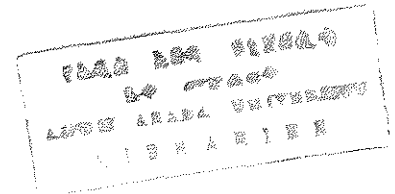


A STUDY ON PRIMARY PRODUCTIVITY AND NUTRIENTS IN
ABIJATA EVAPORATIVE CONCENTRATION PONDS.

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ABSTRACT

Changes in primary productivity and nutrients were studied *in-situ* in three Abijata evaporative concentration ponds (B, C, D), intake channel (A) and the main lake for seven months from October, 1996 to April, 1997 (9 samplings). Data were also recorded for related physical and meteorological parameters including: temperature, wind speed, light, and water chemistry. Phytoplankton biomass was measured as chl-a. Photosynthesis was estimated by oxygen evolution with the Winkler and Miller methods, and ^{14}C was also used three times for comparison during the study period. The level of pond water fluctuated considerably in response to water influent from the main lake, precipitation and evaporative concentration. In all the studied water-bodies, there was no appreciable stratification in temperature except pond D with greater temperature at the bottom. Intensive wind mixing is a common feature in the ponds.

Ionic concentration in pond D exceeded by more than 15 times over the channel and pond B. Similar patterns were observed in the composition of major nutrients, except phosphorus. There was strong positive relationship between increasing salinity and alkalinity but inverse relationship with pH and phosphorus was observed. The concentration of dissolved inorganic nitrogen is extremely high ($>14\text{mg/l}$) in all water-bodies. No nutrient limitation was found during the study period.

A total of 11 phytoplankton genera were identified in the lake, channel and pond B, of which *Anabaenopsis* represent $>50\%$ of the community in number. This persisted as an unialgal population in pond B during the dry months when ionic concentration was also high. Diatoms compose the greater part of the algal community, particularly during the rainy months (March-April, 1997) and increased water level. Among diatoms, *Navicula* and *Nitzschia* species were dominant at all times, except the dry months. *Spirulina platensis* was found in lower frequency when compared with reports from earlier studies.

Mean chl. a concentration in the main lake, channel and pond B were 8.16, 16.14, 4.23 mg m^{-3} , respectively, much lower than values reported by earlier investigators. Areal photosynthetic rates ranged from 0.2 to 1.05 $\text{g C m}^{-2} \text{h}^{-1}$ in the channel, and 0.042 to 0.414 $\text{g C m}^{-2} \text{h}^{-1}$ in pond B. It is about 5 g C m^{-2} when extrapolated to daily rate in pond B while in the lake and the channel it does not exceed beyond 11 $\text{g C m}^{-2} \text{d}^{-1}$. This is much lower than the usual rates for African alkaline-saline lakes. The major factors that influence primary productivity during the study period include the higher level of sulphate, declined alkalinity and higher salinity along the concentration gradient. It was found that Miller method is the best technique of estimation of photosynthetic rate in such alkaline-saline waters.

These data for primary productivity and nutrients are discussed in relation to their implications for large scale production and control purposes in the ponds.

1. INTRODUCTION

Alkaline-saline lakes are less useful for any consideration in irrigation, domestic use and traditional agricultural purposes. The production of fish in saline lakes is limited to those of lower salinity. As the salinity increases, fish populations and the majority of other fauna become less diverse (Beadle, 1981). Thus commercial and game fishing is rather uncommon in inland saline lakes. However, such lakes are of particular ecological interest because of their extremely high primary production rates for the development of aquaculture technology, in view of cultivating for the commercial and nutritional purposes.

Saline as well as subsaline lakes are very important as habitat for a large number of bird and wildlife fauna (Vareschi and Jacob, 1985; Elizabeth Kebede, 1996). Most of the African saline rift valley lakes are of tourist attraction because of such rich fauna. Lakes including Nakuru (Kenya) and the three closely related lakes of Ethiopia (Abijata, Shalla and Chitu) are of special importance in providing feeding and breeding ground for a bird fauna of over 360 species of resident and migratory birds (Vareschi and Jacobs 1985; Wood and Talling, 1988).

Besides their biological uses, saline water-bodies have economic and industrial values, such as trona (sodium sesquicarbonate), soda ash (sodium carbonate) and halite (sodium chloride), all obtained from evaporative sediments by surface mining (Hammer, 1978; Williams, 1981).

The biology of natural saline waters has been studied extensively over the years. Studies on primary productivity of the alkaline-saline lakes: Aranguadi, Ethiopia (Talling and Talling, 1965; Talling et al., 1973); Lake Maruit, Egypt (Aleem and Samaan, 1969); Kenyan soda lakes (Kilham & Melack, 1974; Melack, 1981; Vareschi, 1982); Ethiopian rift valley soda lakes (Amha Belay and Wood, 1984; Wood and Talling, 1988); Lake Chad (Iltis, 1969); saline lakes of Saskatchewan, Canada (Hammer, 1978, 1981 & 1983) and Lake Texococco, Mexico (Ogawa, 1978) have shown that these lakes are among the world's most productive waterbodies. Particularly in the African rift valley soda lakes, such high productivity is usually associated with *Spirulina* blooms (Amha Belay and Wood 1984; Vareschi and Jacobs, 1985).

Such high primary productivity of saline alkaline lakes has raised interest in these water-bodies. Part of this growing interest lies in the potential for commercial exploitation of the algal production for various products. Growth of the eukaryotic alga, *Dunaliella salina* in hypersaline waters, for example, serves as a source of carotenoids and glycerol (Johnson *et al.*, 1968; Bauld, 1981).

Spirulina spp. that grow over a wide range of salinity can be an excellent substitute for protein in human nutrition and is also known for its commercial use as a source of vitamins, essential amino acids and fatty acids (Richmond, 1978; Ciferri, 1983). Thus microbial mass production offers an interesting alternative for biomass production in certain arid and semi-arid zones, using saline water not suitable for conventional

agriculture. Recently *Spirulina* sp. are also reported to have various therapeutic properties because they possess pharmaceutical compounds, dietary vitamins and hormones (Amha Belay *et al.*, 1993).

Several investigators (Melack, 1979b; Beadle, 1981; Wood and Talling, 1988; Elizabeth Kebede, 1996) concluded that *Spirulina* abundance and productivity both artificially and under natural conditions, depend on physical parameters such as high temperature and irradiance and chemical factors such as high pH and alkalinity.

Blue green algae are generally much more tolerant of higher temperature (mesophilic) than other algae. In the laboratory, the optimal temperature for *Spirulina* growth is between 35-37°C with 40°C being injurious. The minimum temperature that still permit some growth of *Spirulina* sp. is about 18°C (Ogawa, 1978).

Although *Spirulina* spp. can tolerate high salinity, up to 270g/l, they are generally characteristics of mesosaline lakes (ca. 20- 50g/l) (Beadle, 1981) Very alkaline conditions (>250meq/l) support massive growth of *Spirulina* sp. But whether the alga can actually assimilate carbon dioxide from carbonate at such high pH is questionable. Many investigations however suggest that carbonate utilization at high pH levels might be a basis for the known high productivity of soda lakes (Talling and Talling, 1965; Iltis, 1968; Wood and Talling, 1988). During *Spirulina* blooms in alkaline soda lakes, phosphate is more likely to be limiting than nitrogen while during low algal densities, the reverse may be true (Melack, 1979b; Vareschi and Jacobs, 1985).

Generally such environmental (meteorological and limnological) conditions are believed to be optimum for the growth of *Spirulina* and enable it to outgrow other species in such a way that it maximally utilizes the limited resources of such harsh environments.

Though there are some published scientific information on the ecology and limnology of phytoplankton in alkaline water-bodies, limnological literature on ponds are very few. The most notable ones which are of interested with respect to fish cultivation ponds are those of George (1961), Cole *et al.*, (1967), Dunn (1967) and Cohen *et al.*, (1977).

Studies on the productivity of alkaline-saline lakes of Ethiopia include those made on Aranguadi (Talling and Talling, 1965; Talling *et al.*, 1973; Demeke Kifle *et al.*, 1995 unpublished) and Rift Valley soda lakes (Amha Belay and Wood, 1984 ; Wood and Talling, 1988; Elizabeth Kebede, 1996). All these investigators concluded that *Spirulina platensis* is the dominant phytoplankton in these lakes.

The productivity of Lake Abijata was first studied by Talling (1965) and later by Kassahun Wodajo (1982) Amha Belay and Wood (1984) and Wood and Talling (1988). Elizabeth Kebede (1996) reported that *Spirulina platensis* (*Arthrospira fusiformis*) is co-dominant of the phytoplankton community in lake Abijata together with a recently described species, *Anabaenopsis abijatae* (Elizabeth Kebede and Willen, 1996). The limnology of evaporative concentration ponds at Abijata has not

been described so far. The present study is the first of its type to be made on the productivity of Abijata evaporative concentration ponds.

A few studies on natural productivity in ponds (eg. Rao, 1955; Zafar, 1964; Cole, 1967; Cohen *et al.*, 1977) have shown that most of the factors influencing the distribution of algae in lakes (also) play a significant role in ponds (as well). Based on the physico-chemical and biological measurements of lakes both *in-situ* and under laboratory conditions, artificial mass production in cultivation ponds has been carried out in different parts of the world such as in U.S.A, Israel, Mexico and Thailand. It is clear that the environmental factors affecting artificial cultivation are much more closely related to natural productivity in a pond than a lake. Thus the aim of the present study was to investigate temporal variation of natural primary production in artificial concentration ponds.

Algal populations are also nuisances or pollutants in drinking water reservoirs (Marshall and Flacnor, 1973; Stanely and Alpers, 1975; Baxter, 1977; Melaku Mesfin, 1983), water-based recreation (Reynolds, 1984), fertilized fish ponds (Lawrence, 1966) and salt evaporative concentration ponds (Cohen *et al.*, 1977). In the concentration ponds of lake Abijata, seasonal occurrence of algal blooms has resulted in coloration of the trona product. This problem of algal bloom has been reported as the cause of reduction in trona quality for the last ten years (Report, Abijata soda ash developmental project 1995-96). However, there is no scientific information on the environmental conditions that lead to the development of these algal blooms.. Moreover, recommendations for proper treatment methods to combat the problem are

non-existent. It was the objective of this study to investigate this problem in some detail.

Limnologists measure photosynthetic rate either as change in dissolved oxygen or carbon fixation. There are several controversies with respect to the choice of methods and comparison of results obtained by the different methods. The old, but still in use method of dissolved oxygen measurement (the Winkler method) has difficulty in very alkaline saline water-bodies. Amha Belay and Wood (1984) reported the problems encountered due to the formation of bubbles (effervescence) upon acidification in lakes Abijata, Shalla and Chitu. All the results obtained are almost certainly underestimates. Kilham and Melack (1974) recognized the problem and used combined methods of ^{14}C , Miller, Winkler and polarographic, after which they chose the polarographic method from the rest. The present study tried to use different techniques and to compare the data with studies of other workers who worked on saline lakes, and the methods between themselves.

The objectives of the present work on Abijata evaporative concentration ponds were

1. to gather basic meteorological and limnological data on the Abijata ponds and identify the factors that govern algal productivity, with the view of using such data for mass production purposes in the long term,
2. to compare the abiotic and biotic factors that determine (affect) the productivity of the evaporative ponds and the lake,
3. to determine plankton composition and productivity along the salinity gradient in the ponds,

4. to evaluate the suitability of the common methods of measuring primary productivity measurements to tropical alkaline- saline waters so as to provide necessary data to develop a standard method of productivity for such water-bodies,
5. to investigate the cause of coloration in the extraction ponds so as to devise control strategies for the coloration problem in the trona product of the Abijata soda ash enterprise.

2. Description of the Study Area

Lake Abijata is situated in the Northern part of the Ethiopian rift valley some 200 kms south of Addis Ababa (Fig1-I). It is a terminal lake within the closed Ziway-Shalla basin.

The lake is of tectonic or volcano-tectonic origin (Dipaola, 1972). Lake Abijata is believed to be part of lakes Langano, Shalla and Ziway as a large rift lake before they were separated by faulting and other crustal movements as well as desiccation (Mohr, 1962).

The lake basin (Fig.1-I) is within the semi-arid climate where evaporation exceeds rainfall. A four months dry season (November-February) is generally followed by a rainy season of eight months with the mean annual rainfall of generally less than 600 mm (Daniel Gemechu, 1977). Apart from direct rainfall, Lake Abijata receives effluents primarily through Bulbula river which comes from Lake Ziway, and the Hora Kello river which originates from Lake Langano.

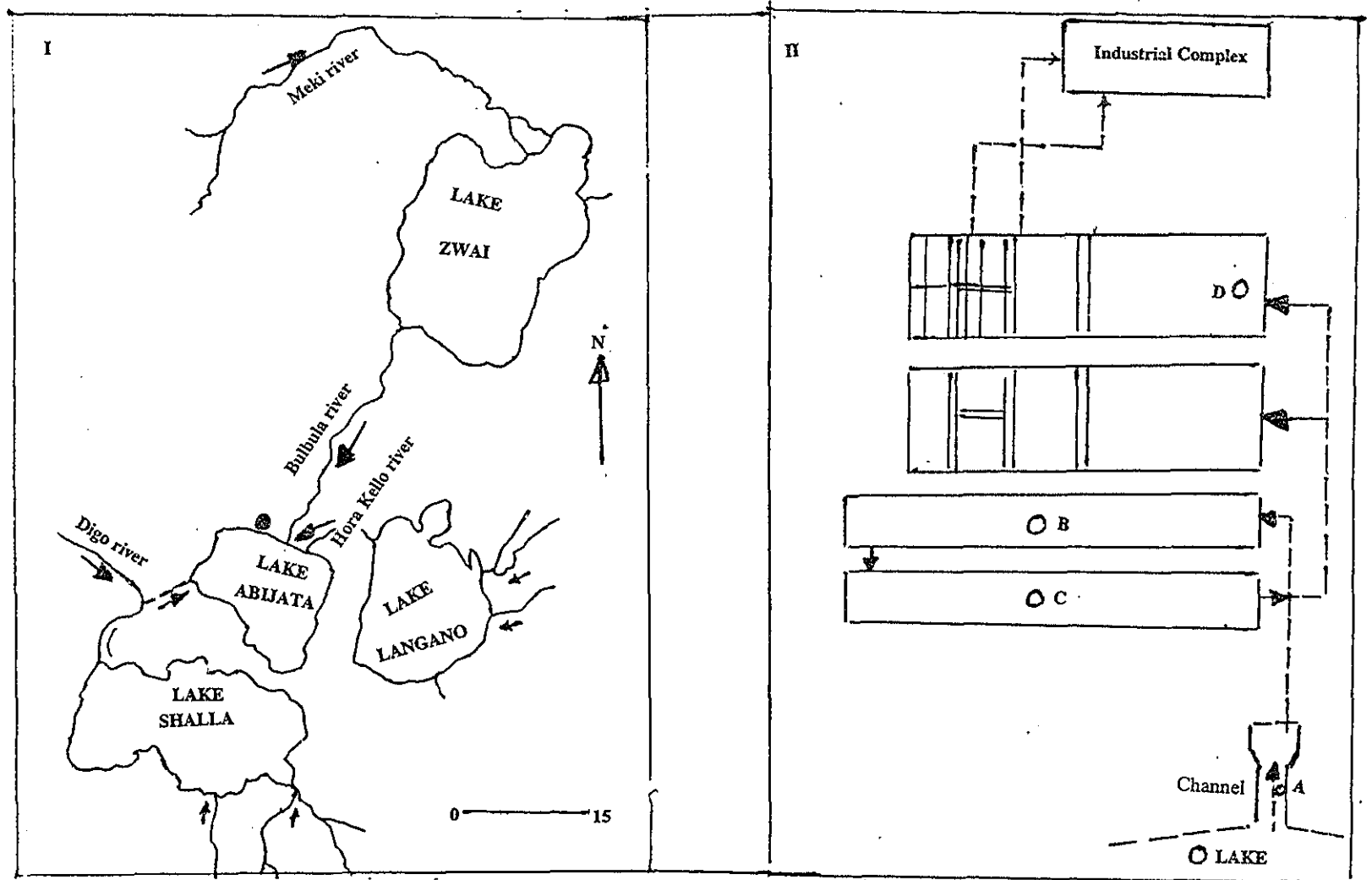


Fig 1. The drainage system of the northern Rift Valley lakes (I) (source Elizabeth Kebede, 1996) and a sketch of Abijata ponds (II, not to scale) with sampling stations indicated by circles.

