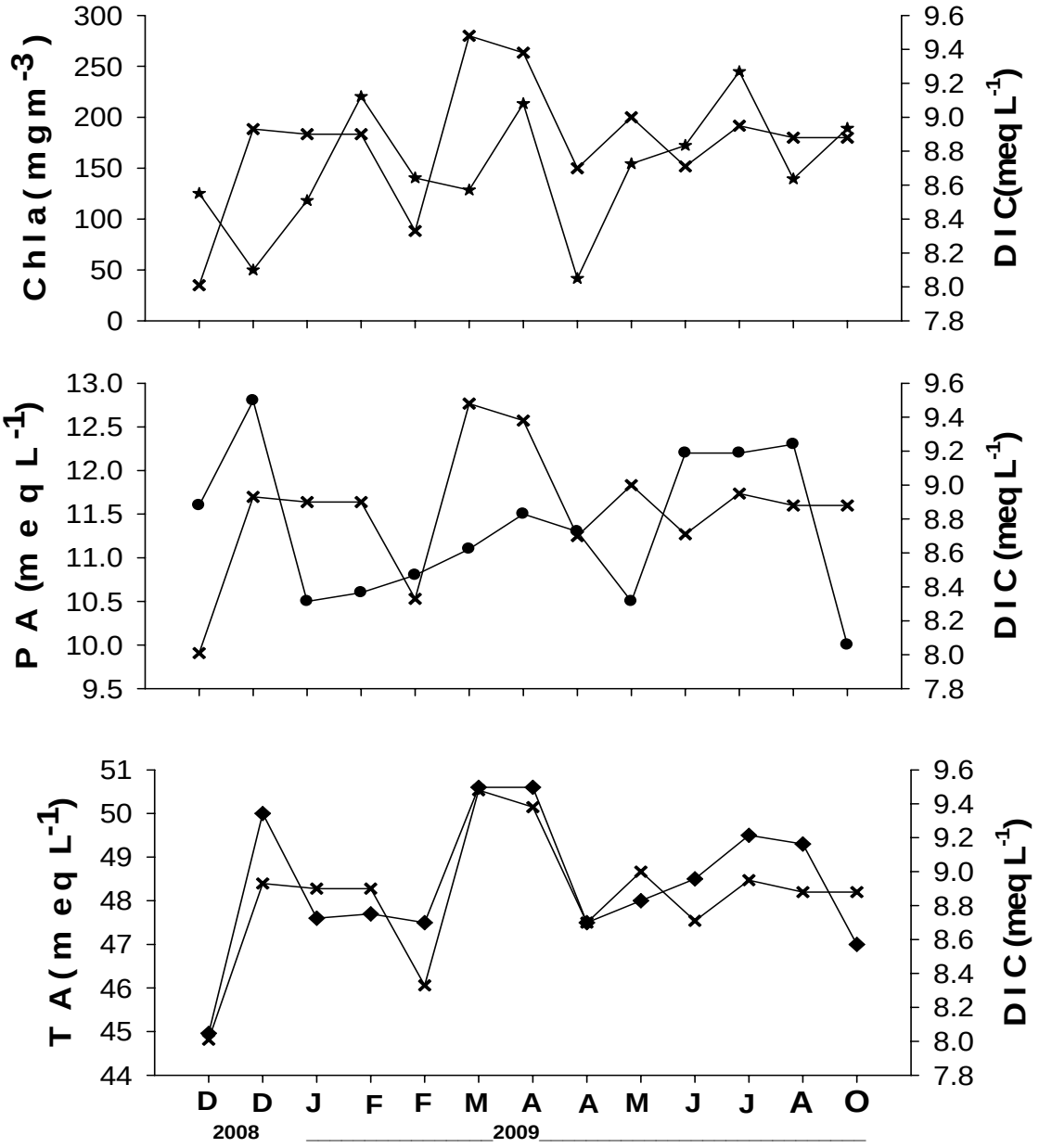


Fig. 5. Temporal variations in total alkalinity (TA) closed diamond, phenolphthalein alkalinity (PA) closed circle, dissolved inorganic carbon(DIC) **X**, in relation to chlorophyll a (closed star) in Lake Arenguade.

The levels of DIC determined for Lake Arenguade are quite high compared to those reported for all other lakes of the same region reflecting the large differences in total alkalinity values of Lake Arenguade and those of the other Bishoftu lakes. According to Talling *et al.* (1973), it is this apparent surplus of inorganic carbon, among other

chemical features of Lake Arenguade, which sustains rapid growth, high standing crops and production rates of phytoplankton in Lake Arenguade.

6.2.3. Inorganic nutrients

The temporal variations in the concentration of inorganic nutrients in relation to phytoplankton biomass in Lake Arenguade are shown in Fig. 6. Concentrations of soluble reactive phosphate (SRP, PO4-P) recorded in this study ranged from 702.1μg L^{-1} in August, 2009 to 2124.4 μg L^{-1}in late February, 2009. The present phosphate values of Lake Arenguade are lower than those reported earlerfor the same lake (3000 μg L^{-1}: Baxter *et al.,* 1965: 3200 μg $L^{-1,}$ Prosser *et al.,* 1968*),* although it is considerably higher than values recorded for other nearby crater Lakes Babogaya (1-11 μg L^{-1} :Yeshiemebet Major, 2006) and Kilole (0.33 – 3.5: Rediat Abate, 2008), and Bishoftu (30-98: Tadesse Ogato, 2007) and the rift valley lakes Ziway (mean value of 90 μg L^{-1}: Getachew Beneberu, 2004) and Lake Chamo (26.4-91.7 μg L^{-1}: Eyasu Shumbulo, 2004). There is a broad trend of increasing soluble reactive phosphate concentration with increasing salinity (Wood and Talling, 1988). Thus, the present reduction in soluble reactive phosphate is probably associated with the dilution of the saline Lake Arenguade of 1960's (5.41 g L^{-1}: Baxter,2002) to the freshwater of this time (2.6 g L^{-1}).

The weak but positive correlation (r = 0.178) between SRP and phytoplankton biomass found in this study is probably the result of the high levels of SRP. Thus, SRP is less likely to play the role of a limiting nutrient for the growth of phytoplanktons in Lake Arenguade.

Nutrient excretion by animals is important in nutrient cycling in freshwater ecosystems (Michael, 2002). Livingstone and Melack (1984) determined the excretory rate of zooplankton and found a rate of 100 mg m^{-2} d^{-1} for phosphate, and 34 mg m^{-2} d^{-1} for nitrate indicating the great role aquatic organisms play in the availability of phosphate for autotrophs. Furthermore, daily phosphate release by *Cladoceran* zooplankton was found to be in the range of 35-60 % of their total body phosphorus and for rotifers values 3-4 times higher are expected (Lehman and Branstrator, 1994). Although the high level of phosphate in Lake Arenguade seem to be associated primarily with the geochemistry of the lake (Talling and Talling, 1965), the contribution of its dominant zooplankton can not be overlooked.

Nitrate-N (NO_3-N), which showed more temporal variations than phosphate and silica, varied from 4.1 in October, 2009 to 78 μg L^{-1} in August, 2009. The levels of nitrate determined in the present study for Lake Arenguade are much higher than those of earlier reports for the same lake (< 5: Prosser *et al.*, 1968: 10 μg L^{-1}; Baxter, 2002).The present high levels of nitrate are probably due to the considerable reduction in the phytoplankton biomass that would, otherwise, remove nitrate in large amounts.