Lake Abijata, like its neighboring Lake Shalla, is of tourist attraction because of its rich bird fauna. The natural vegetation in the area includes *Acacia* and scrub grassland. Macrophytes are entirely absent from the shoreline of the lake. The presence of only one species of fish, *Tilapia nilotica* (*Oreochromis niloticus*) L. has been documented from this lake before (Kassahun Wodajo, 1982; Wood and Talling, 1988). It is believed that climatic variations and recent developments in the shore area of the shallow Lake Abijata have resulted in an overall progressive increase in salinity and alkalinity levels and change of biota (Wood and Talling, 1988).

2.1. Sampling sites

The study was made on three concentration ponds of the Abijata Soda Ash Enterprise, including the lake and channel. The ponds, which are situated at about 4 km from the shore of the lake cover an area of about 150 hectares, and have an average depth of 25 cm. There are two large and more than twenty small ponds at Abijata which are separated by earthen embankments and interconnected by effluent pipes. The ponds get water by water pumped through a pipe from the surface intake channel located near a point source of the lake (Fig. 1-II). The ponds are open and exposed to solar radiation and wind- mixing throughout the day. There are seasonal blooms of algae in the pre-concentration ponds and one can see white salt ashes bordering the banks, and dead algal scums floating on the surface in the highly concentrated ponds (pers. obs.).

The study was carried out on four different ponds coded as A (channel), B (pond 200), C (pond 201) and D (pond 210); the numbers in parentheses are codes of the enterprise. The lake water was sampled only three times (February to March, 1997). The two pre-concentration ponds (B and C), each occupies an area of 500,000 m², with maximum dimension of 6 km by 71 m. The trona extraction pond (D) with an area of 100,000 m² is constructed in the same manner as the previous ones. All pond water lie on impermeable plastic floor (PVC lining). A sketch of the ponds with the experimental stations as labeled above is shown in Fig 1-II.

3. MATERIALS AND METHODS

3.1. Sampling protocol:

Samples were collected every two weeks or monthly from each of the five stations from October 1996 to April 1997. Each selected pond was chosen at an appropriate transect along the salinity gradient. All the samples were taken at approximately the mid-point of each pond. The first two pre-concentration ponds (B & C) were sampled at the same time. However, pond D, the Channel (A) and the lake were sampled on the following day owing to logistic problems that precluded the execution of productivity measurements on the same day.

Pooled water samples were taken with a plastic bucket from each pond. These samples were used for the analysis of chl-a, inorganic nutrients and measurements of photosynthetic production. Aliquots of samples from each pond were fixed with acid Lugol's solution (1ml/100ml sample) for counting of phytoplankton. Duplicate samples were collected with a phytoplankton net of mesh size 25 μ m and fixed with Lugol's solution for the identification of phytoplankton.

3.2. Physical parameters

Meteorological data such as temperature, rainfall and wind speed were obtained from the weather station of the enterprise approximately 50 meters south of the ponds.

In Situ measurements of lake and pond water temperature and dissolved oxygen concentration were carried out with an Oxygen meter (YSI model 58) connected to an oxygen- temperature combination probe. Only surface water temperatures were measured since all ponds are shallow (max. depth, 30cm). However, oxygen was measured at depths of incubation.

Underwater Photosynthetically Active Radiation (Ph.A.R) was measured in $\mu\text{E m}^{-2} \text{sec}^{-1}$ with LI-COR quantum sensor (LI- 192SB) connected to a quantum photometer (LI-18SB).

The irradiance impinging upon the water surface was recorded at 20 minutes intervals during the incubation period using LI-S10B integrator. The reading was converted to absolute units, $\mu\text{E m}^{-2} \text{sec}^{-1}$ using LI-192SB as a standard. Vertical visibility of each pond was estimated with a standard Secchi disc, 20cm in diameter.

Electrical conductivity and salinity were measured with combined conductivity-salinity and temperature probe (YSI-Model 33 *S C T* meter). Temperature corrections were made to 25⁰C as in Wetzel and Likens (1979). pH was measured *in situ* with a digital pH meter (Cole Parmer).

3.3. Chemical parameters

Chemical analyses were made duplicate and unfiltered samples on site. The samples of ponds C and D were diluted 4, 8 or 16 times with deionized water to avoid interference and to record values which exceeded the maximum reading of the meter probes. Most chemical analyses of unfiltered water (except for phosphorus) were done within one hour of collection, with Hach kit, following the procedures outlined in the manual provided by the manufacturer (model DREL/IC). Total alkalinity was determined by titration with 2N sulphuric acid using phenolphthalein and Bromocresol green - Methyl red mixed indicator (Golterman *et al.*, 1978) during the time of incubation. Nitrate, Nitrite, Ammonia, Sulphate and Silicate were measured colorimetrically in the field using a portable Hach kit. Phosphate was determined about six hours after sampling in the laboratory (department of biology, AAU). These analyses were done on water samples filtered through Whatman Glass Fiber filters (GF/C). Orthophosphate (without extraction) was determined spectrophotometrically as blue phospho- molybdate complex. Total phosphorus was determined after digestion of 50 ml duplicate samples with persulphate as described in APHA *et al.*, (1981).

3.4. Biological parameters

Rate of photosynthetic production was primarily measured by the light and dark bottle technique. Two transparent and one opaque glass bottles of 150ml capacity

(nominal) were suspended horizontally at a few depths (0, 15, 25 cm) using a stand with clamps for ponds and vertical hanging with rope for both channel and the lake at depths of 0, 20 and 40 cm. Precautions were taken when siphoning to avoid bubbling. Incubation time was usually two hours between 10 am and 12 noon.

Dissolved oxygen concentration in the bottles was estimated by the Winkler Azide modification (Golterman *et al.*, 1978) and Miller's method. Miller titration was carried out as described in Williams *et al.*, (1970). The Winkler, Miller and C¹⁴ methods were compared in order to determine the most suitable one for measuring photosynthetic rates in very alkaline waters. Depth and time of incubation were the same for all methods although Carbon-14 method was employed less frequently (three times, February to March, 1997).

The Miller method was slightly improvised by using 2 ml graduated dropper and a flask sealed with aluminium foil to avoid uptake of atmospheric oxygen during titration. Dissolved oxygen in mg/l was calculated as in Ellis and Kanamori (1973).

In the carbon-14 method, 1ml of Na₂ ¹⁴CO₃ solution with a specific radioactivity of 2 µci/ml was added to 150 ml incubation bottles with an automatic syringe of the type described by Goldman (1973). At the end of the incubation period, the samples were placed in an ice box. Four hours after incubation, 50 ml subsample was filtered with vacuum pressure onto Millipore membrane filters (25 mm diameter with 0.45µm pore size) in the laboratory (department of biology). Moist filters were transferred to a

scintillation vial containing 20 ml liquid scintillation cocktail. Radioactivity was measured using a liquid scintillation counter (Beckman - LS 5000TD) in the laboratory at the Faculty of Medicine. Rates of photosynthesis in $\text{mgC m}^{-3} \text{h}^{-1}$ were calculated as in Lind (1979).

Phytoplankton biomass was estimated using chlorophyll a concentration and cell number as biomass indicators. A 100 ml aliquot from each of the three sites (lake, channel, and pond B) was passed through Whatman Glass Fiber filters (GF/C), and the pigment extracted over 24 hours in cold 90% methanol. The extract was centrifuged and its absorbance measured at 665 and 750nm with Pye-Unicam SP6-350 visible spectrophotometer (path length, 1cm) before and after acidification with 2 drops of 4N HCl (Wetzel and Likens, 1979).

Identification of phytoplankton species was done both on net and sedimented samples. Subsamples preserved for counting were allowed to settle in sedimentation chamber for 24hrs and enumeration was done with a Nikon,type 108 inverted microscope (mag. 1000X) as described in Jones (1979) and Mackereth *et al.*, (1978).

4. RESULTS AND DISCUSSION

4.1. Physical features:

The lake level increased from October, 1996 to the end of November and declined steadily from December, 1996 to February, 1997. A small rise in the lake water level was observed during March to May, 1997 (wet months). It dropped to a minimum in September, 1996 and April, 1997. The unusual rise in Nov. 1996 (about 400 m) was probably associated with internal seepage from the surrounding Lake Shalla and hydrothermal hot spring near Lake Langano. The decline of the lake level during the dry season was greatly influenced by evaporative concentration and effluents to pre concentration ponds (pers. obs.).

The level of pond waters fluctuate considerably in response to water influent (pumping action) from the lake, precipitation and evaporative concentration.

Mean surface water temperature during the incubation period was 22.07°C in the channel and 28.93°C in pond B. The mean temperature of water in pond D (35.4°C) was the highest value recorded. Unlike other ponds bottom temperature in pond D was higher than the surface, which is due to the high density of the brine (in pond D, because water expansion by heat is not sufficient to allow overturn, relatively stable stratification is observed in bottom water) compared to less saline ponds, B and C.

The water temperature declined steadily from October to the end of December 1996 in both channel and pond B and increased from January to its maximum value, 27°C and 40°C in March 1997 in A and B, respectively (Table 1). In the channel and pond B there was no appreciable stratification in temperature.

Wind speed was very high except in December, 1996 and a range of wind speed (of 8-15Km/h) may produce isothermy during the day time (Fig 2). Twenty Km/h wind speed were common in the afternoon (Meteorological data observation). Furthermore, the mixing potential of pond B was greater than that of channel (deepest of the sampled waters).

Air temperature ranged from 16.4 to 30°C in the study area. Highest air temperature was recorded in March and April, 1997 during the less windy periods. High light intensity of 365 cal/m³ in April, 1997 coincided with peaks in temperature and rainfall (Fig 2).

In the main lake and channel, usually 90% of the surface irradiation was lost above 50 cm, whereas about 50% of the incident radiation reached the bottom in pond B (Fig 11 and 12). Little light penetrates the surface layer of pond D. This could probably be due to a change from the natural color to reddish suspension, caused by organic matter decomposition, phytoplankton detritus and/or large population of bacteria. Attenuation of light reaching to the bottom of pond D may also be caused by sodium bicarbonate precipitates in the water column over the entire pond which settle to the bottom. With time these salt slush compacts to form a concrete-like layer.

Table 1. Some physical features of Lake Abijata and its concentration ponds

	Altitud (m)	surface Area (km ²)	Max. depth(m)	Mean Depth (m)	Max. air Temp. (°c)	Mean air Temp. (°c)	Max. water temp. (°c)	Mean water temp. (°c)	surface insolation ($\mu\text{Em}^{-2}\text{sec}^{-1}$)	Secchi depth (cm)
Main lake	1578	176	14	8	33	30	25	22	2100	20
Channel (A)	-----	0.2	3	3	33	30	27	25	2100	50
Pond B	-----	0.6	0.4	0.35	33	30	32	28	2934	whole depth
Pond C	-----	0.6	0.2	0.2	33	30	35	32	2934	whole depth
Pond D	-----	0.09	0.15	0.15	33	30	40	35	2934	whole depth

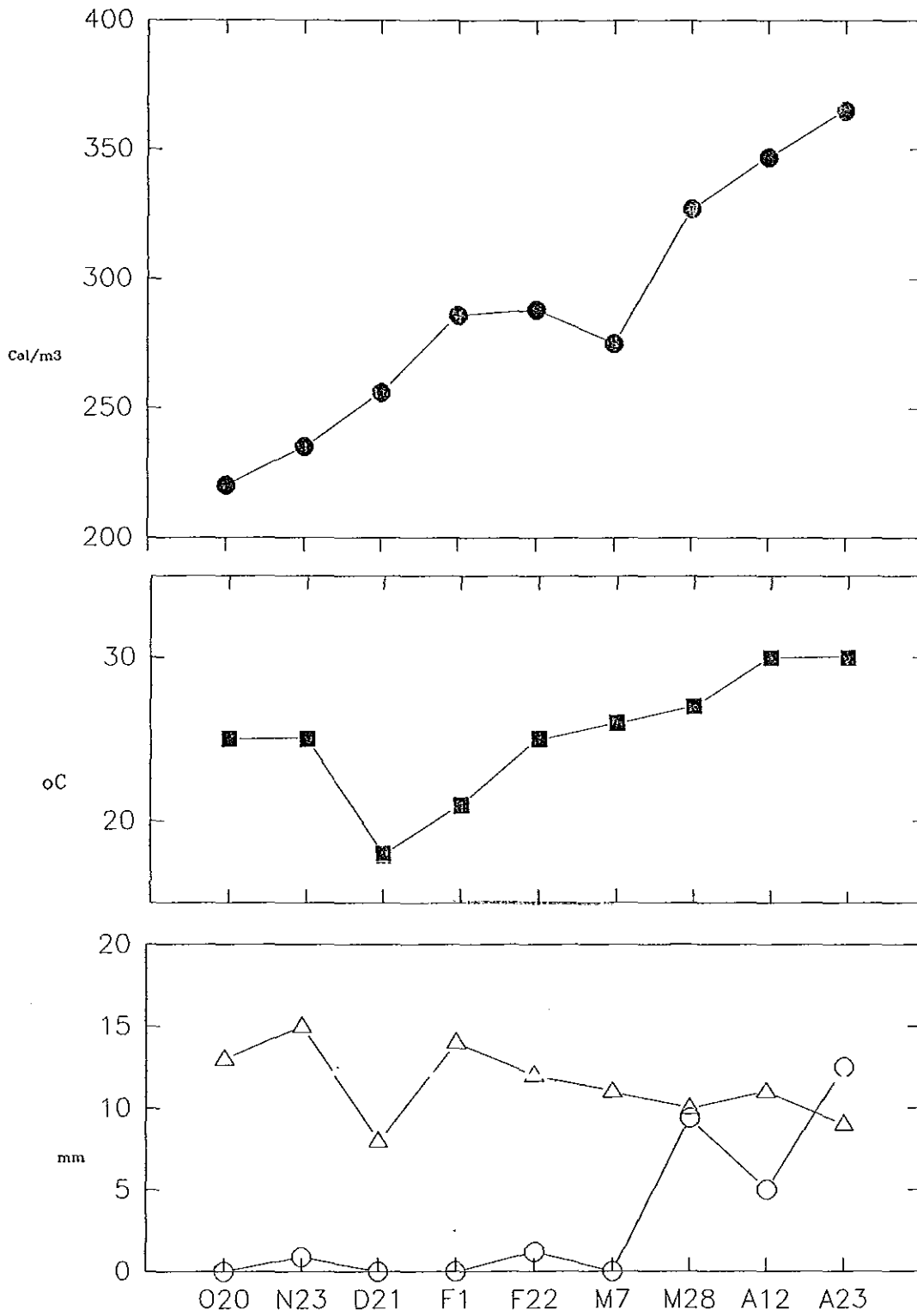


Figure 2 Variation in air temperature (■) Wind speed (∇) Rainfall (O) and solar radiation (●) in Lake Abijata. (source Meteorology station)

Measurements of Secchi disk transparency in the channel (Table 1) were slightly higher (av. 48cm) than typical alkaline saline lakes, such as Simbi and Arenguadi (av. 27 cm) (Melack, 1981). Even though the transparency was lower during rise in water level (usually in pond B), the disk reading was the same as the maximum depth of the pond water which can be seen to the bottom. The lowest Secchi disk visibility that was recorded (20 cm) in March and April, 1997 in the channel was due to cloud cover.

4.2. Chemistry of Ponds

4.2.1. Conductivity and Salinity

Electrical conductivity (K_{25}) was between 11.2 and 19.5mmhos/cm in the Channel and 14 to 24.5 mmhos/cm in pond B (Table 2). Measurements of salinity were highly correlated with conductivity, especially in more saline waters. The relationship of conductivity to salinity along concentration gradient from the channel to the pond D is presented in Figure 4-I. Surprisingly, both parameters increase linearly up to 300 ppt, which is much higher than usual relationships, which start declining at 3-5ppt (Wetzel and Likens, 1979). In pond C, salinity and conductivity varied between 17 to 204 g/l and 32 to 176 mmhos/cm, respectively. Pond D is taken to represent the last phase in the concentration sequence. Salinity of pond D was about 20 times greater than the channel and pond B, and three times that of pond C. In all the ponds, the highest observed salt concentration occurred during the dry season when atmospheric temperature reaches its peak, 30°C (February and early March, 1997).

Table 2 Mean values for some chemical characteristics of the sampled water bodies

study site	Reference	Sampling Date	Cond. (mScm ⁻¹)	Sal. (g/l)	pH	Total Alk. (Meq/l)	TDN (mg/l)	Total Po ₄ -P (µg/l)	SiO ₂ (mg/l)	SO ₄ (mg/l)	Dissolved Oxygen (mg/l)
	Wood & Talling (1988)	Mar. 1964	15.8	16.2	10.3	166.5	-	50	128	22.5	-
Main Lake	Elizabete Kebede (1996)	Mar. 1991	28.1	26	9.85	349	<0.1	511	114	24	-
	Lake shore	Feb-Mar. 1997	16-20 18.3(3)	10-18 15(3)	10-10.6 10.2(3)	111-126 117.67(3)	14.2	820-4625 2230(3)	3.6-6 4.86(3)	20-40 28(3)	9.2-10 9.6(3)
Channel	This study	Oct 1996- Apr 1997	11-29.5 16(9)	9.4-17 12.9(9)	9.8-11.5 10.5(9)	100-260 146.59(9)	16.4	370-4250 980(9)	4.6-7 5.91(9)	15-130 51.53(9)	2.4-6.6 5.17(9)
B	This study	"	14-24.5 18.9(9)	13.8(9) 7.5-21.5	9.8-11 10.4(9)	110-360 185.67(9)	15.8	350-4590 1620(9)	3.5-11 7.55(9)	15-150 67.63(9)	4.5-11.1 7.38(9)
C	"	"	32-176 90.7(9)	81.8(9) 17-204.	9.8-10.9 10.3(9)	320-5900 1243.5(9)	40.3	125-844 308(9)	8-15 10.68(9)	56-400 166.38(9)	0.8-7.9 4.53(9)
D	"	"	144-480 322.8(9)	120-480 255(9)	9.4-10.8 10.0(9)	752-5840 2437(9)	138.9	115-615 349(9)	20-64 44.75(9)	80-1800 400.25(9)	0.4-3.9 2.15(9)

Legend: Numbers above and in front (parentheses) of the average values show ranges and sampling frequency, respectively

Furthermore, salinity increase was detected during the period of prolonged evaporative concentration (at times of no water influent to the pond) in November, 1996 and March to April, 1997. Lower values were recorded during the month of precipitation in March, 1997 and high water influent from the lake in October, 1996 and with decreased in temperature in Dec. 1996 (Fig 3).

Salinity of water in ponds such as solar lakes in Israel resulted from natural accumulation through evaporation. In extreme cases, evaporation may establish homogenous brine conditions (Por,1968). Similar conditions were observed in pond C and D.

Increasing evaporation rates with lowering of the water level lead to increasing salinities. This process is accelerated during the period of high temperature, March and April, 1997. It seems that both the atmospheric temperature and rainfall influence the total solid contents of pond waters. It is noted that, when the temperature rises, the total solids increase enormously, during the rains, it becomes dilute with a sharp fall in the total solids (Zafar, 1964a).

Results from the main lake indicate that as the lake level increases, the salt concentration also tends to increase. Ganf and Viner (1973) is of the opinion that the water level does not always coincide with the rate of salt concentrations, but Njuguna (1988) found an indirect relationship between the two. In the present study, the direct relationship would probably be due to internal seepage from the neighboring Lake, Shalla, though it is situated at lower altitude.

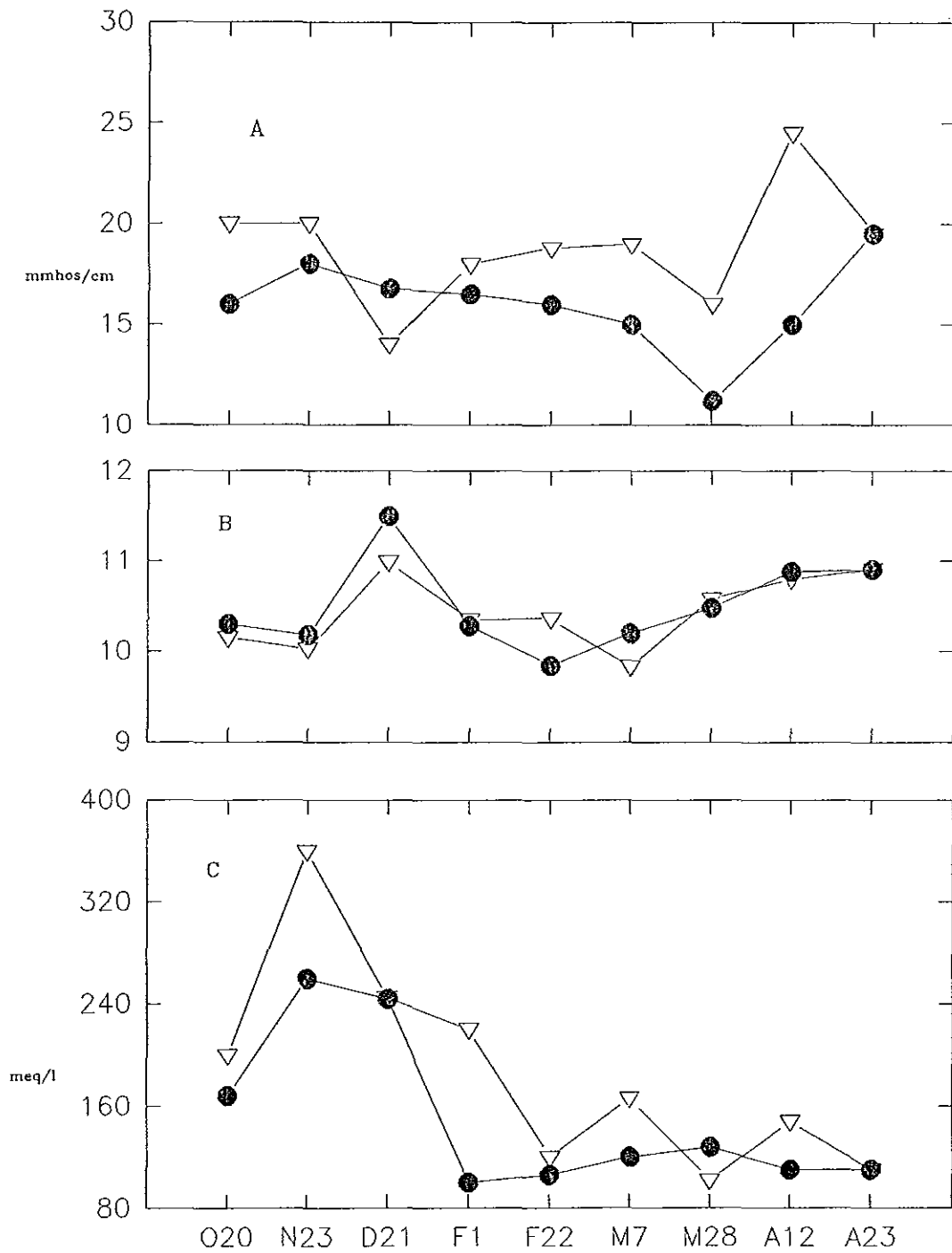


Fig. 3. Temporal variation in (A) conductivity
 (B) pH and (C) total alkalinity of the
 canal (●) and pond B (▽).

4.2.2. pH and Alkalinity

Carbonate and bicarbonate alkalinities varied from 100 to 260 meq/l in the channel and 102 to 360 meq/l in pond B. The highest alkalinity in all ponds were recorded in November, 1996 which is associated with prolonged exposure (about a month) to evaporation compared to other times (usually 15 days) [pers. obs]. High values were also recorded during Feb, 1997 when there was an increase in evaporation rate. During the onset of rainfall in March which reduces the ionic concentration, the total alkalinity declined and then rose in May, 1997 during prolonged evaporative concentration (Fig 3C).

Values for pH vary between 9.84 and 11.5 in the channel, and 9.83 and 10.80 in pond B. No marked temporal variation was observed in pH within each sampled site (Fig 3B).because of high buffering capacity. There was always inverse relationship between pH and alkalinity (Fig 4-II). The relationship between pH and total solids (salinity and alkalinity) does not appear to be a direct one as pointed out by Fogg (1956) and Klemer (1982). This is more evident in pond C and D than in less alkaline, channel and pond B. This agrees with the views of Rao (1953) who pointed out that the alkaline ponds are invariably richer than acidic ones in dissolved solids. In the present study, the inverse relationship between pH and total solids cannot be explained with respect to this point. However it is possible that the degree of pH value depends on certain factors along with total solids, such as nature of the salt content (abiogenic), high rate of decomposition

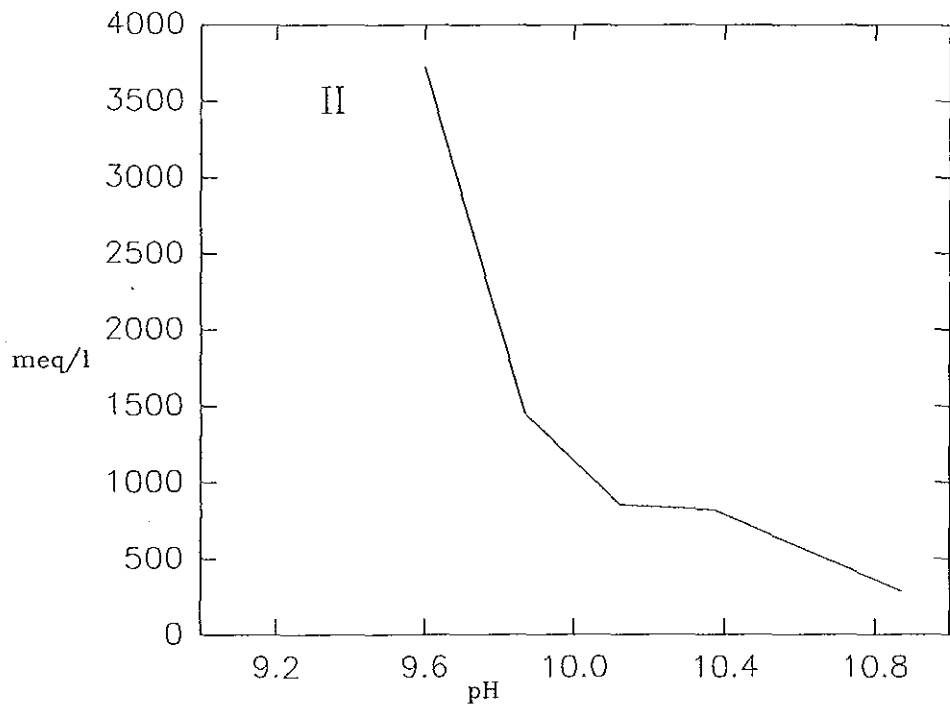
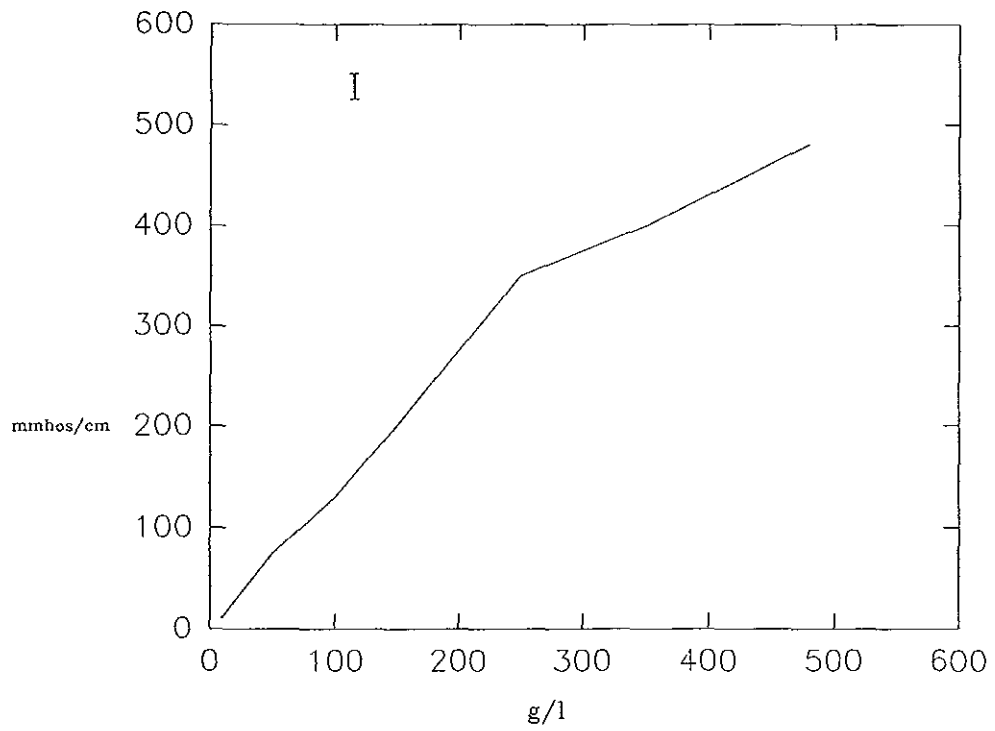


Figure 4. Relationship of conductivity and Salinity (I), and Alkalinity and pH (II) in surface waters of sampled ponds (channel to pond D).

and respiration. The pH gradient along ponds with high alkalinity is probably affected by the reduction processes of highly active heterotrophic bacterial communities (Truper and Genoves, 1968; Cohen *et al.*, 1977). Moreover, Zafar (1964a) has shown that a marked increase in the mineral content of water occurred when the pH was artificially lowered from 6.09 to 2.09 by adding sulphuric acid to the pond water.