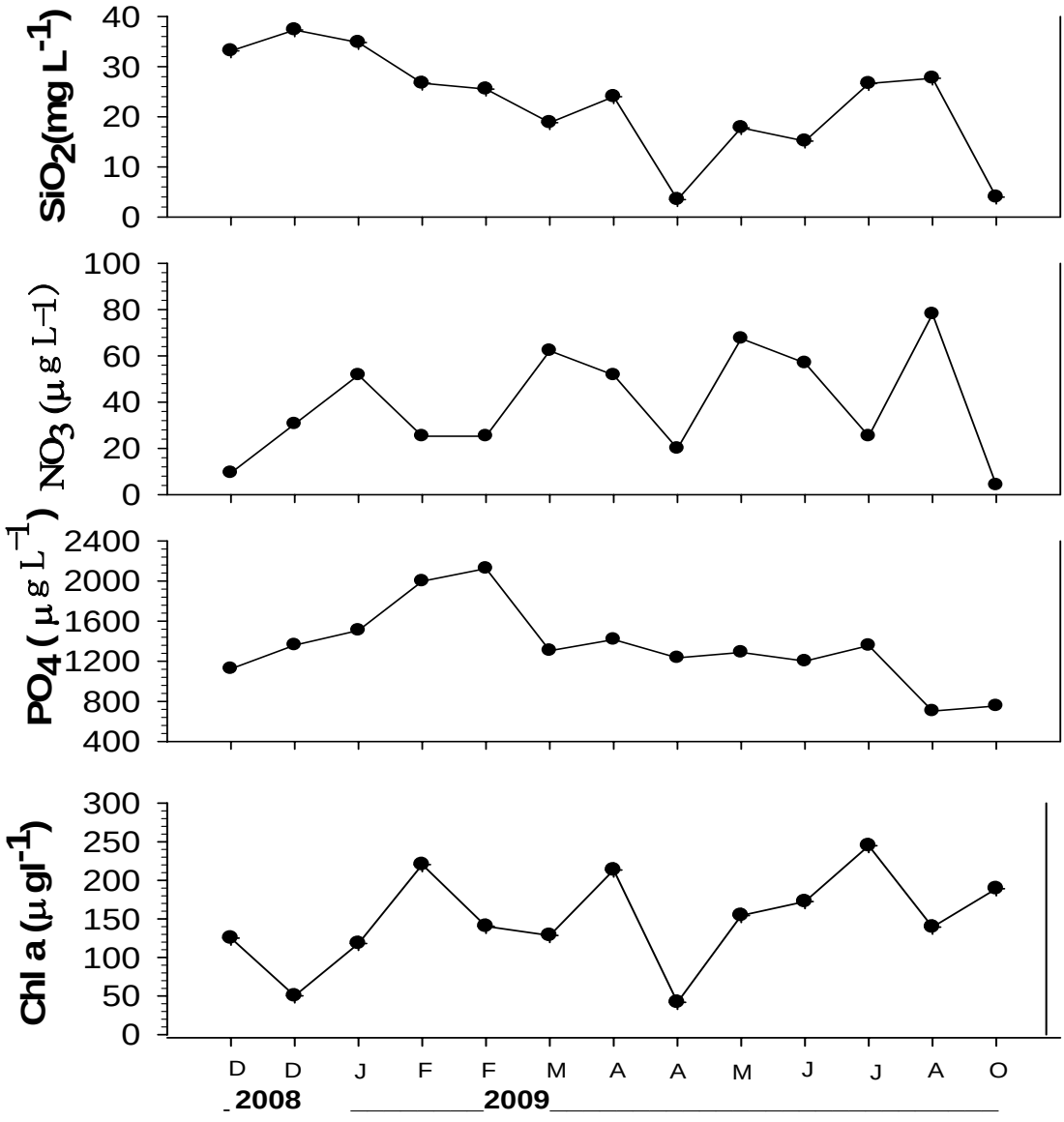


Fig.6. Temporal variations in the concentration of inorganic nutrients in relation to phytoplankton biomass in Lake Arenguade (circle = nutrients, triangle = chl a).

Although the relation between nitrate levels and phytoplankton biomass was not apparent (r = 0.0091), the high nitrate concentrations at times coincided with relatively low phytoplankton biomass and vice-versa.

Wood et al. (1984) generated depth time series data of inorganic nitrogen (largely NO_3^- [1]and NH_4^+) for Bishoftu crater lakes, and showed that nitrate was seldom detectable in surface waters, and only after recent stirring to the surface and oxidation of ammonia, which on a water column basis, represented 90 to 100% of the total inorganic nitrogen. Furthermore, in lakes of unusually high productivity like Lake Arenguade, over 90% of the total inorganic phytoplankton nitrogen is in the algal biomass (Baxter, 2002). One would, therefore, expect nitrogen to play the role of a limiting nutrient for algal growth in Lake Arenguade. The greater importance of nitrogen as a nutrient limiting phytoplankton growth in tropical lakes than in temperate lakes has been emphasized by several workers (Talling and Lemoalle, 1998) due to high rate of denitrification by microbes at high temperatures of the tropics. The natural phosphorus supply to lakes can be traced to the chemical weathering of rocks, which will occur at a considerably higher rates for a given rock type and geochemical setting where the temperature is higher (Lewis, 2000) making supply of inorganic phosphorus to inland waters of the tropics richer. Moreover, nitrogen fixation, which also benefits from the high temperature of the tropics is unlikely to provide more than a small proportion of the total nitrogen budget for a tropical lake (Lewis and Levine, 1984) and denitrification, stimulated by anoxia which is more likely to occur and persist in the tropics, results in the internal loss of nitrogen with consequent depletion of nitrogen in the water column of tropical lakes (Lewis, 1990)..

Molybdate-reactive silica (SiO_2) also showed temporal variations. The recorded values ranged from 3.5 to 37.3 mg L^{-1} in April, 2009 and late December, 2008 respectively. Most of the present values recoded are between 24 and 35 mg L^{-1}, and these values are lower than the value reported previously for the same lake (50 mg L^{-1}; Prosser *et al*., 1968). Generally, the higher values of silica recorded in the present study corresponded to the dry season probably indicating the importance of autochthons sources of silica. Wood and Talling (1988) indicated that the SiO_2 concentrations in 20 Ethiopian lakes studied were very high by world standards and argued that contributory factors include the great mobility of silicates in most tropical soils, the importance of ground-water input

for many lakes, and the enhanced dissolution of solid silicates in saline waters of high alkalinity and pH.

Other possible factors responsible for the variations of silicates include silicate removal from solution in the reverse weathering process of sediment formation and the presence or absence of diatoms as major contributors to the flora of a lake. For example, Baxter and Golobitsch (1971, cited in Wood and Talling, 1988) showed a four-fold increase in silicate concentration at 70 meter depth compared with surface water in Lake Hayq, where diatoms were believed to be a major constituent of a sparse algal biomass. Similarly, in the closed yet freshwater lake fed by ground water and where diatoms play a relatively small role in the phytoplankton, Babogaya (Pawlo), a representative concentration at the surface was 77mg L^{-1} rising to 96 mg L^{-1} in the hypoliminon (Baxter, 2002). The contribution of diatoms to the algal biomas in Lake Arenguade, is obviously insignificant making biological removal of silica unimportant factor to the temporal dynamics of the nutrient.

Declining concentrations of silica have been reported in at least some Ethiopian lakes during the last two decades or so (Elizabeth Kebede *et al*., 1994; Zinabu Gebre-Mariam *et al*, 2002; Girma Tilahun, 2006). The decline in silica levels was attributed to the dominance of diatoms in the saline lake, Shala (Elizabeth Kebede and Willen, 1998) and many fresh water bodies, including lakes Chamo (Amha Belay and Wood, 1984), Chad (Lemoalle, 1983) and Victoria (Hecky and Bugenyi, 1992; Hecky, 1993: Lehman and Branstrator, 1994) and its slower rate of regeneration following accumulation of organic matter (Hecky and Kilham, 1988).

6.3. Biological features

6.3.1. Taxonomic Composition of phytoplankton

For quantitative assessment of phytoplankton, composite sample of lake water taken from the 0 -1 m layer. Table 3. presents a list of the major phytoplankton species identified in samples collected from Lake Arenguade during the study period (those in bold are reported for the first time from present study), including those species identified in the previous studies (Talling, 1973; Brook Lemma, 2008).

Table 3.List of phytoplankton taxa identified in samples from Lake Arenguade.

Phytoplankton group	Species name
*Cyanophyceae (*Cyanobacteria)	***Anabaenopsis elenkinii*** *Chroococcus minutus* *Spirulina platensis (Arthospira fusiformis)*
Dinophyceae	*Glenodinium sp.*
Bacllariophyceae	*Navicula sp.*
Euglenophyceae	***Euglena sp.***

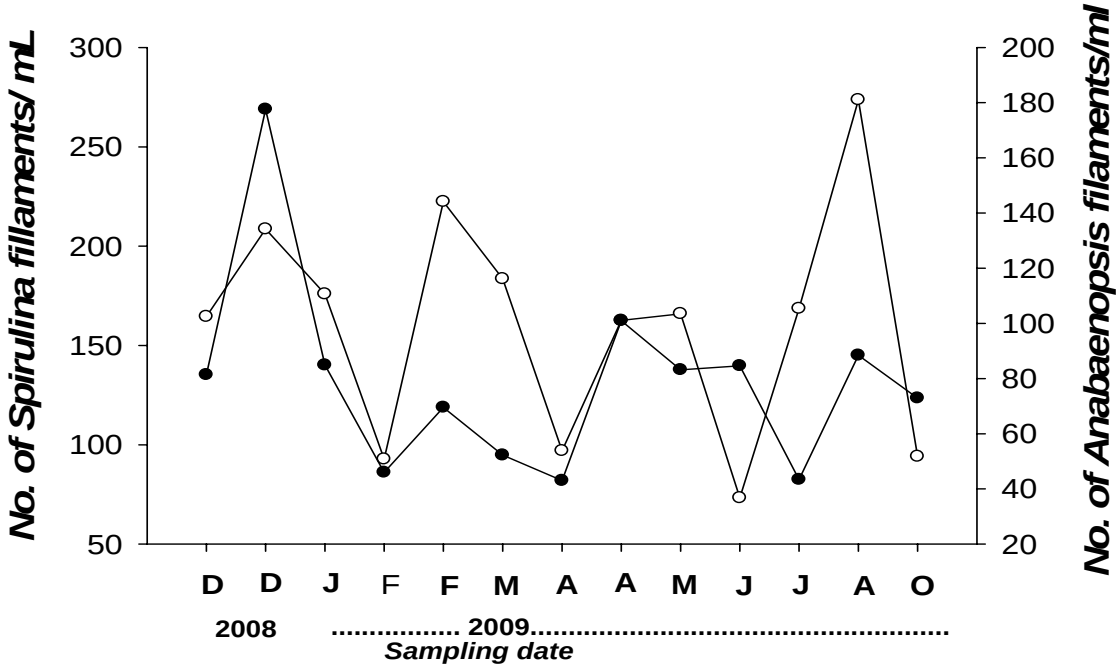


Fig .7. Temporal variations in the abundance of *Spirulina platensis* (open circle) and *Anabaenopsis elenkinii* (closed circle) in Lake Arenguade.