Fluctuations in surface dissolved oxygen (Table 2.) were practically an expression of concentration of dissolved solids and wind mixing (turbulence) which affect the solubility of gases. The highest surface dissolved oxygen (av. 7.38 mg/l, >80% saturation) was especially the result of intense wind mixing, instead of high photosynthetic activity. In pond D, the difference in densities between upper and lower layers prevents circulation which exclude oxygen, resulting in anoxic dense brine layer. Although oxygen concentration is reduced in the deeper water perhaps due to respiration, complete deoxygenation was not attained in the productive ponds. Kilham and Melack (1974) reported similar results in Lake Nakuru where complete deoxygenation was not recorded but remained stratified. In fact the higher supersaturation of dissolved oxygen was more likely to have a significant effect on the biota than oxygen depletion (Owens, 1965 ; Ganf, 1975).

4.2.3. Major nutrients

The total mean dissolved nutrient concentration (NO_3 , NO_2 and NH_4^+) for all sites is shown in Table 2. Major nutrients were found abundant throughout this work. In most cases, nitrate concentrations were very high, varying between 6.5 and 30 mg/l in the channel and 5 to 22 mg/l in pond B. A pronounced increase occurred in October, 1996 and at the end of April, 1997 (Fig 5-1).

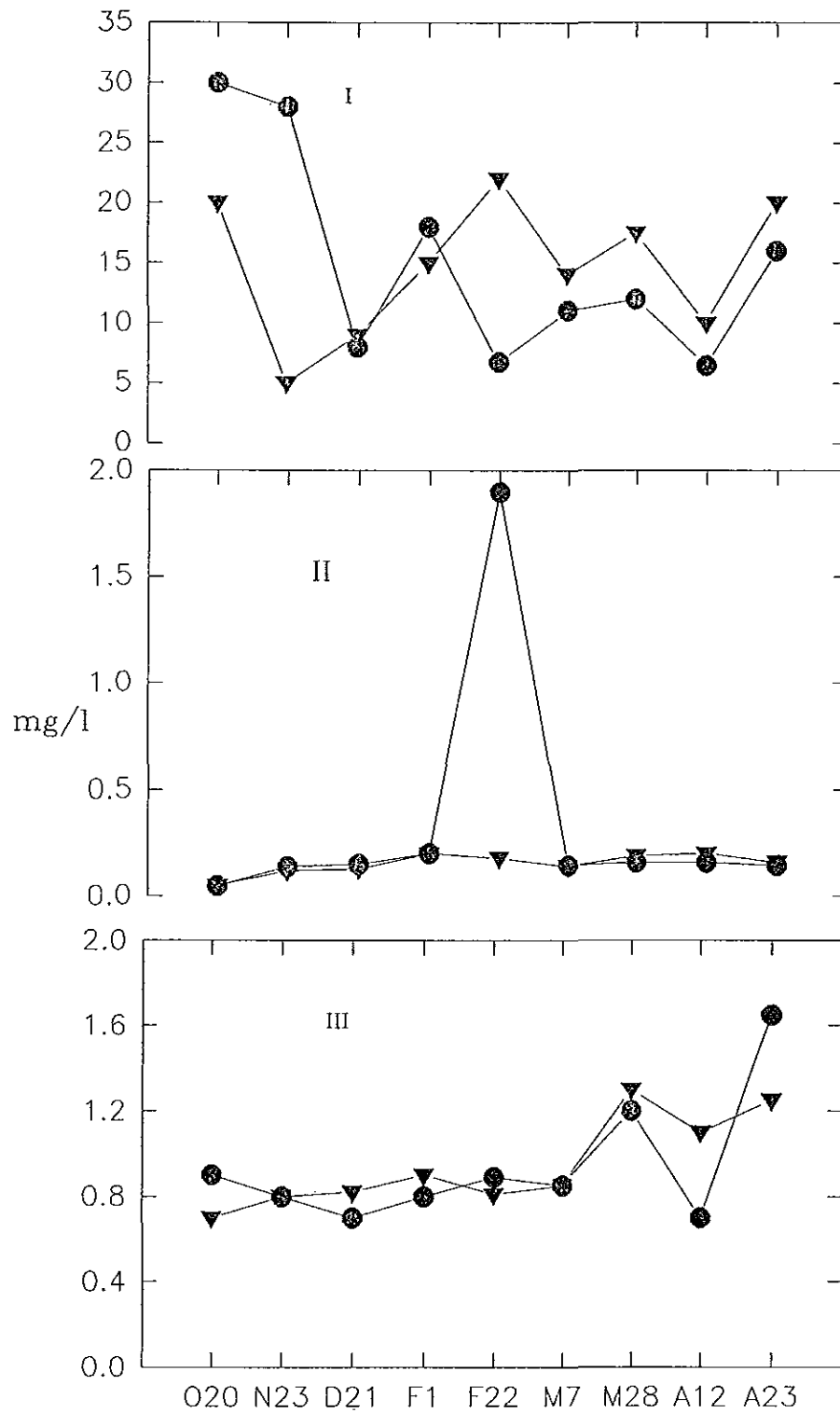


Fig. 5. Temporal changes in nitrate (I), nitrite (II) and ammonia (III) of the channel (●) and pond B (▼)

This could be due to rains that caused dissolution and nutrient loading from the drainage area at the time. Higher level of nitrate was also observed in pond B in Feb, 1997 and this might be attributed to nitrogen fixation by the blue green alga, *Anabaenopsis abijatae* which formed a unialgal population biomass during the dry season (December, 1996—February, 1997) (Elizabeth Kebede, 1996)

Nitrate nitrogen value for the channel and pond B were on the average are about 70 times greater than Nitrite and Ammonia Nitrogen. The rise in reduced form of nitrogen, particularly Ammonia probably coincided with increase in atmospheric temperature and calm weather conditions during March, and April, 1997, which produce slight stratification that facilitate the process of reduction and decrease the solubility of oxygen. Moreover, organic substances may be added to the ponds and channel as a result of flooding due to higher precipitation during March- April, 1997.

Nitrogen concentration is generally very low in saline lakes ($< 1 \mu\text{g/l}$) [Moss, 1969; Njuguna, 1988]. However in this study the concentration of dissolved Nitrogen was unusually high (av. 15 mg/l). Possible factors include intense mixing that causes recycling of nutrients and the large number of cattle herds around the area and bird fauna at the shore of the lake, both of which cause considerable input of nitrogenous wastes into the lake and ponds. Wood and Talling (1988) and Elizabeth Kebede (1996) have reported total dissolved nitrogen of $< 1 \mu\text{g/l}$ for Lake Abijata, which is relatively much lower than the values (av. 14.23 mg/l) found in the present study. This is possibly either due to the difference in the methods used for analyses or decreased biological activities at present (less uptake of nutrients).

The concentrations of the two fractions of phosphorus at the sites investigated is shown in Table 2. The ranges of soluble reactive phosphate was 105 to 4110 $\mu\text{g/l}$ in the channel, and 300 to 4004 $\mu\text{g/l}$ in pond B. In March, 1997 phosphorus concentration increased abruptly (Fig. 6). Total phosphorus followed a similar trend as the soluble one. Similar to Nitrogen, the March, 1997 peak of phosphorus can be associated with rainfall. Although the process of reduction and higher population of zooplankton increase in the release of phosphate from the sediments as a result of temperature rise in March, 1997, the concentration of dissolved oxygen remained high throughout the depth (Workayehu Amare, AAU; pers. comm.)

The concentration of phosphorus declined from A to D along the salinity gradient (Fig 7-II). Decreased phosphorus in pond C and D may be associated with its reaction with other elements (abiogenic factors) or probably bacterial uptake. Its incorporation by phytoplankton and bacteria can cause a very rapid depletion of available phosphate (Shapiro, 1973). High phosphate concentrations have been also reported for many alkaline saline lakes (Talling and Talling, 1965; Prosser *et al.*, 1968; Talling *et al.*, 1973; Kalff, 1983). Direct measures of algal incorporation of phosphorus from a productive soda lake in Kenya, L. Nakuru were $9850 \pm 1000 \mu\text{gl}^{-1}$ for total phosphorous and $149 \pm 53 \mu\text{gl}^{-1}$ for soluble reactive phosphate (Vareschi, 1978). Wood and Talling (1988) reported approximately $3200 \mu\text{gl}^{-1}$ from a less saline and highly productive lake, Aranguadi. In Elmenteita (Kenya) total phosphate was about $910 \mu\text{gl}^{-1}$ (Kalff, 1983).

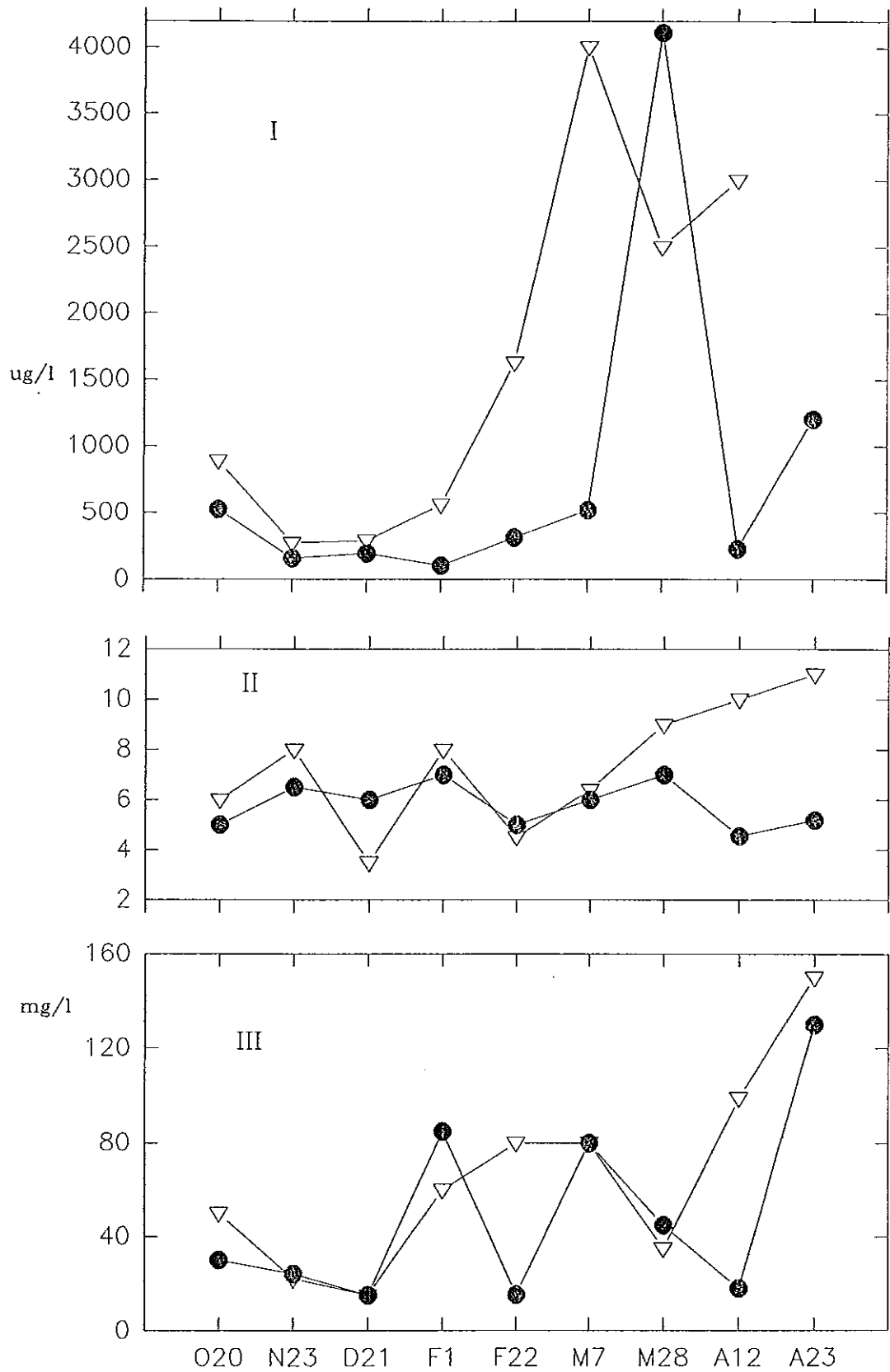


Fig. 6. Temporal variation in (I)soluble reactive phosphate, (II) silicate and (III)sulphate in the channel(▽) and pond B (●).

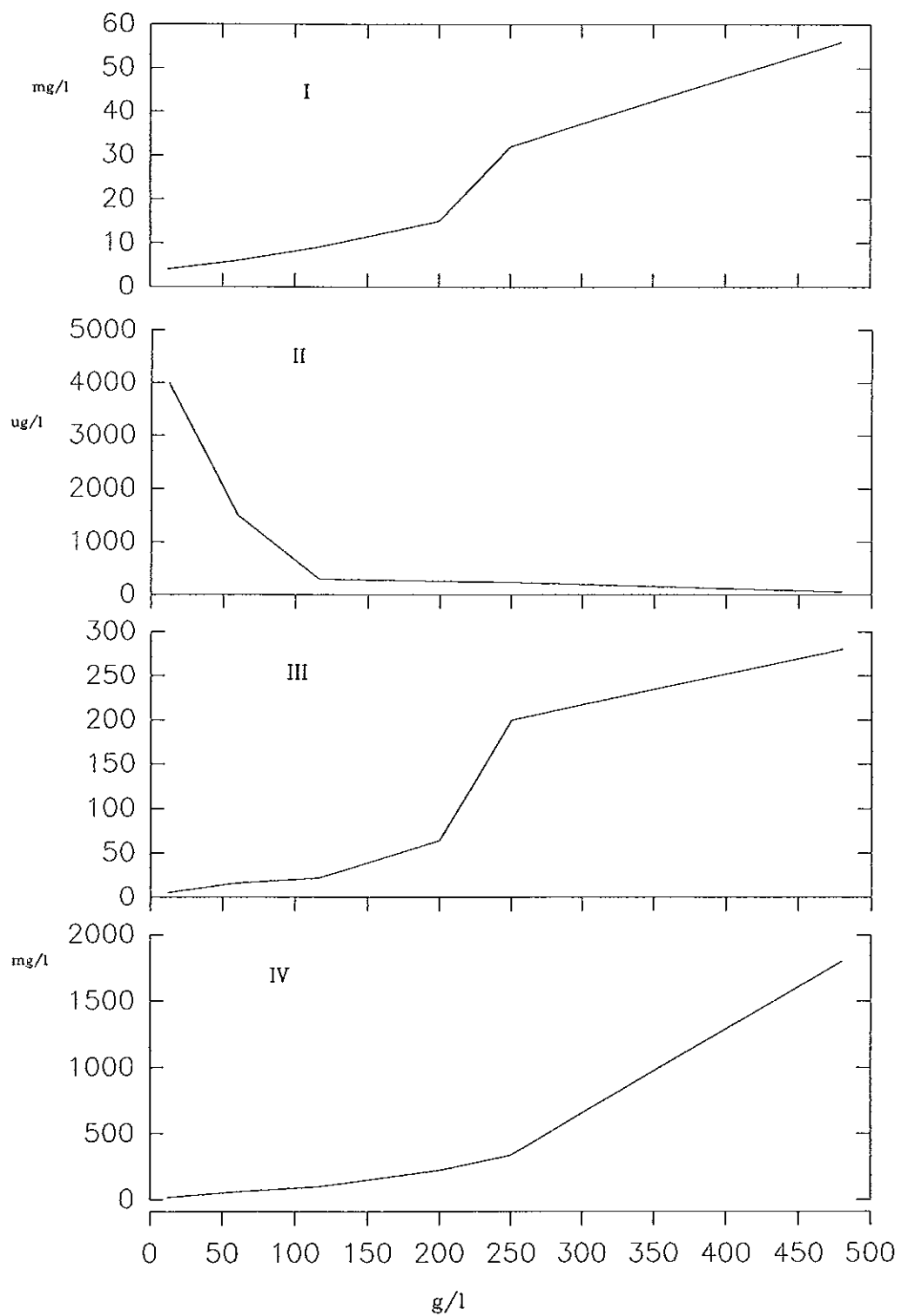


Figure 7. Variation in concentration of (I) silicate
 (II) soluble reactive phosphate, (III) and
 nitrate (IV) sulphate in surface waters of sampled ponds
 with increase in salinity.