The Blue-green algae, with 3 species, were the most diverse and dominant taxonomic group in the phytoplankton assemblage of Lake Arenguade. The two filamentous blue green algae-*Spirulina platensis* and *Anabaenopsis elenkinii* were the most dominant algal species accounting for almost the entire standing crop of phytoplankton in the study lake considering the fact that the other phytoplankton taxa wee rarely encountered. Microscopic analysis of samples from Lake Arenguade has clearly shown that the species diversity of phytoplankton is very low in this lake compared to those of other crater lakes

of the same region. This is consistent with the generalization that species diversity of phytoplankton decreases with an increase in the trophic status of the lake (Wetzel, 2001).

The temporal variations in the number of algal units of the two major species are presented in Fig. 8. The two blue-green algal species were almost equally abundant considering the number of algal units (and not no. of cells). The present results seem to suggest that with further dilution of the lake water *Spirulina platensis* may be completely replaced by *Anabaenopsis elenkinii.*

6.3.2. Phytoplankton Biomass.

Temporal changes in Phytoplankton biomass, measured as chlorophyll *a* concentration, in composite samples collected from the center of the lake, are shown in Fig. 8. The Phytoplankton biomass of Lake Arenguade exhibited temporal variations over the study period varying between 41.7 and 271mg Chl a m^{-3}. The chlorophyll *a* concentration values recorded in the present study are much lower than those reported in earlier investigations which were based on samples collected in the years 1964-1966 (400-5000 mg m^{-3}, Wood and Talling, 1988), 1990 to 1992 (363, 288, and 798 mg m^{-3}, Zinabu Gebre-Mariam, 1994) and 1995 (880 mg m^{-3}, Demeke Kifle *et al*., unpublished) although they are still fairly high in the light of the general experience with phytoplankton.

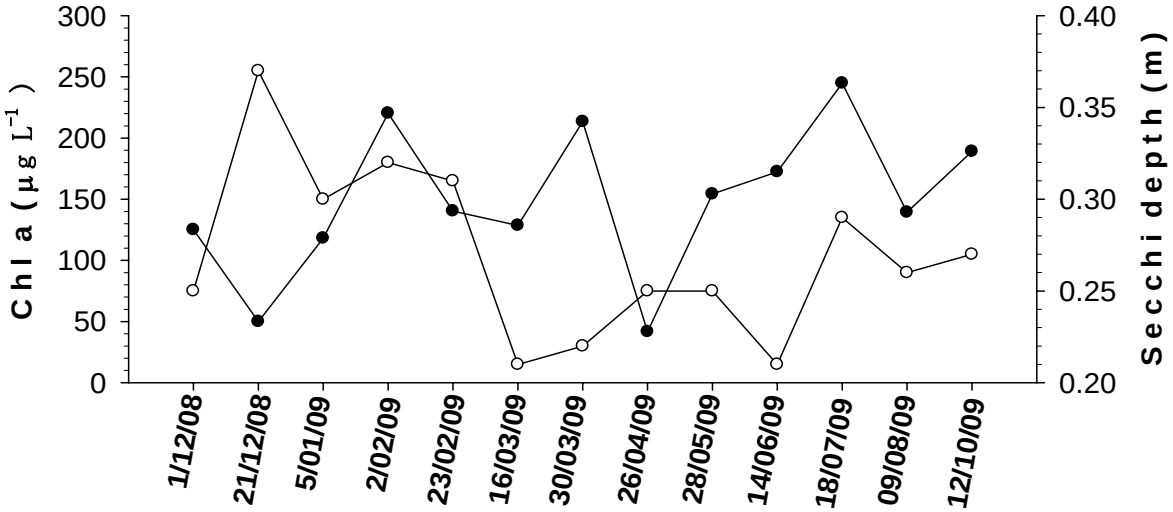


Fig. 8-Temporal variations in phytoplankton biomass (closed circle) and Secchi depth (open circle) in Lake Arenguade.

Although the maximum phytoplankton biomass value of Lake Arenguade is remarkably high compared to biomass values known for almost all Ethiopian lakes (See

Table 4), much higher phytoplankton biomass values are known from shallow East African lakes including Lakes Kilole (Talling et al., 1973), and Chitu (Wood and Talling, 1988) in Ethiopia and lakes Nakuru (Melack, 1976b), and Elmenteita (Kalff, 1983) in Kenya and Lake George in Uganda (Ganf and Horne, 1975)

Table. 4. Phytoplankton biomass measured as chlorophyll a concentration in L. Arenguade and other lakes (Zelalem Dessalegne, 2007).

Lake	**B (mg chl a m^{-3})**	**Data source**
Arenguade	**41.7 – 271**	**Present work**
Koka	16	Elizabeth and Willen (1998)
Babogaya	4-20	Yeshiemebet Major (2006)
Awassa	20-46	Demeke Kifle (1985)
	10.43-25.21	Tadesse Fetahi (2004)
	13 – 26	Girma tilahun (2006)
Hora	29	Zinabu Gebre-Mariam and Taylor (1997)
Abaya	0-33	Zinabu Gebre-Mariam(2002)
Kuriftu	*17.24-55.6*	Zelalem Desallegn, 2007)
Legedadi	2.61-57.33	Adane Sirage (2006)
Bishoftu	60	Zinabu G.Mariam and Taylor(1997)
Chamo	47-108	Eyasu Shumbulo (2004)
Ziway	149.5-212	Girma Tilahun(1988)
	22.9 – 57.5	Girma Tilahun (2006)
Kilole before diversion of River Mojo into it.	382-412	Talling *et al.* (1973)
Chitu	2600	Wood and Talling (1988)
Simbi	200	Melack (1979c)
George	100-400	Ganf and Horne (1975)
Nakuru	1160	Vareschi(1982)

6.3.3. Stratification of Phytoplankton Biomass

Fig. 9 shows depth distribution of Chl a in Lake Arenguade on June 1, 2010.

On June 1, 2010, water samples were taken from different depths in Lake Arenguade to see stratification of phytoplankton biomass. The highest Chl a concentration value (271 mg m^{-3}) was found at the lake's surface although Chl a values as high as 40 and 29 mg m^{-3} were recorded at depths down to 3m and 4m, respectively. Thus, chl a biomass of phytoplankton can be assumed to exhibit strong stratification in Lake Arenguade under calm water column conditions.

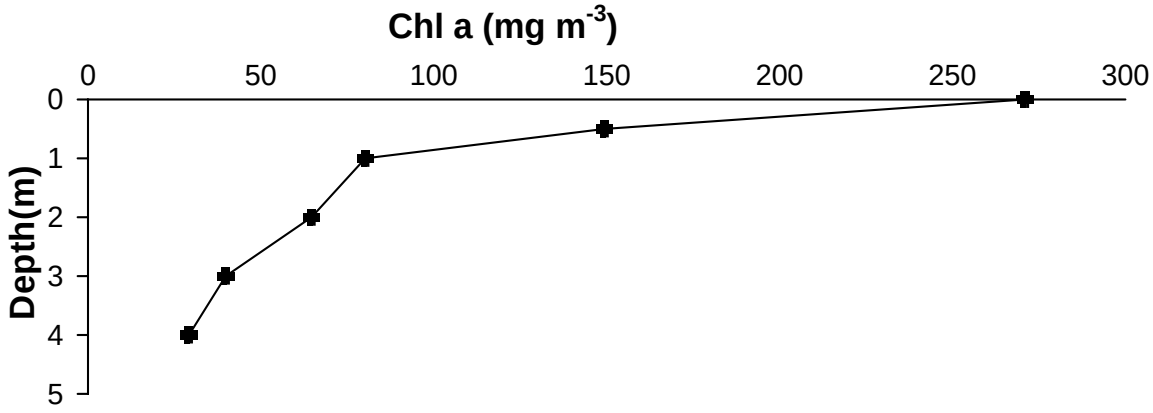


Fig. 9. Stratification of phytoplankton biomass in Lake Arenguade on June 1, 2010.