Total dissolved nitrogen (TN) to soluble reactive phosphorus (weight-volume ratio) ranged from 3.25 to 180.95 in the channel, and from 4.52 to 55.52 in pond B (Fig 8-D). The N:P ratios remained above the Redfield ratio, 16:1 (Shapiro, 1984) for most of the study period. A ratio of nitrogen to phosphate below the Redfield ratio was observed during March and April, 1997 which is attributable to the unusual high concentration of phosphate (4 mg/l).

The phytoplanktonic community was dominated by *Anabaenopsis abijatae* and *Lyngbya* species at pond B which also coincided with N:P ratios lower than the Redfield ratio. Similar conditions have been observed in East African alkaline saline lakes, Nakuru and Bogoria (Tuite, 1981). Moreover Smith (1983) and Shapiro (1973) showed a clear reduction in the proportion of the blue green algae as a result of changes in the TN:TP ratio.

Blue green algae tended to dominate when $TN:TP < 29$ (by weight) and become rare when $TN:TP > 29$. These data are consistent with the present result, where most of the time TN:TP ratio was greater than 29. This provides strong support for the hypothesis that nutrient ratios are one important determinant of the species composition and abundance of natural phytoplankton communities (Ustach and Paerl, 1982; Njuguna, 1988). The increase in N:P was due to the very high concentration of Nitrogen (particularly nitrate) rather than low concentration of Phosphorus. Moreover biological removal of nitrate was presumably low. The sharp decline in N:P ratio (4.52) in pond B coincided with the increase in the concentration of phosphorus in the water column and with the chlorophyll maximum.

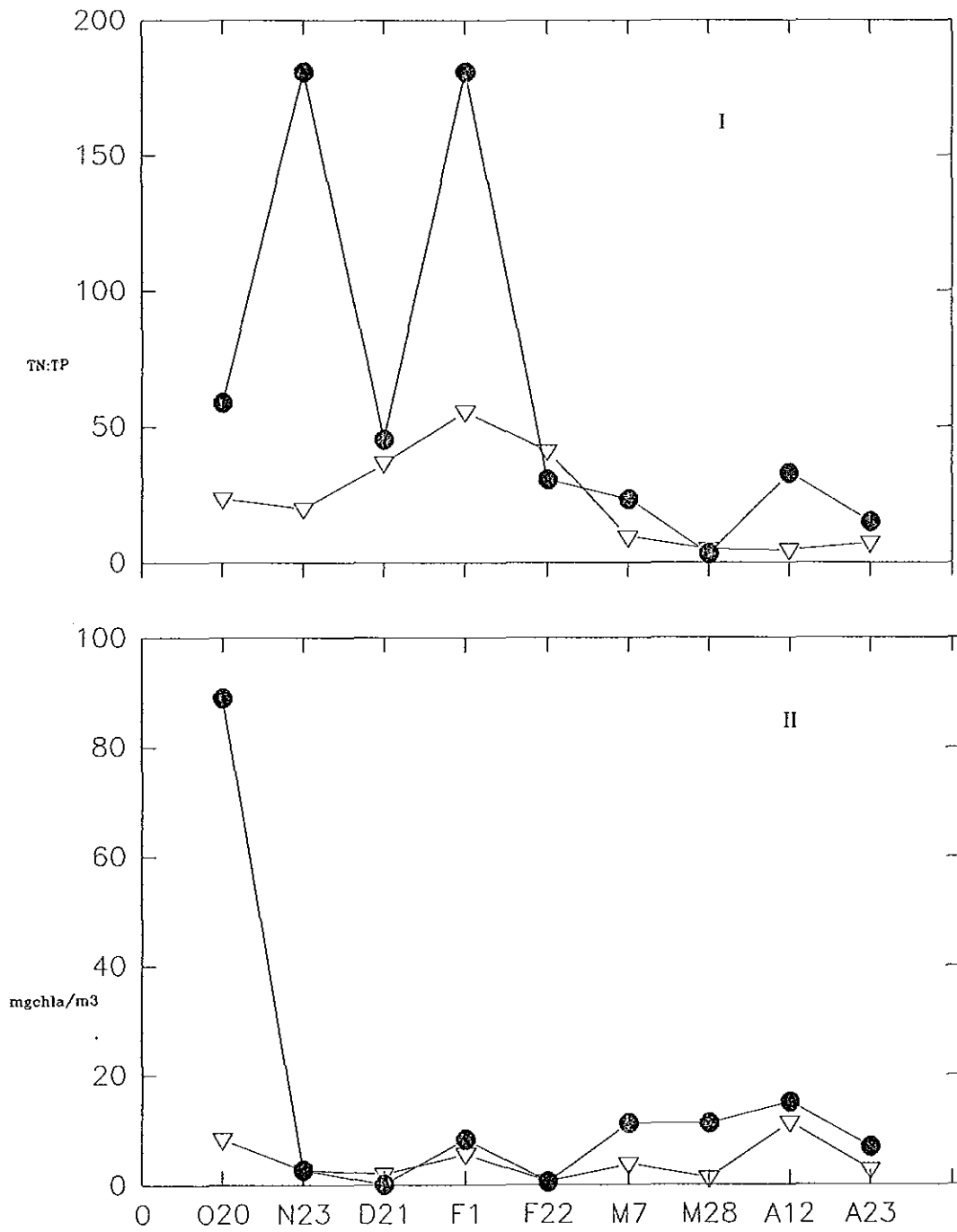


Figure 8. Temporal changes in TN:TP ratio (I) and chl-a concentration (II) in the channel (●) and pond B (▽).

It is evident that pond B was comparatively rich in phosphate, silicate and sulphate. On the other hand, the channel was relatively rich in the average concentrations of nitrate. Ammonia concentration did not change. Both of them however, lie at the same level with regard to the concentration. The high level of nitrate in the channel and lake is associated to the number of bird fauna and cattle herds.

Silicate to phosphate ratio (Si: P) in relation to the biomass of phytoplankton, is shown in Fig. 9. Silicate concentration in pond B showed increased level in April, 1997 like ammonia, phosphate and sulphate. Silicate concentration was almost uniform throughout the study in the channel. This indicates that in both waters relationship between chl.a and silicate concentration was poor (Fig. 6-II).

Temporal variation in sulphate concentration is presented in Figure 6-III. A peak in sulphate concentration occurred in April, 1997, presumably brought about by water influent (flood) from the surroundings and dissolution as a result of heavy rainfall in April, 1997. Moreover the high level of sulphate throughout the study period when compared to the previous ones (Wood and Talling, 1988; Elizabeth Kebede,1996) may probably be due to internal drainage. In general, sulphate contributes the smallest fraction of the major ions in Ethiopian water bodies (Wood and Talling, 1988). This feature, common in East and Central African lakes, can primarily be related to a low contribution from rocks containing little sulphate.

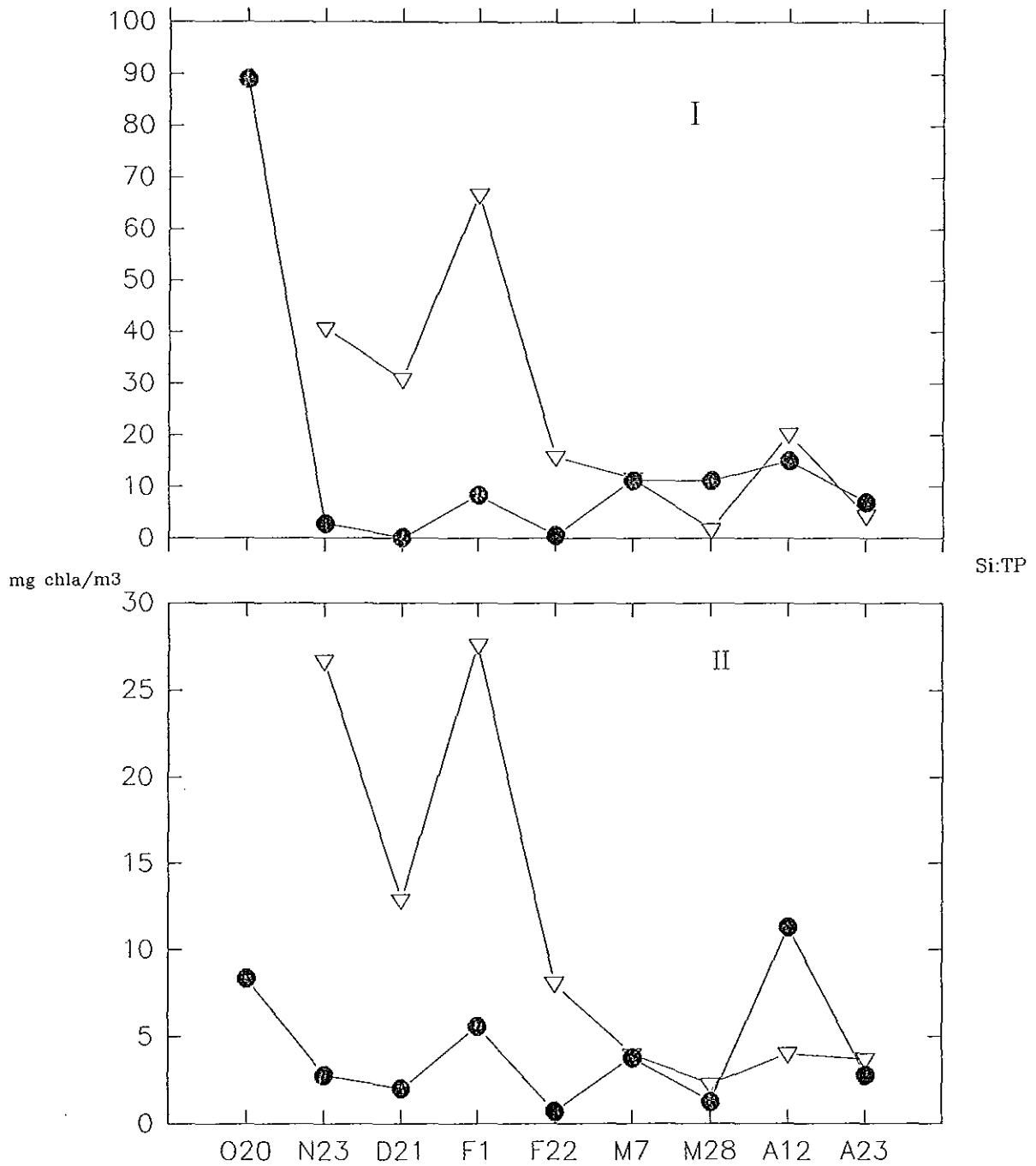


Figure 9. Chlorophyll (●) and Si:TP ratio (▽) relationships in the channel (I) and pond B (II).

Figure 7 summarizes the relationships between concentrations of the three major nutrients (including sulphate) and salinity. Silicate and nitrate are almost linearly associated to salinity while phosphate is negatively related. Similar results have been reported by Wood and Talling (1988), except for phosphorus. Although there is a broad trend of increasing sulphate concentration with increasing salinity, the relationship is still less regular than that for silicate. Among the possible sources of irregularity, abiogenic and biogenic (bacterial activity) transformations in the ponds are likely to be important.

The negative relationship of phosphorus with salinity can be explained more probably by abiogenic rather than biogenic processes. A general increase in nutrients (except phosphorus) along the salinity gradient might be due to evaporative concentration, declined consumption and release of organic decomposition products in the water column.

Nitrogen and Phosphorus concentrations were higher (av. 16.4 mg/l for Nitrogen and 1.6mg/l for Phosphorus) when compared to other alkaline, saline lakes. Nitrate was at lower limits of detection in most saline lakes (Melack *et al.*, 1982; Wood and Talling, 1988; Njuguna, 1988). Soluble reactive phosphate was found to be quite low in the majority of temperate lakes and ponds (Peters and Macintyre, 1976, Cohen *et al.*, 1977). This corresponds well with the findings of the present study where phosphorous was high in all the sampled waters.

4.3. Phytoplankton species composition

A total of 11 phytoplankton genera were identified in the samples collected from the surface of the lake, channel and ponds. Phytoplankton biomass based upon filament or cell number per ml is shown in Table 3.

The phytoplankton diversity was low in composition, so that dominant species were usually readily distinguished. Total number of cyanobacteria do not exceed 15000 cell and/or filament per ml. In both the channel and pond B, filamentous algae *Lyngbya*, *Anabaenopsis* spp. and a number of diatoms were usually important in terms of number and formed the conspicuous population maximum in October, November and April, 1997 (Fig. 10). The channel contained a phytoplankton community dominated by diatoms. Diatoms of *Navicula* (av. 286 cells/ml) & *Nitzschia* (208 cells/ml) species were the dominant plankton algae, except in February, 1997, when they were totally absent. Of the genera of green algae, *Oocystis* (av. 150 cells/ml) species were common. In April, 1997 the phytoplankton community was dominated by masses of blue greens, *Anabaenopsis abijatae* and *Lyngbya* species, with lesser amount of diatoms. In February, 1997 *Anabaenopsis abijatae*, was common as unialgal populations though less abundant (120 cells/ml). A unialgal population in February, 1997 was poorly associated with its ability of nitrogen fixation, since the concentration of nitrogen was high throughout the study period.

Table 3. Variation in phytoplankton biomass (count/ml) in the sampled water-bodies.

	The main Lake		Channel (A)		Pond B	
	Range	Mean	Range	Mean	Range	Mean
Cyanophytes		N=9		N=9		N=9
<i>Spirulina platensis</i>	0-78	48	0-65	39	0-37	17
	120-545	288	95-520	234	20-45	36
<i>Lyngbya</i> sp.	0-45	20	0-22	16	0-14	6
<i>Synechococcus</i> sp.						
<i>Anabaenopsis abijiatae</i>	162-792	480	120-806	390	65-456	171
<i>Chroococcus</i> sp.	0-43	28	3-55	40	0-8	3
<i>Anabaena</i> sp.	10-115	45	5-75	38	---	---
<i>Microcystis</i> sp.	0-17	9	0-42	23	0-25	5
Diatoms						
	190-1400	630	45-663	286	5-215	78
<i>Navicula</i> sp.	145-878	595	23-383	208	5-180	69
<i>Nitzschia</i> sp.	15-235	95	0-65	26	---	---
<i>Melosira</i> sp.						
Chlorophytes						
	65-464	235	45-460	150	0-63	35
<i>Oocystis</i> sp.						

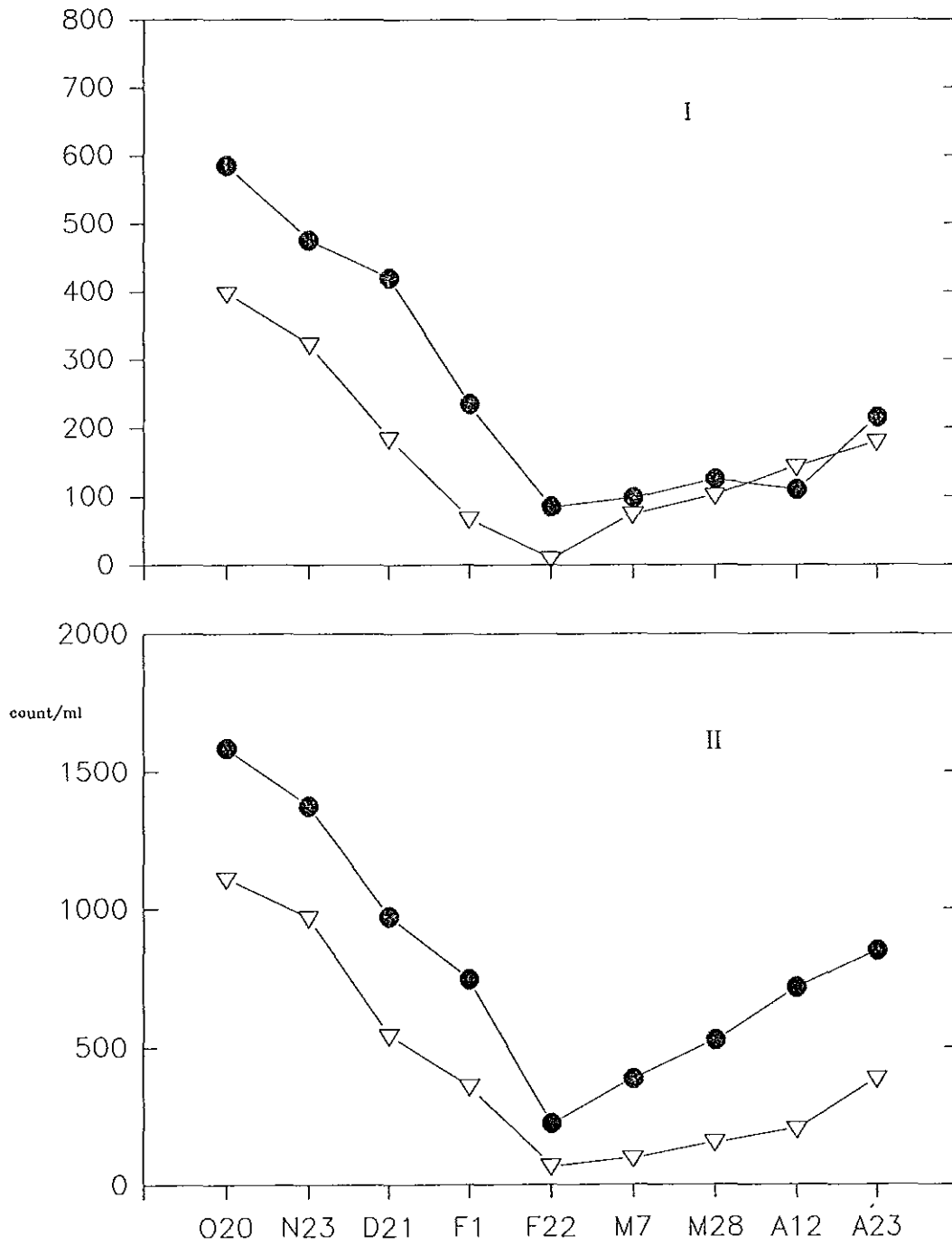


Figure 10. Temporal variation of blue greens (●) and diatoms (▽) in pond B (I) and the channel (II)..

Spirulina platensis was also present in less numbers in October, November 1996 and April, 1997. The absence of *S. platensis* during the rest of the study period both from the lake and the ponds is difficult to explain (even if counts represents only single samples). It may probably be associated with environmental factors which were not favorable during the time of study. Similarly, algal periodicity have been documented in Kenyan lakes (Killham and Hecky, 1973; Killham and Melack, 1974) and other soda lakes (Iltis, 1968). No previous report of phytoplakton count in lake Abijata is available to make comparison. The complete absence of algae in the collection from ponds C and D resulted from their inability to tolerate high salinity (eg. Zafar, 1964b).

The main lake supports a distinctly higher percentage of diatoms than the channel and pond B and the total number of diatoms that attained maxima during the period of observation is 40 to 1435 fil. and/or cells/ml. It is also clear from Table 2 that three sites (the lake, channel and B) are more or less have similar in averages of total nitrogen concentration and differ slightly in silica concentration (higher in B) .However, the main lake and pond B exhibit much higher values of phosphate than the channel, although the latter is richer in nitrogen. This suggests that the very high percentage of diatoms in the main lake is due to higher concentration of phosphate and low sulphate content although phosphorus was not a limiting factor in the ponds. The significant role of phosphorus in the distribution of diatoms has fully been recognized by limnologists. Kalff (1983) found that Lake Bogoria (Kenya) was rich in diatoms with high phosphorus (3.5mg/l). Tuite (1981) has shown that in certain East African lakes diatoms occur when waters are richest in nitrate, phosphate and silica.

On the other hand, the presence of higher concentration of phosphate and silicate were not associated with the growth of diatoms in pond B. The combined effect of salinity relatively low pH and high alkalinity (absence of free carbon dioxide) probably results in the decline of the diatom population. Beadle (1981) and Tuite (1981) have noted species of diatoms to be adversely affected by salinity in waters of East African lakes.

Silica levels tend to have lower concentration as compared to other African soda lakes, such as Aranguadi, Kilotes and Nakuru (50,32, 97 mg/l, respectively). Because of such high silica concentration in these lakes, benthic diatoms contributed at least 50% of the total primary production in Lake Nakuru (Melack, 1976). Low dissolved silica concentration in the present study can be associated to the high diatom population (silica tied up into the cell).

Although the large fluctuations (160 - 5840 meq/l) in the alkalinity of these ponds were an indication of variability in the biota, the reduced number (<50 filament/ml) of *S. platensis* in the productive ponds (<300 meq/l) seems paradoxical. Reduced alkalinity might not be the cause for decline of *Spirulina* since there is no limit for lower alkalinity of growth for *Spirulina* species (Beadle,1981). On the other hand, the same species dominates the algal flora of Lake Chitu (alk. 400 meq/l) and Lake Methahara (alk. 500 meq/l) (Wood and Talling, 1988) . Similar halo- or alkalophilic behavior of *Spirulina* is known in Kanaem Soda lakes, Chad with salinity ranges of 8.5—270 g/l (Iltis, 1968); and in Lakes Nakuru, Elmenteita and Reshitani, with alkalinities of 22, 107 and 164 meq/l, respectively (Kilham and Melack, 1974).

Considerable variations in species composition occurred in this study and the recent investigations made by Elizabeth Kebede (1996). Our observation, especially on species composition and abundance of species also emphasizes the justification for the remark by Melack (1976) who points out the danger of making general statements about the stability of tropical lake ecosystems from the results of short term sampling at restricted number of locations.

Tuite (1981) has classified primary producers community qualitatively into three types in relation to the site of primary production and the structure of the phytoplankton producer community: 1. *Spirulina* dominated phytoplankton production 2. Non-*Spirulina* dominated phytoplankton production and 3. Benthic diatom dominated primary production. In the present observation the primary production was contributed markedly by type 2 community. Some lakes may change in time from a type 1 to a type 2 or vice versa, which is similar to the results compared with the recent data of Elizabeth Kebede (1996). For example, after the decline of *Spirulina* at Nakuru and Bogoria , it was replaced by an assemblage of other species which included *Synechococcus* species, *Oocystis* species and planktonic diatoms (Melack, 1976). Although blue green algal species may be present at the time, they have chl. a concentration ($< 100 \mu\text{g/l}$) as the type 3 state.

In the main lake, the causes of shift from *Spirulina* populations (Amha Belay and Wood, 1984; Wood and Talling, 1988 and Elizabeth Kebede, 1996) to non-*Spirulina*

dominated phytoplankton may be due to the drop of alkalinity and salinity from 349 meq/l and 26g/l (Elizabeth Kebede, 1996) to 117.67 meq/l and 16 g/l, respectively, during the present study. Moreover, marked increase of sulphate, phosphate and pH could have a role in shifting the biota (Table 2). With the increase of the electrical conductivity in lake Nakuru and Elmenteita from 17 to 30 mmhoscm⁻¹, there was disappearance of *S. platensis* which coincided with a rapid increase in salinity (Vareschi, 1979). Melack (1988) summarized that a rate of change of conductivity greater than 5 mmhos cm⁻¹ per month and a salinity exceeding 25 mmhos cm⁻¹ cannot be tolerated by phytoplankton. However in the present study, the decreased salinity within five years time (in 1991, cal. 26 g/l and in 1996, it drops up to- cal. 16 g/l) may probably result in lowering of *S. platensis*.

Tuite (1981) reported that diatoms do not survive beyond salinity 20 g l⁻¹. However, Iltis (1968) and Beadle (1981) reported the occurrence of *S. platensis* in soda lakes where the concentration of total dissolved solids ranged from 8.5 to 270 g l⁻¹. The salinity tolerances of other algae were below this value. This supports the idea that the disappearance of *S. platensis* in lake Abijata is not only due to change in salinity but also to other factors, such as unusual increase of sulphate, decreased alkalinity and fluctuation of nutrient ratio (ionic ratio) in the lake.

Lesser flamingoes (*Phoeniconaias minor*) were seen in pond B and C including the lake, but never in pond D. Their abundance decreased with the decline in the water level of ponds, and gradually increased as the level increased. Tuite (1981) has shown

that in lake Nakuru their number decreased with the decline in the phytoplankton biomass during the dry season, but returned back as the benthic algae increased. Flamingoes were observed feeding selectively along the shoreline in the main lake but they dip their beak while feeding in ponds (feeding on benthic organisms), which suggests that there is high primary production at deeper depths in ponds.

Tuite (1978) has shown that flamingo number at Nakuru are correlated with *Spirulina* density. He made a general study of their ecology and behavior on their diet, which consisted almost exclusively of either *Spirulina* or benthic diatoms, and their distributions and migration patterns are closely related to the availability of these resources. However in this study, the presence of such large flocks of flamingoes was not related with the presence and absence of *Spirulina*, and is; therefore surprising. This observation leads us to speculate that they may probably feed on items other than algae, such as cladocerans or corixids, or both.

Fish were reported to have totally disappeared since 1986; however small fry were observed in the channel during this study. This seems to be an indication of recovery although the reason is unknown. A high proportion of greater flamingoes (*Phoenicopterus ruber*) and pelicans (*Pelecanus onocrotalus*) was typical of the lake before the disappearance of fish (Amha Belay and Kassahun Wodajo, 1984).

4.4. Phytoplankton biomass

Chl-a concentrations varied temporally by more than an order of magnitude, and ranged from 0.1 to 88.96 mg chl-a m⁻³ in the channel and from 0.7 to 11.26 mg chl-a m⁻³ in pond B (Fig 9-II). Between October and November, 1996 chl-a declined from about 88.96 to 2.78mg chl-a. m⁻³ in the channel. A further drop then took place between Dec.1996 and Feb. 1997. In March, 1997 a partial recovery occurred and this lasted until the end of the study period.

In pond B , high values in October (8.34 mg chl-a m⁻³) were followed by alternative increase and decrease with a pronounced maximum in April,1997 reaching a concentration of 11.26 mg chl-a m⁻³ (Fig 9-II).

The chl-a concentration values of the lake recorded in the present study (11.26 mg chl-a m⁻³) are lower compared to those reported by earlier investigators, such as 65 µg/l (Amha Belay and Wood, 1984) and 135 µg/l, Elizabeth kebede (1996). Methodological differences invalidate direct comparison of these values with the present data, (The *Spirulina* abundance was evidently comparatively lower during this study). In the present study, estimation of chl-a concentration was made after degradation (unlike earlier study) which might underestimate the result.

It is evident that high algal standing crop was not observed in most of the samples. The October and April, 1997 chl-a peak was associated with a high density of blue green algae and diatoms, whereas the February, 1997 phytoplankton bloom dominated by only *Anabaenopsis abijatae* in pond B. The channel and pond B exhibit quite high algal crops between December and beginning of February, 1997; however, chl-a values determined at the time were very low. Euphotic zone in December, 1996 was about equal to that of October, 1996 (1.2m) in the channel, although clearly the biomass of algae is not the sole or even prime cause of light attenuation. Possibly salt turbidity due to higher wind turbulence dominates the light climate there where only $0.1 \mu\text{g chl-a l}^{-1}$ was measured. On the other hand the high incident radiation which reaches the bottom in pond B, (>30% of surface irradiance) may be due to low algal density and its shallowness.

The concentration of chl-a (Fig 9) and the numerical abundance of algal species (Table 3 and Fig.10) are usually low in all sampled waters when compared with those of other saline lakes. In Lake Nakuru, Jenkin (1936) reports 6000-9000 trichomes per ml and Kilham and Melack (1974) estimated a mean of 13350 trichomes. Melack (1979b) estimated $800 \mu\text{g chl-a. l}^{-1}$ in the same lake. Moreover Melack *et al.*, (1982) recorded a value of $80 \mu\text{g l}^{-1}$ when the level of water increased in Lake Elmenteita and Sonachi. Vareschi and Jacobs (1985) found high concentration of chl-a (1000 mg m^{-3}) and numerical abundance (12000 filaments/ml) of *S. platensis* in Lake Nakuru.

Tuite (1981) reports show that the population of *Spirulina* sp. exhibits irregular fluctuations in Lake Elmenteita. Melack (1976) recorded a significant fall in the number of *S. platensis* and *S. laxissima* trichomes between February and November and this was correlated with a decrease in total phytoplankton chlorophyll from 250 $\mu\text{g l}^{-1}$ to 10 $\mu\text{g l}^{-1}$. Samples collected in the same lake by Jenkin (1936) in May contained 1600 trichomes per ml. From these and the present study, it is evident that standing crop densities of algae in alkaline saline water bodies are extremely variable with time.

4.5. Photosynthetic activity

The results of the *in situ* photosynthesis experiments and associated parameters in the channel, pond B and lake shore are shown in Table 4 and Figures 11 and 12. Rates of photosynthesis calculated from change in dissolved oxygen and converted to carbon varied from 100 to 3000 mg C m^{-3} in both the channel and pond B. Areal photosynthetic rates determined by Grid method ranged from 0.2 to 1.05 $\text{g C m}^{-2} \text{h}^{-1}$ in the channel, and 0.042 to 0.414 $\text{g C m}^{-2} \text{h}^{-1}$ in pond B. On the basis of three determinations in the lake, it varied from 420 to 2383 $\text{mg C m}^{-3} \text{h}^{-1}$.