6.3.4. Photosynthetic productivity

The depth profiles of gross photosynthetic rates per unit water volume (A, mg C m^{-3} h^{-1}) are shown in Figure 10. Photosynthetic production measured as oxygen evolved was converted to mg C m^{-3} h^{-1} assuming a photosynthetic quotient of 1.2 (Wetzel and Likens, 2000). The distribution of gross photosynthesis per unite water volume (A, mg C m^{-3} h^{-1}) exhibited the typical pattern for phytoplankton with maximum production rates at depths below the surface on most sampling dates (Talling et al., 1973; Demeke Kifle and Amha Belay, 1990). Since samples pooled from several established depths were used for all incubations, the variations in the photosynthetic rates with depth were not an expression of varying photosynthetic biomass of the algae but were the responses of uniform algal material to different light intensities.

Lack of surface inhibition was observed in the *Spirulina*-dominated Kenyan Lakes, Nakuru (Melack and Kilham, 1974) and Simbi (Melack, 1979c), which was attributed to inadequate resolution of the photosynthetic rates in the upper 20 cm of the water column. In most of the algal species studied, some photoinhibition was observed with light intensity at 60-70% of full sunlight (Vonshak, 1987). Demeke Kifle *et al*. (unpublished), reported absence of photoinhibition in (photosynthetic depth-profiles the) then *Spirulina*-dominated phytoplankton community of Lake Arenguade, which was attributed to the resistance of some *Spirulina* strains to high light-intensities (Vonshak and

Richmond,1988). But, the present results are indicative of the occurrence of photoinhibition, which may be associated with the change in the species composition of the phytoplankton community supported by the lake.

The depth profiles of photosynthesis of Lake Arenguade showed variations in the maximum rates attained and in the extent of surface depression of photosynthetic activity.

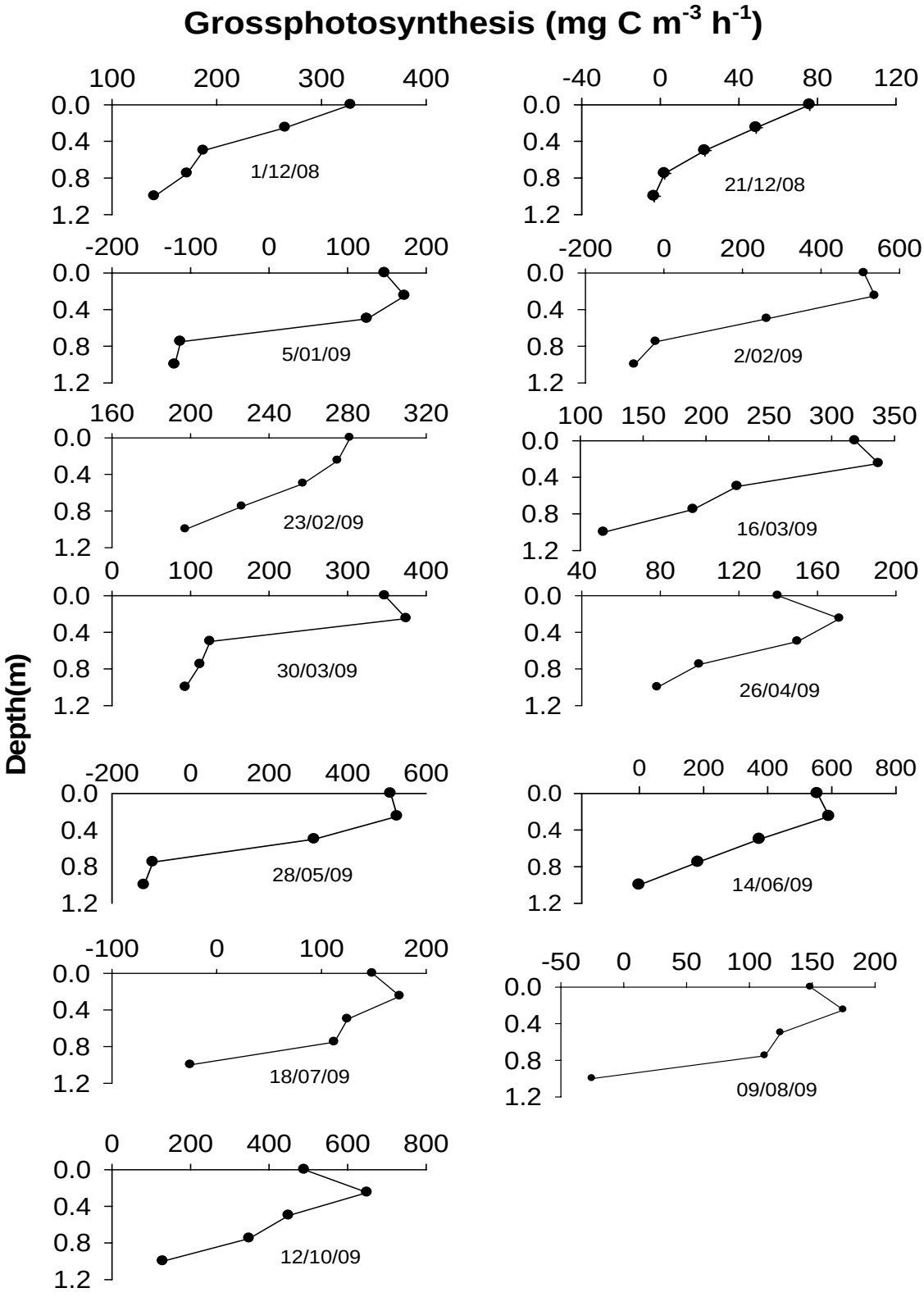


Fig. 10. The depth profiles of gross photosynthetic rates in Lake Arenguade.

During the study period, the depth-profiles of gross photosynthesis exhibited a sub–surface maximum rate of gross photosynthesis at 0.25 m in all sampling months except December, February, and August, 2009 when the maximum was observed at the surface of the water column coincident with a period of low air temperature or overcast. Profiles with reduced photosynthetic activity at the surface have been reported from many 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), Chad (Lemoalle, 1983), Kenya (Talling, 1965; Melack, 1979b, 1981; Vareschi, 1982) and Tanzania (Melack and Kilham, 1974). Lower photosynthetic rates of phytoplankton at a lake's surface are linked to photoinhibition, which is believed to occur when light exceeds physiological saturation and results in excess of photons that do not become dissipated by photosynthetic carbon-fixation (Long *et al.*, 1994; Falkowski and Raven, 1997). The decrease in photosynthetic rates at the surface is associated with photooxidative disruption of pigment systems (Amha Belay and Fog, 1978; Falkowski and Raven, 1997), inactivation of photosynthetic enzymes (Steemann-Nielsen, 1962; Steemann-Nielsen and Jørgensen, 1962) and increased photorespiration (Harris and Lott, 1973; Osmond, 1981).
The extent of percentage reduction in gross photosynthesis from A_{max} due to photonhibition was estimated by calculating the difference between maximum gross photosynthetic rate and gross photosynthetic rate at the surface and expressing it as a percentage of the former. The reduction in photosynthetic rates due to photoinhibition varied from 0 to 24.6 %.

6.3.5. Photosynthetic characteristics

The temporal variations in Light-saturated rate of gross photosynthesis ($A_{max,}$ mg O_2 m^{-3} h^{-1}), hourly integral rates of gross photosynthesis (**ΣA,** g O_2 m^{-2} h^{-1}**)** in relation to Chl a biomass (mg m^{-3}) and Secchi depth (m) are shown in Fig. 11. The light-saturated rates of gross photosynthesis (A_{max}) ranged from 76.14 to 650 mg C (243.64–2080 mg O_2) m^{-3} h^{-1}.