The depth profiles of photosynthesis had maximum rates (A_{max}) below the surface. Vertical distribution of photosynthetic rate with typical pattern for phytoplankton (Fig. 11 and 12) of surface light inhibition was observed unlike the pattern for most tropical

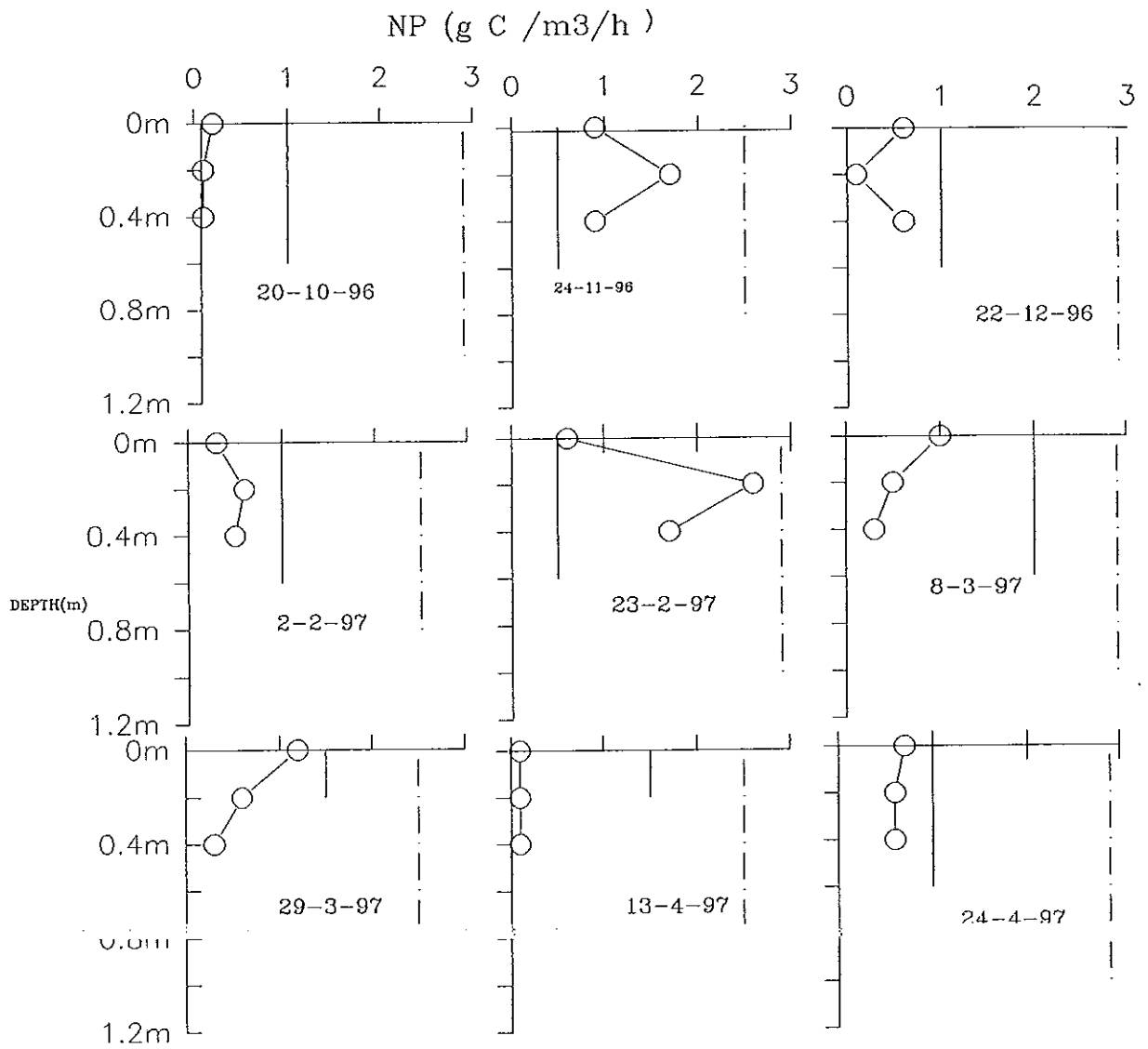


Fig. 11. Temporal changes in vertical distribution of net photosynthesis determined by oxygen evolution (o-o), incident light (|) and secchi depth (|) in the channel.

* 11.00 am is the midpoint for all incubation .

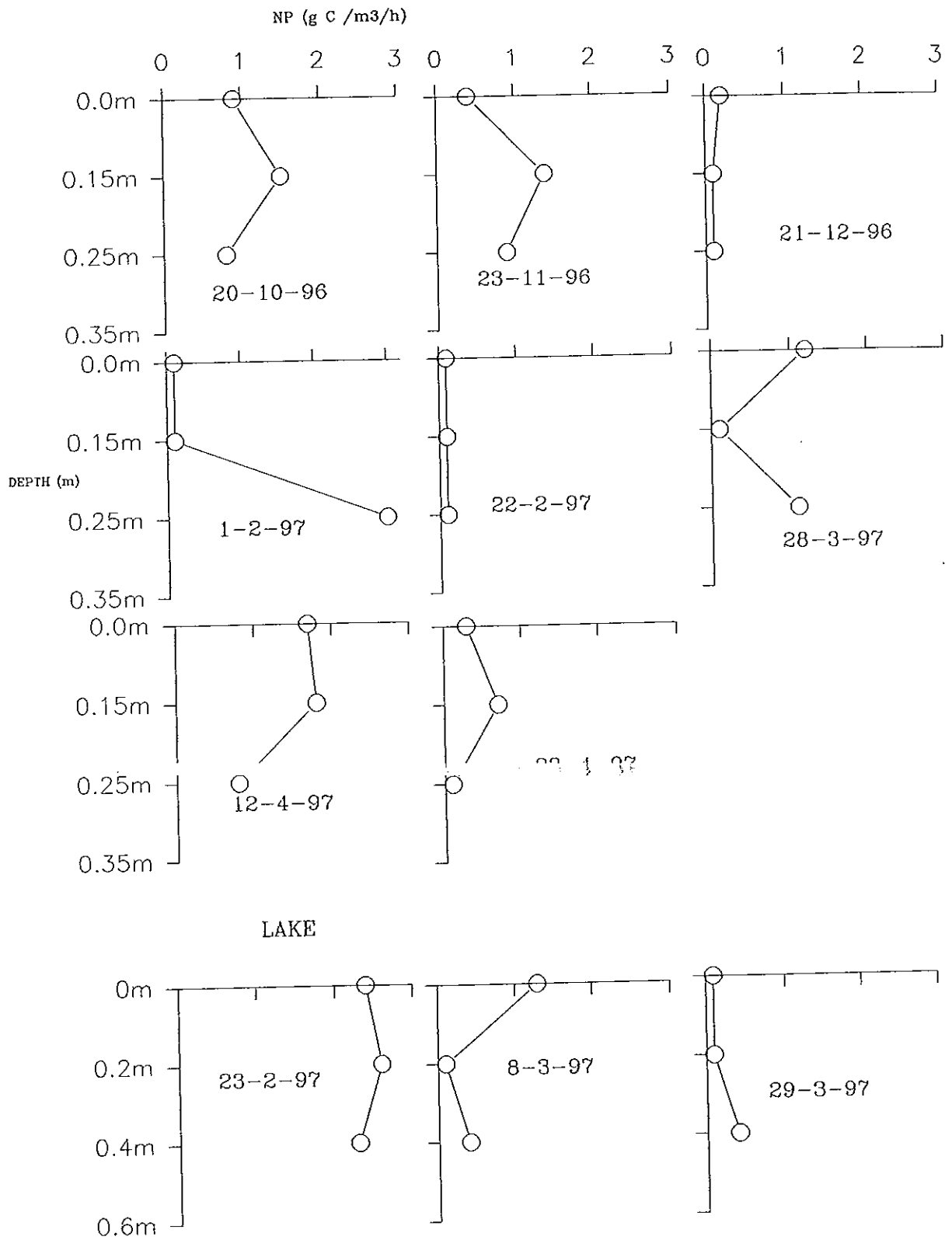


Fig. 12. Vertical distribution of net photosynthesis in pond B and the lake4..

Table 4. Measurements of the photosynthetic rates of phytoplankton and associated parameters in the lake, channel and pond B.

	Time interval midpoint	Amax: mg C m ⁻³ h ⁻¹		ΣA: mg C m ⁻² h ⁻¹		Q max : (mg C m ⁻³ h ⁻¹ /mgchl-am ⁻³)		B: mg chl-a m ⁻³		Surface insolation during incubation μEm ⁻² sec ⁻¹		Secchi depth-SD (cm)	
		Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Lake shore	11 am	400-2380	1070	20-1290	655	36-1333	495	1.95-11.26	8.16	1500-3400	2100	20	20
Channel (A)	11am	100-2600	600	200-1050	488	2.25-4600	1292	0.1-88.96	16.14	1500-3400	2100	23-60	50
Pond B	11am	100-3000	700	40-414	221	100-960	354.70	0.7-11.26	4.27	1705-4500	2934	whole depth	whole depth

alkaline, saline lakes with maximum production rates almost always at the surface (Kilham and Melack 1974; Melack, 1979; Shapiro, 1984). The occurrence of surface photo-inhibition in the present study sites, (based on the photosynthetic depth-profiles) was associated with few or no standing crops of *Spirulina*, which is attributable to its resistance to high light intensities (Demeke Kifle *et al.*, 1995, In prep.).

In pond B, active photosynthetic rates were observed in all sites except for one experiment where change of oxygen was not detected (March, 1997) and one with no net photosynthesis rate in December, 1996. This reduced synthesis is also related to the dry season of high evaporative concentration that result in increased salt concentration.

Beginning in Feb. 1997, the depth distribution of photosynthesis shifted from profiles with conspicuous subsurface maxima and narrow euphotic zones to profiles of surface maxima in the channel (Fig. 11), whereas in pond B, surface maxima up to Feb, 1997 were shifted to profiles of bottom maxima and with synthesis occurring to the bottom (Fig. 12). Usually the euphotic zone in pond B was the entire water column of the pond and production took place throughout the depth because light was not a limiting factor. However, incubation at a very shallow depth may create difficulty in resolution of the depth of light-saturated rate of photosynthesis (Melack, 1979a).

Based on Cole's *et al.*, (1967) suggestion that environmental conditions which are associated with a lake have an implication to the natural ponds (such as ponds of the present study), comparison of photosynthesis and other factors can be made among different water bodies. Although comparisons made between results of different studies are complicated by the use of different techniques and different periods of incubation, alkaline saline lakes are generally productive. It has been reported that the broad range of Amax values for saline lakes vary from 13 to 1200 mg C m⁻³ h⁻¹ in Canadian saline lakes (Hammer and Hynes, 1978); from 48.1 to 6199 mg C m⁻³ h⁻¹ in Australian saline lakes (Hammer, 1981); and from 767-5,000 mg O₂ m⁻³ h⁻¹ for African saline lakes (Talling *et al.*, 1973; Kilham and Melack 1974).

Areal rates from the highest integral photosynthesis coincided with maximum volumetric photosynthetic rate in the channel. Furthermore, it reaches a peak when depth distribution photosynthetic profiles and light irradiance without obvious maxima and with synthesis occurring to the surface and bottom in both ponds. The highest daily rate in pond B is 5 g C m⁻², while the main lake and the channel have rates of 11 g C m⁻² d⁻¹. Mean gross productivity for the world's productive lake is about 11 g C m⁻² d⁻¹ (Kilham and Melack 1974). The highest rates in East African Alkaline Lakes are in lake Aranguadi & Nakuru, with values greater than 25 g C m⁻² d⁻¹ (Talling *et al.*; 1973) which is greater than the results of this study.

Values of photosynthetic efficiency [Qmax: mgC₂ (mg chl- a)⁻¹ .hr⁻¹] ranged from

2.25 to 4600 in the channel and 100 to 960 in pond B (table 5). Although some of the values seem to be within the range of a study made by Amha Belay and Wood (1984), 15 in Lake Abijata, they considerably exceed even the highly productive lakes of Africa (Q_{max} , 11- 18). These unusually high values resulted from the lower values of chl. a concentration ($< 1 \text{ mg chl-a m}^{-3}\text{h}^{-1}$). Hammer (1978) states that for eutrophic and mesotrophic lakes, maximum P_{max} ($\text{mg C m}^{-3} \text{ h}^{-1}/\text{mg chl-a m}^{-3}$) value exceed the equivalent of $6.67 \text{ mg C h}^{-1} (\text{mg chl-a})^{-1} \text{ m}^{-3}$. Lake Aranguadi and Simbi are less than this value [$6.43 \text{ mg C h}^{-1} (\text{mg chl-a})^{-1} \text{ m}^{-3}$] in spite of their eutrophic nature (Melack, 1979; Demeke Kifle *et al.*, 1995 In prep.). This implies that it is possible to inoculate alkalophilic species in the Abijata evaporative concentration ponds since there was no problem of self shading.

The unusually high surface illumination (approx. $1003 \mu\text{E m}^{-2}\text{sec}^{-1}$) enhances surface primary production, and may probably create photo-oxidative conditions. The light intensity reaching the bottom of pond B was higher than 30% of the surface light and the depth of maximum production was frequently shallower than 15cm. It reached up to 78% of the surface light during the dry seasons of Feb, 1997 when the water level declined. Equally this amount of light ($450 \mu\text{E m}^{-2}\text{sec}^{-1}$) is sufficient for oxygenic photosynthesis (Cohen *et al.*, 1977a).

Photosynthetic rate in pond B was inversely related to insolation (Fig. 12). This saturation at low light levels, with some of the curves showing slight lack of photo-

inhibition at higher level intensities (e.g., Fig. 12; March 28, 1997), may be related to lack of light limitation at the bottom of pond B which might have resulted due to shallowness and wind mixing. Therefore, such situations create upwelling of benthic diatoms (Feb. 1997) which are preferred at attenuated light levels (optimum light condition). Similar results have been obtained for solar lakes (Cohen *et al.*, 1977b).

In fact, detailed analyses of benthic algae were not done here. However the occurrence of highest light saturated photosynthetic rate coincident with large population of benthic algae has been reported by several limnologists. Melack (1976) reported that benthic algae can make substantial contribution to productivity in the shallow Kenyan lake, Elmenteita. He indicated that benthic diatoms contributed at least 50% of the total primary production.

Benthic diatoms were abundant in the water column during the dry season, and were numerous in the deeper layers of the water column. This high production is consistent with the fact that wind induced turbulence currents prevailed. Studies on benthic diatoms in temperate lakes indicate that their abundance in the water column results from mixing generated by strong winds (Round, 1981; Harris, 1986).

There was no time with pronounced thermal stratification throughout most of the daylight in pond B. So it is difficult to observe the influence of mixing depth on photosynthesis. Melack and Kilham (1974) obtained similar gross photosynthetic rates during both periods of pronounced stratification and mixing to the bottom in all days

in Lake Nakuru. This is attributable to the enhancement of photosynthesis caused by greater turbulence which results in a large number of phytoplankters exposed to light, and suppression of photosynthesis in the region of high light and oxygen.