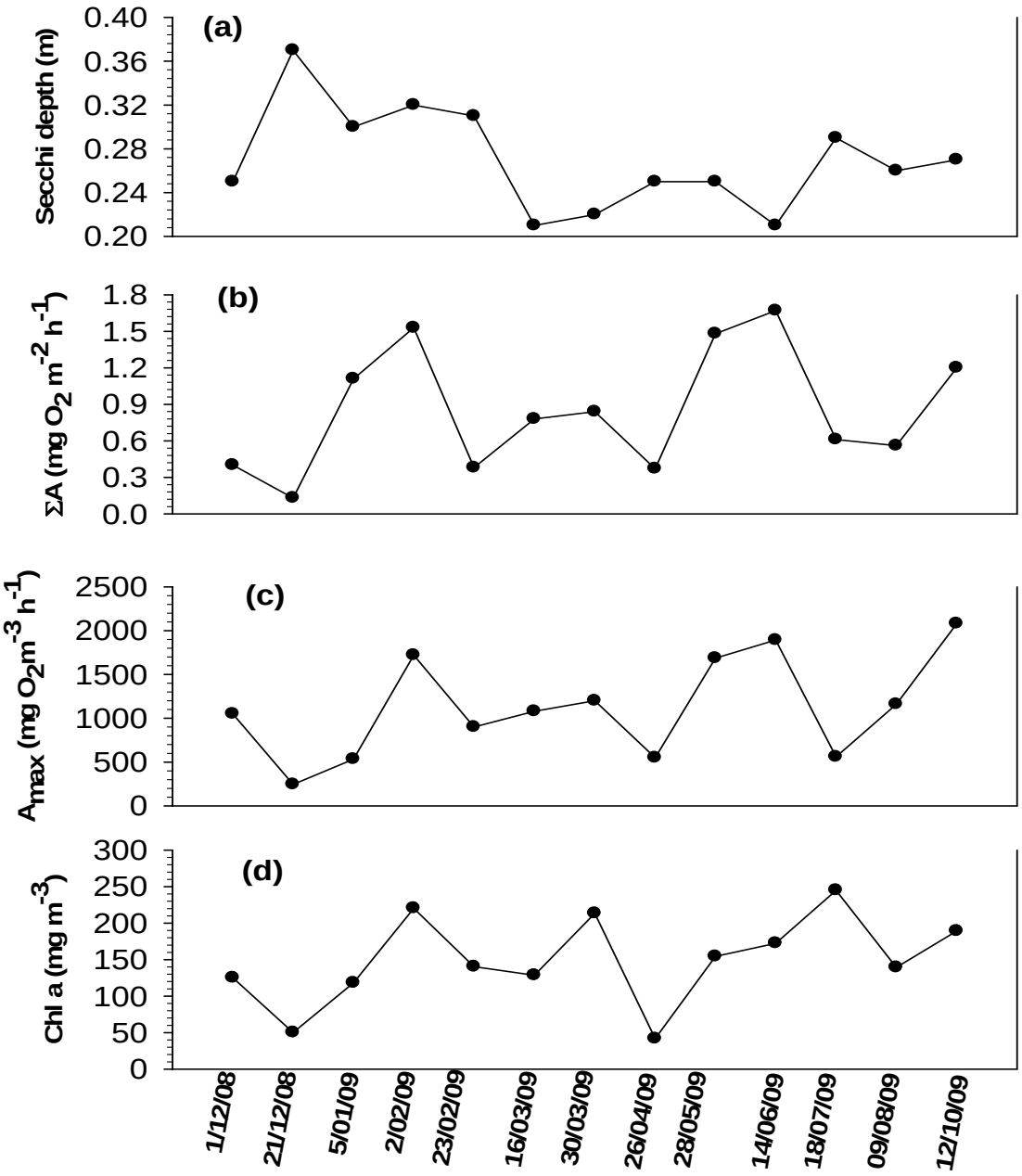


Fig.11. Temporal variations in Light-saturated rat of gross photosynthesis (c) ($A_{max,}$ mg O_2 m^{-3} h^{-1}), hourly integral rates of gross photosynthesis (b)(g O_2 m^{-2} h^{-1}**)** in relation to Chl a biomass (d) (mg m^{-3}) and seccchi depth (a) (m).

.

The highest light-saturated photosynthetic rate (A_{max}) was 650 mg C (2080 mg O_2) m^{-3} h^{-1} and was achieved with algal concentration of about 189.1 mg Chl *a* m^{-3} (see Table 5 for comparison with values reported for different lakes).

The observed high values of light-saturated rate of gross photosynthesis are higher than those reported for Lakes Abijata (Amha Belay and Wood, 1984), Awassa (Demeke Kifle and Amha Belay, 1990), and Babogaya (Yeshiemebet Major, 2006), all in Ethopia and Lakes Naivasha and Crescent Island Crater (Melack, 1979a) and Sonachi, in Kenya (Melack, 1976b). Much higher values of Amax have been reported for the Ethiopian crater Lakes Kilole and Arenguade (Talling *et al.*, 1973), the shallow rift valley Lake Ziway (Girma Tilahun, 1988) and Lake George in Uganda (Ganf, 1975) and Lake Simbi in Kenya (Melack, 1970).

Generally, higher rates of light-saturated photosynthesis were observed at times of high phytoplankton biomass in Lake Arenguade. Higher photosynthetic rates in Kenyan freshwaters were also recorded when chlorophyll a concentrations were also high (Melack, 1979a). The correlation between A_{max} and phytoplankton biomass in Lake Arenguade was positive and modest (r=0.53). A stronger positive correlation (r=0.67) between maximum (light-saturated) rates of photosynthesis and chlorophyll a concentrations were reported for Welsh lakes (Pentecost and Happey-Wood, 1978). Positive but weak correlation between A_{max} and phytoplankton biomass was also reported for the Ethiopian lakes, Lake Chamo (r=0.3, Eyasu Shumbulo,2004), and Ziway (r= 0.36; Girma Tilahun, 1988). Interestingly, high biomass values of 172.4 and 220.3 mg chl a m^{-3} were associated in Lake Arenguade with A_{max} values of 1893.4 and 1720.00 mg O_2 m^{-3} h^{-1}, respectively. The highest biomass (~245) yielded a lower A_{max} (560). Similarly, Talling *et al*. (1973) found relatively low light- saturated rate of photosynthesis with a high algal crop and the relatively low algal crop was found to yield the highest maximum rate (A_{max}) in Lake Arenguade. The lack of correspondence between biomass and A_{max} was also reported for phytoplankton of Lake Awassa (Demeke Kifle and Amha Belay, 1990) and several reservoirs in Sri Lanka (Silva *et al*., 2002) . High maximum rates associated with low algal biomass are the result of high specific activity [ϕmax, mg O_2 (mg chl a $)^{-1}h^{-1}$].

Table. 5. Light-saturated rates of gross photosynthesis (Amax) and specific-rates of gross photosynthesis at light-saturation (ϕ_{max}, mg O_2 (mg Chl a)$^{-1}$ h^{-1}) for different lakes.

Lake	**Amax**	**ϕ_{max}**	**Data Source**
George	1900-6000	-	Ganf(1975)
Nakuru	1100-2300	-	Melack and Kilham(1974)
Simbi	950-12900	15-17	Melack(1979c)
Naivasha	150-240	-	Melack(1979b)
Arenguade	10000-30000 244– 2080	11-18 2.3 – 13.2	Talling *et al*, (1973) Present study
Kilole	4000-10000	16.3-33.7	Talling *et al*, (1973)
Ziway	1640-4670	9.6-22.5	GirmaTilahun(1988)
Chamo)	716-1789	10-34	EyasuShumbulo(2004
Kuriftu	571-1136	20.2-33	Zelalem Dessalegn(2006)
Babogaya	106-407	19-29	YeshiemebetMajor(2006)

Harris (1986) and Smayda (1990) indicated the general stimulation of growth and photosynthetic activity of phytoplankton by nitrate alone or in combination with phosphorus. Algal communities may respond to a decreased supply of a limiting nutrient either by decreasing the optimum photosynthetic rate or by producing less efficiently at suboptimal irradiances (Schindler and Fee, 1975).

Biomass-specific rates at light-saturation (ϕ_{max}, photosynthetic capacity) ranged from 2.3 to 13.2 mg O_2 (mg Chl a)$^{-1}$ h^{-1} with most values between 8 and 11 mg O_2 (mg Chl a)$^{-1}$ h^{-1}. These values are lower than those reported for Lake Arenguade (11 -18) by Talling et al.(1973) and Demeke Kifle et al. (unpublished, 14.70 -16.47) and for such other Ethiopian lakes as Babogaya (19-29 ;Yeshiemebet Major , 2006), Chamo (10-34; Eyasu

Shumbulo, 2004), Lake Kilole (16.3 - 33.7; Talling *et al*., 1973) and Koriftu (18.78 to 33; Zelalem Dessalegne, 2006) and for Lake Simbi in Kenya (15-17, Melack, 1981) and Lake George in Uganda (17-19; Ganf and Horne, 1975).

The photosynthetic capacity of phytoplankton is directly affected by temperature (Eppley, 1972), nutrient regimes (Falkowski and Stone, 1975), light (Falkowski, 1981), and cell size (Malone, 1971).In the tropics, algal type including cell size, nutrients and CO_2 supply may be considered to be of greater importance in determining the magnitude of photosynthetic capacity of phytoplankton than temperature and light for these factors are generally favorably high in the tropics.

Lemoalle (1981), comparing mean photosynthetic productivity in the trophogenic zone of tropical and temperate lakes concluded that higher tropical rates originate from high photosynthetic capacity, which may be the result of higher temperature in the tropics. Lewis (2000) stressed that the high tropical temperature favors the availability of nutrients (which affect photosynthetic capacity of phytoplankton) in the trophogenic zone due to high hypolimnetic temperature that forms isothermal layer relatively easily with metaliminion and epiliminion when cooling which entails mixing making nutrients available in the trophogenic zone.

Tropical soda lakes can show a combination of high phytoplankton standing crop and above-average biomass-specific rates, partly due to the large reserve of CO_2 for localized photosynthetic activity in condensed photosynthetic zones (Talling *et al*., 1973). This has been shown for Lake Arenguade (Talling.et al., 1973), Lake Simbi, Kenya (Melack, 1979) and Lake Chad in Chad (Lemoalle,1973).

6.3.6. Production rates per unit area

The hourly photosynthetic rates per unit area ($\sum$A) were determined by the Gird Enumeration Analysis (Olson, 1960). Hourly integral photosynthesis ranged from 0.13 (December, 2008) to 1.67 g O_2 m^{-2} h-1(June, 2009) (Fig. 11). This value is lower than that reported for the same lake (1.43 to 2.56) by Demeke Kifle *et al*. (unpublished), but still higher than those reported for Lakes Ziway (0.0574 to 0.726; Getachew Beneberu, 2004), Babogaya (0.47 to 0.86; Yeshiemebet Major, 2006) and Awassa (0.3 to 0.725;

Demeke Kifle and Amha Belay,1990). The seasonal peaks of hourly integral rates were associated with peaks of chlorophyll a concentration and light-saturated rate of gross photosynthesis (Amax). The correlations between hourly integral rates and chlorophyll a concentration (r= 0.53, r^2=0.28 at p=0.0605 and A_{max} (r = 0.78, r^2=0.62 at p=0.0014), were positive and strong. As one might expect, secchi readings were lower where chl a and hourly integral rates were at their peaks probably due to biological turbidity (self-shading).

The daily integral rates of photosynthesis (ΣΣA g O_2 m^{-2} d^{-1}, of Lake Arenguade were also determined from the hourly-integrated rates by multiplying with the factor of 0.9 used by Talling (1965) for other East African Lakes. The products were then multiplied by the number of hours of sunshine (12). The calculated values ranged from 1.40 (December, 2008) to 18 g O_2 m^{-2} d^{-1}(July, 2009). The highest daily integral value of Lake Arenguade is lower than those values reported for the same lake by Talling et al. (1973 ; 19.7 -27.6 g O_2 m^{-2} d^{-1}) and Demeke Kifle et al.(unpublished : 11.25-44.83 g O_2 m^{-2} d^{-1}) although it is still higher than those of the other Bishoftu creater lakes: Kilole (1.49-2.4; Talling *et al*., 1973), Babogaya (1.01-5.98; Yeshiemebet Major, 2006), and Koriftu (6.174 to 9.45; Zelalem Dessalegn, 2007), all in Ethiopia and Lake Muzahi in Uganda (6 to 9.5; Mukankomeje *et al*., 1993) and Baringo in Kenya (3.8; Patterson and Wilson, 1995).

6.3.7. Models relating daily integral rates of photosynthesis (ΣΣA, g O_2 m^{-2} d^{-1}) and euphotic zone Chlorophyll a (ΣB, mg chl a m^{-2}).

Lemoalle (1981) devolped a model relating daily integral rates of photosynthesis (ΣΣA, g O_2 m^{-2} d^{-1}) to euphotic zone Chlorophyll a (ΣB, mg chl a m^{-2}) for African lakes based on studies conducted on Lake Chad, and proposed that the relation **ΣΣA= 0.14 ΣB** was representative of many African lakes, including Lake Arenguade. While developing the model, Lemoalle incorporated ΣΣA and ΣB measurements made by Talling *et al*. (1973) for Lake Arenguade .

Table 6.**ΣΣ**A and ΣB computed using measurements made by Talling et al., (1973).

Sampling Date	***ΣΣA, g O_2 m^{-2} d^{-1}**	**ΣB, mg chl a m^{-2}**	**∑∑A / ∑B**
Feb. 25, 1964	16.38	325	
Jan. 15,1966	23.04	221	0.064.Thus,
Jan. 16,1966	16.11	248	**ΣΣA** = 0.064**∑B**
Jan. 16,1966	12.87	267	
Mean	17.10	265.25	

*

As far as Lake Arenguade is concerned, the model proposed by Lemoalle (1981) for East African lakes, i.e, **ΣΣA= 0.14 ΣB** is not a very good representative, even for the measurements made at that time, and this is clearly shown in Table 6. But, the model presented in Table 3 above, which was based on the measurements of Talling *et al.*(1973) is very similar to the present finding (see Table 7).The present study reveals that **ΣΣA = 0.077 ΣB** , which is similar to the above computed relation based on Talling *et al*.'s (1973) measurements. Thus, careful measurements of Chl a and reliable estimates of ΣB can be used to estimate the daily integral rate (**ΣΣA).** The relation **ΣΣA = 0.077 ΣB** was also based on ten hours of sunshine and a factor of 0.9, which were used to convert hourly rates into daily rates (Talling,1965). If twelve hours of sunshine is used to convert hourly rates into daily rates, the above model becomes **∑∑A = 0.093 ∑B.**

Table7. Measurements of ∑∑A and ∑B of Lake Arenguade.

Sampling Date	∑B, mg Chl a m^{-2}	*∑∑A (g O_2 m^{-2} d^{-1})	**∑∑A (g O_2 m^{-2} d^{-1})
1/12/08	85.10	3.6	4.32
21/12/08	50.04	1.17	1.40
5/01/09	95.70	9.99	11.99
2/02/09	191.70	13.77	16.52
23/02/09	117.93	3.42	4.10
16/03/09	73.30	7.02	8.42
30/03/09	128.00	7.56	9.10
26/04/09	85.10	3.33	4.00
28/05/09	85.10	13.32	15.98
14/06/09	104.92	15.03	18.00
18/07/09	198.33	5.49	6.60
09/08/09	98.96	5.04	6.00
12/10/09	138.00	10.80	12.96
Average	98.37	7.66	9.18
∑∑A / ∑B		0.077	0.093
The resulting relationship		**∑∑ = 0.077∑B**	**∑∑A=0.093∑B**

*The conversion from hourly rates into daily rates was using 10 hours of sunshine.

** The conversion from hourly rate into daily rate was using 12 hours of sunshine.

6.3.8. Zooplankton

The zooplanktons of Lake Arenguade are presented in Table 8. In highly productive lakes, such as Lake Arenguade, the chlorophyll content is so high that small sized zooplanktons such as rotifers are not expected to exist. This is due to easy blockage of their filtering apparatus by larg-sized and very high algal material (Seyoum Mengistou, personal communication). But two species of Rotifers, *Brachionus dimidiatus and B.plicatilis* were reported to exist (Brook Lemma,2008).

Table 8. Zooplankton identified in Lake Arenguade (data from Brook Lemma,2008).

Zooplankton	
Rotifera	*Brachionus dimidiatus* *B.plicatilis*
Copepoda	*Lovenula africana*

In the present study, only *Lovenula africana* was identified. This calanoid zooplankton is unusually large, probably due to absence of predation by fish as there is no fish inLake Arenguade due to anoxic environment of the lake (Afowerki Gebrai, 1992).

7. GENERAL CONCLUSISONS AND RECOMMENDATIONS

The moderately deep, sub-saline and alkaline eutrophic lake, Lake Arenguade,is undergoing drastic changes with sharp declines in its primary productivity and standing crop (biomass). In the 1960's, production rate as high as 30 g $O_{2\ m}{}^{-3}\ h^{-1}$ from diel free water analysiswas reported from Lake Arenguade (Talling *et al.*, 1973).Compared to the previous rate, the current maximum hourly rate of gross photosynthesis (2020 mg $O_{2\ m}{}^{-3}\ h^{-1}$) is very small. Similarly, the biomass dropped from the remarkably high value of 2170 (Talling *et al*., 1973) to 271 mg Chl a m^{-3}. There are also changes in the lake's algal composition, alkalinity, conductivity and salinity. Lake Arenguade was one of the few natural environments that sustained a nearly pure culture of *Spirulina platennsis* (Talling *et al*., 1973). The current situation of the lake contradicts its past history in that the change is not only in algal composition, but also in the abundance of *S. platensis.* Currently, the bluegreen(cyanobacterium) *Anabenopsis* , is almost abundent as *Spirulina* clearly indicating a shift in algal composition of the lake from monoalgal to various algal forms. According to Prosser et *al*., (1968), the salinity of Lake Arenguade in the 1960's was 5.41g gL^{-1}, now , this figure is 2.62 which is a reduction in more than 50%. *Anabenopsis elenkinii*, is almost as abundant as *Spirulina* clearly indicating a shift in algal composition of the lake from a nearly monospecific community to that in which two species have become co-dominant. Currently, there are no unequivocal explanations for the enormous limnological changes that have taken place in Lake Arenguade. The prominent change in the lake's water chemistry might have emanated from a natural force or human-induced process. There is, therefore, an urgent need for the initiation and

sustenance of a full-fledged environmental impact assessment program in which limnologists, geologists and environmental scientists will be actively involved in uncovering the cause for the environmental degradation in Lake Arenguade and develop workable strategies for its restoration.

8. References

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

Aleem, A.A.and Samaan, A.A. (1969).Productivity of Lake Mariut, Egypt .Part II Primary productivity. *Int.Revue ges .Hydrobiol*. **54:**473-490.

Afeworki Ghebrai (1992). Zooplankton structure and dynamics in two contrasting soda lakes (Debrezeit creater lakes: Ethiopia)MSc. thesis, Addis Ababa University, Addis Ababa, 98pp.