Integral photosynthesis and chl-a were found to have similar pattern in pond B, with a peak during the rainy month in April, 1997 (Fig.13). This indicates that standing crops were not high enough to affect the light penetration i.e. shading was absent. In most African alkaline lakes, areal photosynthesis at greater Chl-a concentration is very low due to the effect of self-shading (Talling *et al.*, 1973, Melack, 1981). Moreover, the occurrence of higher rates during the rains in pond B shows that it is highly sensitive to little changes in the environment (physical and chemical parameters). The lower photosynthetic rates and Chl-a concentration of pond B as compared to the lake and the channel may probably be associated with an increase of total solids and vigorous wind mixing that induce instability.

Hammer (1978) classified lakes into 'Eutrophic' and 'Oligotrophic' according to the relative concentration of nitrogen, phosphorus and calcium in water. The present study of waterbodies approach Hammer's 'eutrophic lakes' as they are rich in the above nutrients even though they are rich in sodium in place of calcium. Ponds C and D occupy a peculiar position with totally no production. Moreover, the most productive waterbodies tend to have relative high pH values, i.e., 9.0 to 10.5 (Hammer, 1981). Thus pH values are within or above the world's range and higher alkalinity enable the water to be well buffered and stable at high pH levels.

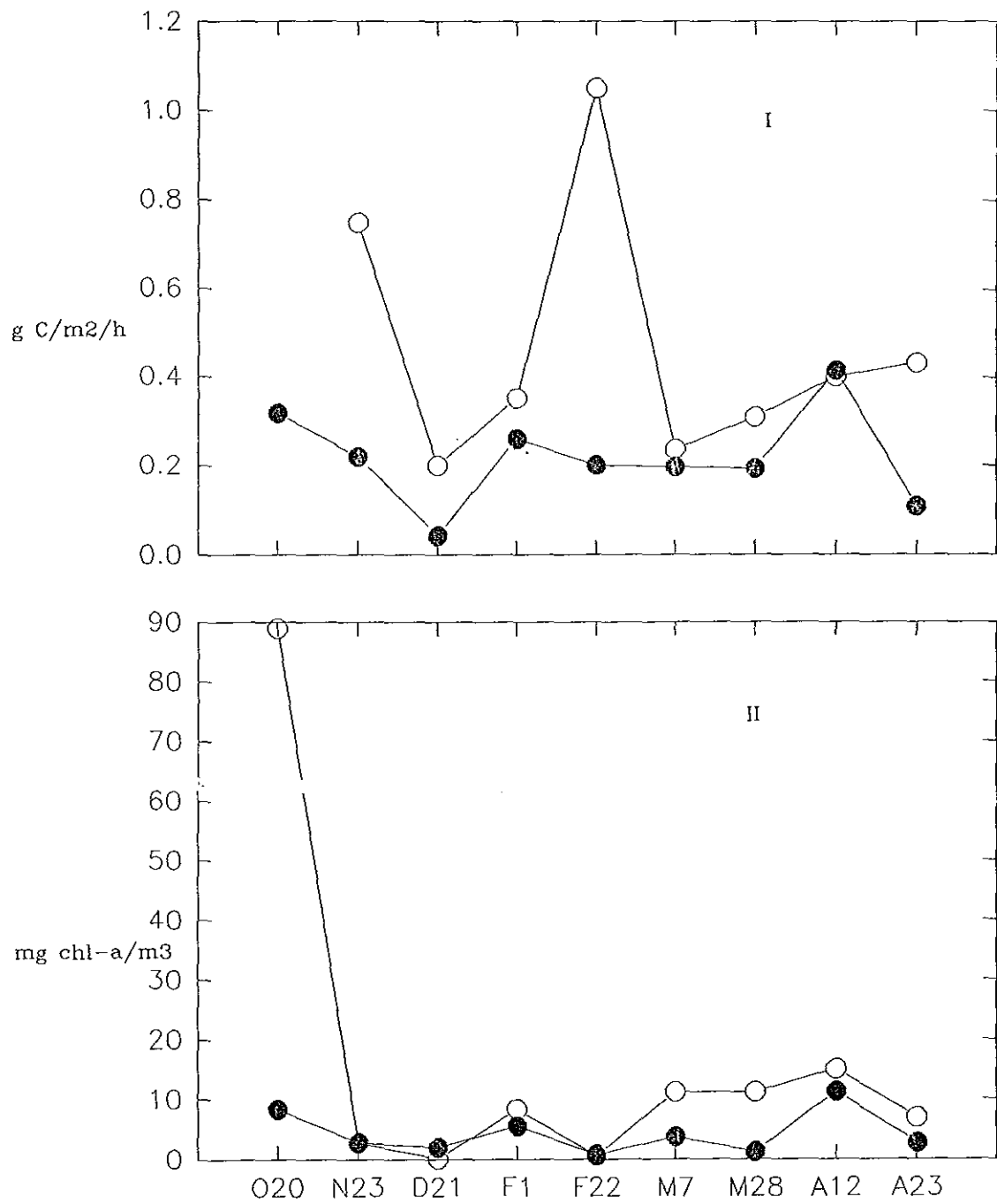


Fig. 13. Variation in areal photosynthesis (I) and chl-a concentration (II) in the channel (O) and pond B(●).

4.6. Methods for Photosynthesis Measurements

Independent estimates of primary production were made from the differences in dissolved oxygen and carbon-14 uptake method. As shown in Table 5, Miller titration gave values, more than the Winkler method over the range of carbon fixed from 342 to 2383 mg C m⁻³ h⁻¹ for the channel and from nearly zero to 2500 mg C m⁻³h⁻¹ for pond B. The carbon- 14 values lie between Winkler and Miller measurements for most of the time (Table 5).

Considerable controversy has always been associated in estimating photosynthetic rate with the choice of method, the frequency of measurement, the length of production incubations and the comparison of results employing different methods estimating primary production (Hammer, 1981)

Ryther and Dunstan (1956) have pointed out that of these three methods, C¹⁴ uptake is the most sensitive. Although the degree of accuracy of these methods vary, neither methods are without drawbacks. Kilham and Melack (1974) recognized the difficulty in measuring dissolved oxygen in alkaline saline waters. In the very carbonate rich waters of Lake Abijata and Lake Shalla, problems were encountered with formation of bubbles upon acidification using the Winkler method (Amha Belay and Wood, 1984). Cole *et al.*, (1967) were unsuccessful in measuring dissolved oxygen by the Winkler method in saline Arizona ponds. Similar results were obtained in pond C and D of the present study. Although the hot subsurface layer of D was

Table 5. Comparison of the Winkler, Miller and ¹⁴C results for the Lake, channel and pond B.

	Channel(A)			The main Lake			Pond B		
	Winkler mg C m ⁻³ h ⁻¹	Miller mg C m ⁻³ h ⁻¹	C-14 mg C m ⁻³ h ⁻¹	Winkler mg C m ⁻³ h ⁻¹	Miller mg C m ⁻³ h ⁻¹	C-14 mg C m ⁻³ h ⁻¹	Winkler mg C m ⁻³ h ⁻¹	Miller mg C m ⁻³ h ⁻¹	C-14 mg C m ⁻³ h ⁻¹
Dec., 1996	579	625	--	--	--	--	200	400	--
Feb.1, 1997	289	322	--	--	--	--	22	358	--
Feb.22,19 97	600	833	--	2383	3250	--	8	50	--
Mar.7, 1997	1050	1500	1200	1270	1580	1120	0.000	0.000	66
Mar.28, 1997	1200	2383	1104	38	2800	176	1183	1262	950
Apr.12, 1997	0000	342	65	--	--	--	1712	2500	1640
Apr.24, 1997	719	856	600	--	--	--	317	342	228

anoxic, we are certain of oxygen production (using oxygen probe) at least at the surface layer in these highly concentrated ponds. Therefore addition of 2N sulphuric acid, no matter how slowly, brought about a violent reaction (effervescence) with loss of a portion of fixed samples.

Miller (1914) showed that his method provides results comparable with, but less precise, than those of Winkler method for fresh water and for salt solution. On the other hand, Ellis and Kanamori (1973) modified the method and obtained relatively higher values than Winkler for distilled water and salt solution. Similar patterns were seen in the present *in-situ* experiments. Other measurements from Lake Nakuru recorded values of 7.91 and 7.37 mgO₂/l, with Miller and Winkler methods, respectively (Kilham and Melack, 1974).

In practice, using Miller method, a pH of less than 10.5 leads to indistinctly end points, with the indicator color being discharged and then reappearing after a few seconds. However, in the present productive ponds, the pH is greater than the above values. Therefore, it can easily attain its optimum pH (12.2 to 12.6) by addition of very little amounts (2 ml) of alkaline tartrate during titration. This indicates that the problem of underestimation which appeared with the Miller method may be associated with low alkalinity of water, that does not maintain its pH at a higher level.

There is also difficulty to determine whether carbon—14 incorporated in 'algal cells' represents gross or net photosynthesis. Similar problems were encountered in

hypersaline Mono lake, California (Melack, 1988). However the results in this study seems to represent net photosynthesis since radiocarbon in the solution (recycled or released to the medium) was not estimated.

Both the carbon-14 and Winkler methods do not reflect algal photosynthesis alone but also the assimilation of carbon by photosynthetic bacteria in the former case and the flux of oxygen between algal/bacteria/zooplankton community in the latter one. Such bacterial carbon fixation ($345 \text{ mg C m}^{-3}\text{h}^{-1}$) was readily verified in one experiment made in the less productive pond C. However, Miller's method can provide estimates of photosynthetic rate by oxygen evolution (The results of dissolved oxygen in dark and light bottle were equal in pond C and D).

Bottling effect, such as the problem of mixing, super saturation (oxygen tension), depletion of carbon in combination with the errors in the measurement of dissolved oxygen and carbon-14, certainly make our determinations of photosynthetic rates underestimates (Table 5). Evidence to this is provided by Talling *et al.* (1973), Kilham and Melack (1974) and Melack (1979b). These investigators of African soda lakes reported estimates of photosynthesis based on changes in dissolved oxygen in open water (using polarographic electrode) which are substantially in excess of those based on changes inside bottles. Mora as cited by Melack (1981) reported that vertically cycled bottles give estimates of integral photosynthesis, 19 to 87% higher than estimates from a static ones.

Although Polarographic electrode and carbon-14 methods are very sensitive, Miller's technique was found to be effective and an easily applicable method in very alkaline saline lakes. Moreover, determination of dissolved oxygen with Miller method reduce the problems of effervescence. The result of this study confirm the importance of this method over the others in saline, alkaline waters. The higher value of Miller measurements are probably associated with leakage of atmospheric oxygen into both the reagents and samples during titration.

5. CONCLUSION AND RECOMMENDATIONS

The five water bodies studied exhibit a wide range of depth and gross chemistry which is summarized in Table 2. These differences can be explained largely in terms of salinity, conductivity and alkalinity gradients. Although the salinity of the ponds has an influence on the optical properties, it is compensated by intense wind mixing. However in pond C and D the change of salinity exceed the physiological tolerance of the algal community.

All the examined productive water bodies (A, B and the lake) mainly exhibited the typical photosynthesis versus depth curve with maximum rates (A_{max}) below the surface. This might be due to high temperature, high oxygen, high irradiance and the absence of free carbon dioxide that are all pre-requisites for photo-oxidative death. However this scenario is not common in most alkaline saline lakes. *S. platensis*, an algal species that efficiently uses bicarbonate and can tolerate higher irradiance and temperature was either absent or rare in the study sites. In most of the study sites alkalinity and salinity are negatively correlated with pH unlike other East African waters.

Temporal variations in photosynthetic rates were most closely related with changes in water level, i.e. evaporative concentration that brings about change in chemical compositions. The effect of seasonal variations on daily radiation was probably unimportant. Moreover photosynthetic activity was dependent on algal distribution

within the euphotic zone. The maximum photosynthetic value in pond B was probably related to the dark carbon assimilation of bacteria and benthic diatoms which attain optimal condition at light climate. Almost all nutrients were found to be quite high. The most productive lakes which are not highly saline (usually less than 30 mS cm^{-1}), have high alkalinities and thus high pH and are rich in soluble phosphorus. All the ponds have characteristics of productive lakes with respect to nutrients. The concentration of inorganic nutrients were high during the dry months with high evaporative concentration. The concentrations in the channel and pond B were more or less similar. A slightly less concentration in the channel was associated with uptake by relatively higher number of algal populations.

Maximum chl-a concentration was associated with large number of phytoplankters, but did not coincide with peaks in primary production. Thus production was highly associated with benthic diatoms especially in pond B. Mean chl-a concentration in all ponds are below the values usually considered indicative of eutrophic water-bodies ($>500 \text{ mg chl-a m}^{-3}$).

The co-dominance of *S.platensis* with *Anabaenopsis abijatae* in earlier investigations was not observed in the present study. Thus further studies on the hydrology of the lake and ponds are required for effects of chemical treatment and extraction of soda ash or/and natural changes. These are believed to be the major cause for the change of biota, such as the low number of *S. platensis* and fish species.

Photosynthesis was estimated by oxygen evolution during the seven months of investigation. Since considerable effervescence on acidification is a problem with the Winkler method and handling, cost and environmental hazard associated difficulties of C-14 method; the Miller's method was found to be reliable for such alkaline saline waters.

Some of the major recommendations are listed below:-

Implications for large scale production

1. The low level of *S. platensis* might also be associated with the type of strain. The physico- chemical parameters in the productive ponds are within the optimal range for *Spirulina* blooms. In addition to this, meteorological parameters offer good conditions for the cultivation of this species. Thus it is possible to inoculate, may be other strains of *Spirulina*, particularly from Lake Aranguadi for out-door production. Nowadays, Lake Abijata and its surroundings are poor in fresh water resource, and thus lack the basis for traditional agriculture. This is the background for the interest in *Spirulina*, which could be grown in water resources not suitable for agriculture.
2. Since mixing is a regular event in pond B, industrial application may not involve the need for paddle wheel for agitation. No unusual, sophisticated or even imported parts are needed. Furthermore there seems to be no need of addition of fertilizers. Outdoor mass culture of *Spirulina* in such water-bodies seems technically feasible without any mechanical and chemical manipulations. However several

physiological and taxonomic aspects of *Spirulina platensis* remain to be clarified in order to derive the best benefits from this opportunity.

3. There is a possibility to increase primary productivity in pond B by making it more deeper in order to raise the euphotic zone since greater than 30% of the surface irradiance reaches the bottom.

Implications for control of algal coloration

1. Although the dead scum of algal debris and zooplankton float over the surface of the trona pond (D), it is derived from the preceding productive ponds. Whether the coloration of the trona is due to algal scum or bacterial activity still needs further studies on the type and effect of bacteria on this pond.
2. Since the plankton community disappear with higher salinity, exposure of the water in pond B for a longer period of evaporative concentration may limit the growth of algae and other communities that affect the color of the trona.
3. Although nutrient removal by shifting the optimal ratio is often practiced in water quality programs, it may also result in undesirable outcome such as flourishing of other species. So the feasibility in this needs to be studied closely.
4. If treatment has practical value, pond B is the best one that should be manipulated. Moreover it is possible to carry out both cultivation of *Spirulina* and extraction of trona in parallel or alternatively, that is cultivation during wet season (May-October) and extraction as usual during the dry season (November- April).

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