Amha Belay and Fogg, G.E. (1978). Photo-inhibition of photosynthesis in *Asterionella formosa (Bacillariophyceae). J.Phycol*, **14**:341 - 347.

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

Bartram and Chorus, 1999 Toxic Cyanobacteria in Water: a guide to their public health consequences, monitoring and management, Geneva, World Health Organization, 1999.

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

Baxter, R.M., 2002. Lake morphology and chemistry. In: Tudorancea, C.,Taylor, W.D. (Eds.), Ethiopian Rift Valley Lakes. Backhuys, Leiden, pp. 45–60.

Brook Lemma 1994 .Changes in the limnological behavior of a tropical African explosion crater Lake: L.Hora- Kilole, Ethiopia .*Limnologica* **21(1):** 57-70.

Brook Lemma (2008). Introduction to lake ecology, aquaculture and fisheries in Ethiopia. Haramaya University, Haramaya ,Ethiopiaa ,440pp.

Chan, T.U.,Hamilton, D.P. and Robson, B.J. (2002). Modelling Phytoplankton succession and biomass in a seasonal West Australian estuary. *Verh. Intrnat. Verein. Limnol.* **28:** 1086 – 1088.

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, 108 pp.

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.

Demeke Kifle, Seyoum Mengistou and Amha Belay (1995).Biomass and photo - synthetic production of *Spirulina (Arthrospira*) in an Ethiopian alkaline sodalake, Lake Arenguade. Short communication (unpublished), Department of biology, Addis Ababa University, Ethiopia: 13pp.

Elizabeth Kebede, Zinabu Gebre-Mariam and Ahlgren,I.(1994).The Ethiopian rift valley lakes.Chemical characterstics along a salinity alkalinity series. *Hydrobiologia*. **288**:1-22.

Elizabeth Kebede (1996). Phytoplankton in a salinity-alkalinity series of lakes in the Ethiopian Rift Valley.Ph.D. Dissertation, Uppsala University, Uppsala, Sweden.

Elzabet Kebede (1997). Response of *Spirulina platensis*(*Artherospira fusiforms*) from Lake Chitu, Ethiopia, to salinity stress from sodium salts. *J. Appl. Phycol*. **9:** 55 – 558.

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

Elzabet Kebede (2002). Phytoplankton distribution in lakes of Ethiopian Rift Valley. In : Tudorancea, C., Taylor ,W.D(Eds), Ethiopian Rift Valley lakes. Backhuys Leiden, 289pp.

Eppley, R.W. (1972). Temperature and phytoplankton growth in the sea. *fisheries Bulletin*, **70**: 1063-1085.

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. (1981). Light-shade adaptation and assimilation numbers. *J. Plankt. Res.*, **3**:203-216.

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

Falkowski, P.G. and Raven, J.A. (1997). Aquatic photosynthesis.Blackwell sciences,Oxford, 375 pp.

Franks, P.J.S and D.M. Anderson, 1992. Alongshore transport of a toxic phytoplankton bloom in a buoyancy current: Alexandrium tamarense in the Gulf of Maine. *Marine Biology*. **112:**153-164.

FOX, R.D. (1996): Spirulina: potential and production. EDISUD, France.

Ganf, G.G. (1975). Photosynthetic production and irradiance photosynthesis

relationships of phytoplankton from a shallow equatorial lake (Lake George, Uganda). *Oecologia.* **18:** 165 – 183.

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

Gasse, F. (1986). East African diatom Taxonomy, ecological distribution. J. Cramer in der Gebrüder Borntraeger Verlagsbuchhandlung. Berlin Stuttgart.

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 Ababa201pp.

Girum Tamire.(2006).Zooplankton Community Grazing Rates in Lake Koriftu .M.Sc thesis, Addis Ababa University, Addis Ababa, 72PP.

Habte Jebessa (1994). Zooplankton community grazing rates in some lakes and reservoirs in Ethiopia. M.Sc. Thesis, A.A.U. 67pp.

Hammer, U.T. (1981). Primary production in saline lakes. *Hydrobiologia,* **18**:47-78.

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

Harris, G.P. (1986).Phytoplankton Ecology:structurfunction and fluctuation. Chapman and Hall, London, 384pp.

Hecky,R.E.and P.Kilham.(1988).Nutrient limitation in freshwater and marine environments a review of recent evidence on the effects of enrichment.*Limnol. Oceanogr*. **33 :** 796-822.

Hecky,R.E.and Bugenyi,F.W.B.(1992).Hydrology and chemistry of African Great lakes and water quality issues:Problems and Solution *Mitt.verein.neternat.Limnol*., **23**:4554.

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

Holmes, R.W. (1970). The Secchi disc in turbid coastal waters.*Limnol.Oceanogr*.**15**:688-94.

Hötzel, G. and Croome, R. 1999.A Phytoplankton Methods Manual for Australian Freshwaters. Land and Water Resources Research and Development Corporation. Canberra, Australia.

Hendrson, H.F, Ryder, R.A. AND Kudhogina, A.W. (1973).Assessing fishery potentials of lakes and reservoirs. *J.Fish.Board Cand*. **30**:2000-2009.

Henrikson, R. (1989): Earth Food *Spirulina.* Ronore Enterprises. - Kenwood, california.

Jeeji-Bai, N., Hegewald, E. and Soeder, C. J.(1977). Revision and taxonomic analysis of the genus Anabaenopsis. Arch. Hydrobiol. 51:3-24.

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.

Klemperer, S. L. and Cash, M. D. 2007. Temporal geochemical variation in Ethiopian Lakes Shala, Arenguade, Awasa, and Beseka: Possible environmental impacts from underwater and borehole detonations. Journal of African Earth Sciences 48:174–198.

Lehman, J.T. and Branstrator, D.K. (1994). Nutrient dynamics and turnover rates of phosphate and sulfate in LakeVictoria, East Africa. *Limnol. Oceanogr.*, **9(2):** 227-233.

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. (1983). Phytoplankton production. In: Lake Chad: Ecology and productivity of a shallow tropical ecosystem. J.P.Carmouze, R.Durandand C. Leveque (eds.), ,Monogr. Biologicae **53,** the ague, Junk. pp. 357-384.

Lewis Jr W. M., and Levine, S. N.(1984) . The light response of nitrogen fixation in Lake Valencia, Venezuela. Limnol.Oceanogr. **29**: 894 – 900.

Lewis, Jr W. M.(1990). Comparisons of phytoplankton biomass in temperate and tropical lakes. Limnol. Oceanogr. **35(8):** 1838—1845.

Lewis, Jr W. M. (2000). Basis for the protection and management of tropical lakes. Lakes and reservoirs : *reaserch and management*. **5 :** 35 – 48.

Livingstone, J. A., Melack, D. M. (1984).Some lakes of sub-Saharan Africa. *Lake and reservoir ecosystems*. **23** : 467- 497.

Long, S.P., Humphries, S. and Falkowski, P.G. (1994). Photo-inhibition of photosynthesis in nature. *Ann. Rev. Plant Physiol. Plant. Mol. Biol*., **45**:633-62.

Maberly, S.C. (1996). Diel, episodic and seasonal changes in pH and concentrations of inorganic carbon in a productive lake.*Freshwat. Biol*., **35**: 79-598.

Malone, T.C. (1971). The relative importance of nanoplankton and netplankton as Primary producers in the California Current System. *Fish. Bull*., U.S., **69**:779-20.

Mackereth, F.*J.H., Heron, J.and* Talling, J.F. (1978). Water analysis:Some revised methods for limnologists. FBA. Scientific publication. No.36.120 pp.

Melack, J.M. (1976a). Primary productivity and fish yields in tropical lakes.*Trans. m. Fish. Soc.*, **105**:575-580.

Melack, J.M. (1976a). Primary productivity and fish yields in tropical lakes.*Trans. m. Fish. Soc.*, **105**:575-580.

Melack, J.M. (1976b). Limnology and dynamics of phytoplankton in Equatorial African lakes. PhD. thesis.Duke University Durham, N.C,453 pp.

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

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

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

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

Melack,J.M.(1988).Primary Producer dynamics associated with evaporative concentration in a Shallow equatorial Soda lake (Lake Elmenteita,Kenya). *Hydrobiologia*, **158**:1-14.

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.

Michael,J.V.(2002).Spatial and Seasonal Variation in nutrient excretion by benthic invertebrates in eutrophic reservoir. *Freshwater Biology*. **47(6)**:1107-1121.

Oglesby, R.T. (1977). Relationship of fish yield to phytoplankton standing crop, production and morphoedaphic factors. J. *Fish. Res. Bd, Can.,**34**:2271-279*

Osmond,C.B. (1981). Photorespiration and photosynthesis: some implications for the energetics of photosynthesis .*Biochim.Biophys.Acta,***639**:77-98.

Rediet Abate (2008). Seasonal studies on phytoplankton in relation to some biological and physico-chemical factors in Lake Hora-Kilole, Ethiopia. Msc. Thesis, Addis Ababa University, Addis Ababa, 66pp.

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

Ryder, R.A. (1974).The morphic –edaphic index, fish yield estimator-review and evaluation.*J.Fish.Res.Bd.Can.**31***:663-668.

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

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

Saunders,G.W.,Trama,F.B. and Bachmann,R.W.(1962).Evaluation of modified C14 technique for Shipboard estimation of photosynthesis in large lakes. *Mich.Univ.Great Lakes.Rs.Div.Publ,*8.61pp

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

Seyoum Mengistou (2006). Status and challenges of aquatic invertebrate research in Ethiopia: a review. *Ethiop. J. Biol.Sci.* **5(1):** 75 – 115.

Silva, E.L.L., Amarasinghe, U.S., De Silva, S.S, Nissanka, C. and Chiemer,F.(2002). Some aspects of photosynthetic characteristics in a set from perennial irrigation reservoirs located in the river basins in Sri Lanka *Hydrobiologia*, **485:**19-33.

Steemann-Nielsen, E. (1962). Inactivation of the photochemical mechanism in photosynthesis as a means to protect the cells against too high light

intensities. *Physiol. Plant*. **15**:161-171.

Steemann-Nielsen, E. and Jorgensen, E.G. (1962). The physiological background for using chlorophyll measurements in hydrobiology and a theory explaining daily variations in chlorophyll concentration. *Arch. Hydrobiol*., **58**:349-357.

Schindler,D.W., and Fee,E.J.(1974).Primary production in freshwater, p.155-158.*In proc.Int.Congr.Ecol.(1st)*The Hague.

Smayda, T. (1990). Novel and nuisance phytoplankton blooms in the sea: Evidence from algal epidemic. **In**: Toxic marine phytoplankton (Granchi, E., Sundstrom, B., Edler, L. and Anderson, D. M., eds), pp. 29-40, Elsevier, New York.

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.

Talling,J.F.and Driver,D.(1963).*Some problems in estimation of Chlorophyle 'a' in phytoplankton.* Proc.Conf.on primary productivity measurement, marine and freshwater U.Satomic energy comm.TID7633.Pp142-146.

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

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.

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

Talling, J. F. (1987). The phytoplankton of Lake Victoria (East Africa). *Arch. Hydrobiol. Beih.Ergebn. Limnol.* **25**:229-256.

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

Talling, J.F. (1995).The Photosynthetic activity of Phytoplankton in East African lakes. *Int.Rev.ges.Hydrobiologia*.,**50**:1-32.

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

Talling, J.F.and Driver, D. (1963). Some problems in estimation of Terrestrial algae. The British Physiological Society, Cambridge Taxonomic analysis of the

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.

Tenalem Ayenew (2009). *Natural lakes of Ethiopia.* Addis Ababa University Press, Addis Ababa,206pp.

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

Vnoshak, A. (1987): Biological limitations in developing the biotechnology for algal mass cultivation.- Sciences de 1` eau, **6**:99-103.

Vonshak, A. & Richmond, A. (1988): Mass production of the blue-green alga *Spirulina*: an overview.- Biomass **15**:233-247. mass cultivation.- Sciences de 1` eau, **6**:99-103.

Wetzel, R.G. and Likens, G.E. (2000). *Limnological analyses*. Third edition. Verlag, New York, Inc. N.Y. 357pp.

Wetzel, R.G. (2001). *Limnology: Lake and River Ecosystems.3*rdedition, Academic Press, New York. 1104pp.

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. (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.

Zelalem Dessalegn (2006).Temporal dynamics of biomass and primary production of

phytoplankton in relation to some phsico-chemical factors in Lake Kuriftu, Ethiopia.

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 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.

Zinabu Gebre-Mariam (2002). The effect of wet and dry seasons on the concentration of solutes and phytoplankton biomass in seven Ethiopian lakes .*Limnologica* **32**:169-179.

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.

9. APPENDIX I. **Formulae used for the estimation of physical, chemical and biological parameters**

1. Alkalinity (meql^{-1}) :……..(Wetzel and Linkens, 2000)

$$\frac{(\text{N of acid} \times 1000) \times V_{\text{acid}}}{\text{V of sample titrated}}$$

Where N=normality

V=volume

2. Phytoplankton Abundance (Hotzel and Croome, 1999; Wetzel and Likens, 2000).

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

Where = 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

3. Phytoplankton biomass estimation

a) Chl a (μgL^{-1}) = $\frac{13.9(E_{365} - E_{750})\, V}{V_s \times Z}$ (Talling and Diver, 1963)

Where,

E_{665} = extinction at 665 nm

E750 = extinction at 750 nm

V_e = volume of extract (in ml)

Vs = path length of the cuvette (spectrophotometeric cell) (in cm)

b) Euphotic zone chl a,

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

4. Euphotic depth (Z_{eu}) .... ……(Kalff, 2002).

$Z_{eu} = 4.6/K$, K = 1.7 / Z SD, where SD –secchi depth(m)…… (Kalff, 2002).

K SD

5. Primary production (Wetzel and Likens, 2000; APHA, 1999; Lind, 1997).

a) determination of oxygen mg O 2 L^{-1} = (ml titrant)(N of thiosulphate)(8000) / (ml sample titrated))

b) Gross photosynthesis, GP (mg C/m3/h):

GP (mg C / m3/h) = [O2, LB)-(O2, DB)] [(1000) (0.375)]/PQ (t)

OR

GP(mgO2/m3/h) = [(O2,LB)-(O2,DB)](1000)] /t

Where, t = hours of incubation, O2 = oxygen in mg/l, LB =light bottle ,DB =dark bottle

1000 = conversion factor from liter to m^{-3}

0.375 = the ratio of mole of carbon to moles of oxygen (12mg C/32 mg O2)

PQ = photosynthetic quotient, assumed to be 1.2

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

NP (mg C/m3/h) =

$$\frac{[(O2, LB)-(O2, IB)]\ [(1000)\ (0.375)]}{(PQ)(t)}$$

Where IB =Initial bottle

d) Respiration (mg C/m3/h) = (O2, IB)-(O2, DB) (1000) (0.375)] /(RQ) (t)

or

R = (mg O2/m3/h) = [(O2, IB)-(O2, DB) (1000) /(t)RQ

where RQ =respiratory quotient assumed to be one

e)Daily integral photosynthesis,

A (O_2 m $^{-2}$ d $^{-1}$) = A x 12 x 0.9 (Talling ,1965)

f) Biomass –specific hourly rate of gross photosynthesis, p

P (mg O 2(mg chl a)-1 h -1 = A (mg O_2 $m^{-3}h^{-1}$) / mg Chl a mg $^{-3}$

6. From Saunders *et al*., 1962

mg DIC = (TA-PA) X0.240 , where

DIC is the total free carbon dioxide (dissolved inorganic carbon) in mg/l.
TA-Total AlkalinityPA-phenolphthalein alkalinity.

APPENDIX II. Collective chemical features of Lake Arenguade: pH, Total Alkalinity (TA), Phenolphthalein Alkalinity (PA) and calculated dissolved inorganic carbon (DIC) of Lake Arenguade .

Sampling date	PA (meq L^{-1})	TA ((meq L^{-1})	DIC (mg L-1)	pH
1/12/08	11.6	44.96	8.01	
21/12/08	12.8	50.00	8.93	
5/01/09	10.5	47.60	8.90	
2/02/09	10.6	47.70	8.90	
23/02/09	10.8	47.50	8.33	
16/03/09	11.1	50.60	9.48	
30/03/09	11.5	50.60	9.38	
26/04/09	11.3	47.50	8.70	
28/05/09	10.5	48.00	9.00	
14/06/09	12.2	48.50	8.71	
18/07/09	12.2	49.50	8.95	9.62
09/08/09	12.3	49.30	8.88	9.84
12-10-09	10.0	47.00	8.88	
28/01/10	-	33.00	-	9.67
1/06/09	12.6	47.90	8.47	9.77

.

APPENDIX III. Statistical relationships among physico-chemical and biological parameters measured in Lake Arenguade .

Independent	Dependent	Sample				The

variable	Variable, Y	size (n)	R	R^2	P	resulting equation
Chl a	Z_{SD}	13	- 0.1897	0.0361	0.5349	y = - 0.0001x + 0.2919
Chl a	Amax	13	0.5333	0.2838	0.0609	y = 5.0887 + 368.69
SRP	Chl a	13	0.1271	0.0153	0.6871	y = 0.8162 + 1214.4
NO_3^-	Chl a	13	0.0089	0.00008	0.9764	y = 0.236 + 148.13
SiO_2	Chl a	13	0.0264	0.0007	0.9296	y = 0.1555x + 152.57
Chl a	max	13	- 0.3276	0.1073	0.0025	y = 0.0166x +10.427
Chl a	∑A	13	0.5334	0.2845	0.0605	y = 0.0044x + 0.2845
Amax	∑A	13	0.7860	0.6177	0.0014	y = 0.0007 + 0799